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ADAPTATION AND BACKWARD MASKING EFFECTS  
WITH SINUSOIDAL PHASE GRATINGS

by  
Ronald Szoc

A Dissertation Submitted to the Faculty of the Graduate  
School of Loyola University of Chicago in Partial  
Fulfillment of the Requirements for the  
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December

1979

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## VITA

The author, Ronald Szoc, is the son of Antoni Szoc and Helen (Sieczka) Szoc. He was born May 25, 1948, in Flenzberg, Germany.

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## INTRODUCTION

The research reported here focuses on an examination of adaptation and backward masking effects obtained with sinusoidal phase gratings. It is organized according to the following sections:

Spatial Frequency Effects. This section presents a broad overview of the application of Fourier analysis to human psychophysical data. It attempts to illuminate the various themes that occur in the relevant literature.

Spatial Phase Effects. This section discusses the psychophysical studies that have dealt with spatial frequency phase effects in human vision. There are remarkably few such studies, given the wide currency of linear systems application in human psychophysics, that have directly tested the notion of visual processing of phase information.

General Methodology. Of the six experiments conducted, four employed an adaptation paradigm while two employed a backward masking paradigm. This section will first describe the construction of the stimuli and the experimental apparatus used. It will next describe those aspects of the data collection methods common to all the experiments.

The Adaptation Studies. This section will detail each

of the four adaptation studies along with their results and a brief discussion of each.

The Backward Masking Studies. This section will describe each of the two backward masking studies along with their results and a brief discussion of each.

General Summary and Discussion. This section will summarize the main results of all of the experiments and will attempt a synthesis of the findings.

In studying the visual system by Fourier analysis, it is important to keep a number of notions distinct. On one level, Fourier analysis is only a mathematical tool for mapping one set of numbers into another set of numbers; it is a rule for mapping between two function domains. On another level, Fourier analysis may well describe a process that actually takes place in the visual system. The perspective taken here is that, regardless of whether the visual system "computes" a Fourier transform of the stimulus or not, Fourier analysis has been shown to have a certain amount of predictive validity. If the studies bear out the predictions of the analysis, then its use as a predictive tool is enhanced. If not, the utility of this analytical approach is lessened.

## SPATIAL FREQUENCY EFFECTS

In 1968, Campbell and Robson published a classic paper dealing with the psychophysics of vision. They obtained contrast sensitivity functions (CSFs) for a variety of stimuli: sine waves, square waves, and rectangular or saw-tooth wave forms. The results were interpreted in terms of the Fourier components of the various stimuli, rather than in terms of a simple pattern matching scheme. In the Fourier domain, a sine wave contains only one frequency component; a square wave consists of a sine wave component of the same fundamental frequency as the square plus an infinite number of the odd-numbered harmonics of the fundamental frequency at decreasing amplitudes. Campbell and Robson found that, over a large variety of spatial frequencies, the contrast threshold (which is that point at which the grating is seen about 75 percent of the time it appears) of a grating was determined by the amplitude of the fundamental Fourier component in the composite waveform. In Figures 3 and 4 of their article, the CSFs for sine wave gratings and for square wave gratings are identical above approximately 1 cycle per degree. Since the fundamental Fourier component for all stimuli used had the greatest magnitude of all the components, the threshold value for the appearance of the grating (as opposed to a homogeneous blank field) was

reached when the fundamental threshold value was reached. Gratings having complex Fourier spectra (complex meaning more than one component) could not be distinguished from pure sine wave gratings until their contrast had been raised to a level at which the higher harmonic components reached their independent thresholds. In other words, the visual system was responding, not to the stimulus configuration on a point by point basis, but to the sinusoidal components making up the Fourier spectrum of that stimulus.

Campbell and Robson tentatively suggested a neuronal mechanism consisting of independent "channels", each channel maximally sensitive to a different frequency band, and thus, each channel having its own CSF. The envelope of all the CSFs for these spatial frequency channels would constitute the CSF for the visual system as a whole. Neurophysiological work in the retinal ganglion cells in cats provided some biological evidence for a frequency sensitive mechanism (Enroth-Cugell and Robson, 1966).

This early paper addressed a number of issues that are still found in the literature that applies Fourier analysis to the processing of sensory-perceptual information.

The first issue involved the primary assumption that the visual system can be treated analytically as a linear system under certain conditions (at threshold, for example). Fourier analysis implies the addition and the subtraction of

sine and cosine waves to represent any function. The visual system was assumed to be linear by Campbell and Robson so that Fourier analysis techniques could be justified theoretically.

The second issue involved the proposed mechanism for explaining the results. The explanation posited the existence of a set of frequency channels, each sensitive to a relatively narrow band of frequencies, with a bandwidth of plus or minus one octave on either side of the center frequency for that channel (plus one octave doubles the frequency, while minus one octave halves it).

The third issue involved the implicit link that was drawn between a mathematical description of a process (Fourier analysis of a visual phenomenon) and a neurophysiological reality actually taking place inside the visual system. The link consisted of the premise that the visual system, at some level, was actually decomposing the visual stimulus into its constituent sinusoidal parts. Although intriguing, this link was not critical for explaining the results.

The first theme, that of the linearity of the visual system, had been studied somewhat earlier (e.g., Davidson, 1965) and would be studied again to reveal those conditions under which the visual system responded in non-linear ways (Burton, 1973; Nachmias, et. al., 1973).

The second theme, that of multiple channels, each



sensitive to a particular narrow band of frequencies, had been the subject of a great deal of controversy in the literature. Some researchers (Campbell, Carpenter, and Levinson, 1969) find results that are consistent with a single channel model where one CSF is applicable to the data. On the other extreme, researchers (e.g., Kulikowski and King-Smith, 1973) find not only frequency channels, but also "edge channels," "bar channels", and "sustained" and "transient" channels.

The third theme, that of the visual system actually "computing" a Fourier transform of visual input has the least amount of data to support the theoretical underpinnings. While Fourier analysis predicts the results for grating and bar stimuli well, it has found limited application in studies of cognitive functions, such as recognition of letter or word patterns, with a few exceptions (Weinstein, Montalvo and Ozog, 1973).

Fourier analysis has been somewhat successful, however, in predicting results for complex patterns that contain broad bands of frequency components. Ginsberg (1973) has shown that a number of classic Gestalt principles such as closure, proximity, and similarity can be explained by the visual system emphasizing the low and medium range of frequency. Ginsberg (1975) has also shown that a figure which contains an illusory triangle contains frequency

components of a similar "real" triangle. In other words, the frequency information for the triangle that is illusory is present in those discs and their configuration which give rise to the illusion. The reason the illusion is perceived is that the frequency information is being "processed" by the visual system.

Harvey and Gervais (1978) used pictures of sinusoidal gratings which were distributed such that any one photograph showed the sum of a broad band of spatial frequencies centered around some center frequency. Four different center frequencies were used. They had their subjects sort the photographs into piles (from two to five piles) along a similar/dissimilar dimension. They found results consistent with the notion that the subjects were using frequency information along three different dimensions: low, medium and high frequencies.

Finally, Tieger and Ganz (1979) studied the recognition of faces in the presence of two dimensional sinusoidal gratings. They found that recognition was significantly affected by the presence of a 2.2 cycles per degree sinusoidal mask. This finding led them to speculate that the visual system processes complex information such as facial features in terms of its frequency components, and the visual system emphasizes the importance of the lower and middle frequency range at the expense of the higher frequency components. Implicit in their interpreta-

tion, and made explicit by Harvey and Gervais (1978), was a two-step hierarchical model in which a pattern is first analyzed into its Fourier components and, then, these components were further emphasized (beyond that which can be explained by the human modulation transfer function) by a second stage in pattern processing.

### Models of Frequency Analysis of the Visual System

There have been few critical psychophysical tests of the spatial frequency hypothesis that rule out local feature adaptation explanations. Consequently, there have arisen two forms of models for the extant data: space-domain models and frequency domain models.

Space domain models (e.g., Macleod and Rosenfeld, 1972a, 1972b; Wilson and Giese, 1977) typically assume the presence of the visual system of receptive fields with excitatory centers and inhibitory flanks, much like that found neurophysiologically in cats (Rodieck, 1965). In these space domain models, the salient feature of a grating is not its spatial frequency or phase but its bar width and position.

Frequency domain models (Sachs, Nachmias and Robson, 1971; Pollen, Lee and Taylor, 1971; Graham, 1976) typically assume the existence of a finite number of spatial frequency channels, each "tuned" or responding maximally to a different center frequency with probability summation among the

channels giving rise to a threshold response of detection of the stimulus grating. In contrast to space domain models, frequency domain models are sensitive to the spectral characteristics, or Fourier components, of the stimulus pattern.

The distinctions between frequency domain and space domain models of pattern processing are not often as clear cut as the previous discussion would seem to imply, both as treated in the literature and on more theoretical grounds. This fogging of distinctions occurs because of the fundamental premise implied in both types of models with regard to the hypothetical receptive fields used to predict the results. In space domain models, for example, the predictions are typically based on a receptive field organization with excitatory centers and inhibitory surrounds. The lateral inhibitory interactions within a receptive field and between receptive fields can be used to compute bar-width sensitivity and response to bar position within a receptive field (Macleod and Rosenfeld, 1972a, 1972b). In frequency domain models, predictions are based on a contrast sensitivity function or an envelope of a family of contrast sensitivity functions. The commonality in these two approaches is that a contrast sensitivity function can be computed for any hypothetical (or real) receptive field and a receptive field can be computed from any hypothetical

(or real) contrast sensitivity function. In short, a contrast sensitivity function and a receptive field organization are the "real world" manifestations of a Fourier transform pair. Thus appealing to either space-domain models or to Fourier models to explain the results of any particular experiment becomes somewhat of a logical equivalence.

The distinction between space domain and frequency domain models is further blurred in those models that have been developed to take the inhomogeneity of the retina into account (Wilson and Giese, 1977; Wilson and Bergen, 1979; Limb and Rubenstein, 1977). These models postulate a number of spatial frequency channels that vary with regard to their peak frequency as a function of distance from the fovea. Typically, higher frequency channels are thought to be near the fovea, while lower frequency channels are posited farther out in the periphery of the retina. This general class of models have been termed space-variant, while those models that posit high, medium, and low frequency channels at all locations in the retina have been termed space-invariant models (Graham, Robson and Nachmias, 1978). The space-variant models can be thought of as a collection of space domain mechanisms since they will selectively respond to a given frequency within a small area of the retina. The space-invariant models can be thought of as Fourier analyzers since their response can

be elicited from any portion of the retina.

Many experiments are not performed with the distinct goal to distinguish space domain from frequency domain models. This is especially true for those adaptation studies that have used full field grating stimuli where the results can be predicted from consideration of the interaction of single periods of the gratings (i.e., one bar) rather than the whole grating. On the other hand, there have been a number of studies where the results can be predicted only from the Fourier spectra of the stimuli rather than the image that impinges on the retina. Weisstein and Bisaha (1972) showed in an adaptation paradigm that a bar masked a bar better than a grating masked a bar. They also showed that a bar masked a full-field grating uniformly across the visual field. If bar-width alone were responsible for adaptation effects, then a bar should have little subsequent effect on a grating (except perhaps at the center of the grating where the masking bar had been) and a grating should mask a bar as effectively as one bar superimposed on another. Weisstein, Szoc, Williams and Tangney (1973) extended this finding to aperiodic stimuli with different orientations. Space-domain models as exemplified by Macleod and Rosenfeld cannot predict these results because they assume a local (i.e., one receptive field) space domain mechanism.

The subtle difference between the frequency domain and the space domain models then lies in the emphasis on what is the salient variable for prediction: the frequency components of the pattern, or the various collections of bar widths (or line segments) present in the pattern.

Perhaps the simplest level of approach in distinguishing between these two types of models for the purposes of the research reported here is one of terminology and definition of stimulus attributes. In this context, frequency refers to the sinusoidal components that are present in the stimuli after they undergo a Fourier transformation. Phase is the Fourier representation of the relationship between two components when the transform of a stimulus is a complex valued quantity or expression. With the space domain, size will refer to the physical bar width of the stimuli while position will refer to the relative displacement of one bar when it is summed with another bar in the stimulus gratings. Alternatively, a grating can be specified by giving its bar width and position in the space domain (i.e., subtending 5 minutes of arc, visual angle, for example) or by giving its frequency and phase in the frequency domain (i.e., sin 5 + 15 cycles per degree, 45 degrees phase).

For most of the experiments reported here, full field gratings of a constant frequency were used. In this case, frequency and phase are exactly equivalent to bar width and

position. In those experiments using gratings that were not constant across the visual field, the space domain and frequency domain models differ both in describing the stimulus and in the prediction of results. The term "phase/position" is used in this report in order to give equal initial credence to both the space domain and the frequency domain models. For full field grating, frequency is exactly correlated with size and phase is exactly correlated with position. It is not being used to imply that phase differences are always equivalent to position differences between bars or between the maxima and the minima in the grating patterns.

The general class of models that are of interest in this dissertation are of the space-invariant kind. That is, it will be assumed within the context of the experiments performed here that the visual system contains a number of spatial frequency channels, each sensitive to a different band of frequencies, spread more or less evenly over the visual extent (about 8 degrees) used here. One of the implications of this assumption is that variation of bar width across the lateral extent of the grating should not have any effect; rather, it should be the variation of the frequency components in the Fourier domain that result in any obtained experimental effects.

If it can be shown that the visual system is sensitive



to the magnitude and the phase of the Fourier components, a space-invariant Fourier model would be indicated. If the visual system can be shown to be sensitive to the relative bar width and position of a pattern, such a model would not be supported. A more detailed description of the model that is implied here will be given in the next chapter, after the studies on spatial phase effects have been reviewed.

## PHASE/POSITION EFFECTS

One of the first studies of the processing of phase information was that of Kulikowski and King-Smith (1973). As previously discussed, they used a subthreshold summation technique to measure the contrast sensitivity functions for lines, edges, and gratings. Along with obtaining the contrast sensitivity as a function of the frequency of the subthreshold grating they measured the contrast sensitivity as a function of the phase angle of the test stimulus. Phase angle was defined for the edge, line or grating relative to the subthreshold background: for example, the dark bar falling on a dark striation of the grating was 0 degrees phase, and the dark bar falling on a light striation was 180 degrees phase. They found that for a "line detector" contrast sensitivity varied with the cosine of the phase angle; that is, sensitivity was greatest at 0 degrees phase and least at 90 degrees phase. For the "edge detector" the contrast varied with the sine of the phase angle; that is, sensitivity was greatest at 90 degrees phase and least at 0 and 180 degrees. This study showed that the visual system was sensitive to the phase of stimuli, and that at least two different phase/position functions were obtainable.

Kulikowski and King-Smith speculated as to the potential neurophysiological ramifications of their results:

each type of detector could be evidence for a particular type of receptive field. If this were an accurate assumption, then the phase results would be predicted from consideration of the position of the test stimuli with respect to the excitatory and inhibitory flanks of that field. These units or detectors were sensitive to the frequency and the relative phase of the stimuli.

Stromeyer, Lange, and Ganz (1974) extensively studied phase sensitivity in human vision using a paradigm inspired by the McCullough effect, a long-lasting effect that is sensitive to both orientation and spatial frequency. They had their subjects adapt for 30 minutes to a pair of colored gratings that were interchanged every 10 seconds. The grating pairs consisted of (1) left or right facing sawtooths; (2) the sum of the first two harmonics of the sawtooths; (3) equal amplitude, first and second harmonics summed in either +90 degrees or -90 degrees phase; (4) equal amplitude, first and third harmonics summed in peaks-add and peaks-subtract phase; (5) equal amplitude, first and fourth harmonics summed in either +90 degrees or -90 degrees phase. The dependent measure was obtained by the subject looking at gratings that were the same as the adapting gratings, but at frequencies above and below as well as at the frequencies of the adapting patterns. The degree of color saturation was the dependent measure.

The data were reported for left and right facing, or peaks-add and peaks-subtract patterns, and showed the greatest McCullough effect when the test pattern was identical to the adapting pattern. With a change of frequency of the test pattern, the effect showed a decrease. Stromeyer, et. al., (1973) interpreted this as evidence for the existence of phase sensitive effects by the human visual system.

However, there are a number of problems in interpreting their results. First of all, their data is reported in graphs that have spatial frequency of the test grating as the X-axis and degree of subjective color saturation as the Y-axis. This manner of presentation is rather odd -- it is closer to a contrast sensitivity function of spatial frequency rather than as a function of phase. This method of presentation makes it difficult to compare their data with that of other studies. Additionally, by testing with gratings above and below the frequency of the adapting grating, Stomeyer, et. al., confounded phase effects with spatial frequency effects, making it impossible to discuss the effects separately. But their results are important insofar as their data were obtained under suprathreshold conditions for grating patterns with frequency components differing as much as a factor of four. Graham and

Nachmias (1971) found no phase-specific differences for phases 0 and 180 degrees, corresponding to peaks-add and peaks-subtract compound gratings. Stromeyer, et. al., showed that phase differences may be obtained at supra-threshold conditions if his results can be interpreted as supporting phase sensitivity.

Atkinson and Campbell (1974) reported a study in which an observer inspected a compound grating composed of a 1 cycle per degree and a 3 cycle per degree sine wave. Relative phase between the two components was varied in 25 steps between 0 degrees and 360 degrees. The dependent variable was the number of perceptual changes (monocular rivalry) per minute observed in the composite grating. The resulting functions showed minima at 0, 180, and 360 degrees, and maxima (meaning the greatest number of perceptual changes per minute of viewing time) at 90 and 270 degrees. Atkinson and Campbell interpreted their results in terms of a phase sensitive mechanism in the visual system.

de Valois (1977) used an adaptation paradigm to examine phase specific adaptation to gratings having the same duty cycle ( a duty cycle is the combined width of a black bar and a white bar) but differing black-bar-width to white-bar-width ratio. The spectral components of a grating in which black bars are twice as wide as the white

bar are identical to a grating in which the white bars are twice as wide as the black bars except for a phase difference of 180 degrees. Using perceived bar width as her dependent measure, she found phase/position after effects.

Furchner and Ginsberg (1978) further investigated the paradigm originally reported by Atkinson and Campbell. In the first experiment in their report, subjects reported the amount of monocular rivalry in terms of apparent relative contrast of the component gratings and the apparent waveform shape. They found phase-specific changes in perceived waveform shape but not for relative contrast. In the second experiment they reported, they found a shift of the stimulus with contrast fixation was sufficient to produce an apparent change in the perceived waveform.

Finally, Westheimer (1978) found that the minimally detectable amount of lateral displacement of a grating patch .5 degrees high by 12 cycles wide remained the same regardless of the spatial frequency of the grating patch. This result would seem to imply that, at least for a simple grating pattern, lateral displacement was being coded as position (in the space domain) rather than phase (in the frequency domain).

The above six studies have all dealt with identification of the basic phenomena: phase-specific effects in the human visual system. With the exception of Kulikowski and King-

Smith (1973), all of the above studies employed supra-threshold stimuli, although the contrast of the stimuli across the studies varied a great deal. The studies, taken as a group, raise a number of experimental questions with regard to the manner in which the visual system processes phase/position information.

First, as stated previously, it is unclear whether the phase metric is relative or absolute; that is, whether the effects can be termed phase effects in the Fourier sense, or as position in a space domain sense. Secondly, for the phase processing to be done by Fourier analyzers rather than by size detecting units it must be shown that phase is encoded uniformly across the stimulus field rather than by a local point by point process.

In addition, none of the above studies have examined the temporal effects that might be associated with phase/position information. For a Fourier-type of model, any spectral component is completely specified in terms of its magnitude and phase. For a space domain model (e.g., a bar detecting unit) a grating pattern would be completely specified by its bar width and its position. In either case, there are two characteristics of the pattern to which the visual system must be sensitive. There have been a number of theoretical speculations that phase may be encoded through temporal latencies at the individual cell level

(Cavanaugh, 1972; Westlake, 1968; Swigert, 1968) as well as some physiological data. Pollen, Lee and Taylor (1971) have recorded from complex cells of a cat that show a response latency shift as a function of position of a spot of light on the receptive field. Maffei and Fiorentini (1973) have recorded the responses of simple and complex cells of the cat to various grating patterns. They found that phase/position variations resulted in differences in firing latency of the cell.

Thus, there are two characteristics that are suggested from psychophysical and neurophysiological data that can be examined experimentally: magnitude of effect, and temporal properties of the effect. Prior to describing the studies that were conducted, it might be helpful to describe the model that is implicit in the research reported here. Figure 1 displays such a model. There are five elements.

The first is the stimulus that is being presented. It is assumed that the physical stimulus will be transformed at a first stage by the optics of the eye, perhaps with the Modulation Transfer Function (MTF) as discussed in Cornsweet (1970). This first stage would also include any transformation of the stimulus due to dark of light adaptation (Graham, 1965), such as the variation of a threshold level. Of main experimental interest are the next three stages. Here it is assumed that there exist a number of



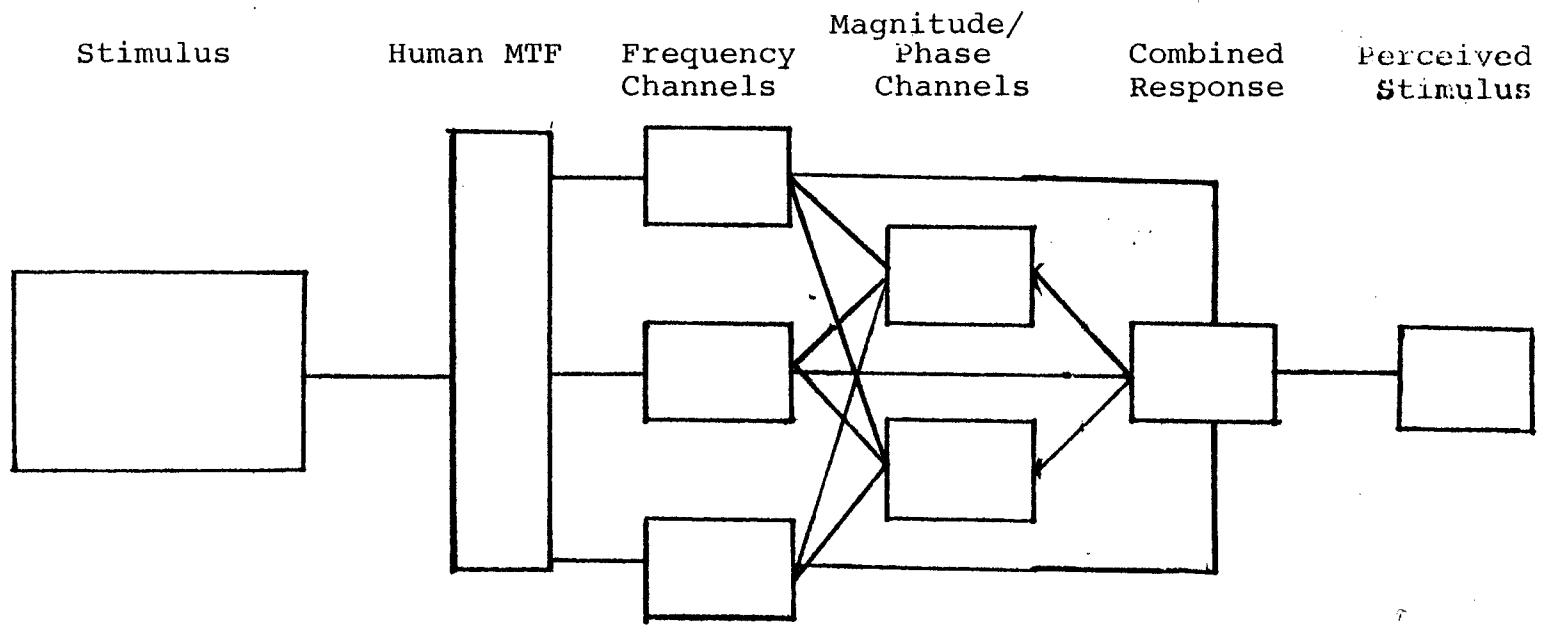


Figure 1. Postulated Model of Adaptation

channels sensitive to a relatively narrow band of frequencies with a peak response to a single frequency. The exact bandwidth of the channels is not at issue, as long as it is assumed that the bandwidth is approximately one octave. This minimum bandwidth assumption is typically of those studies that have tried to measure the bandwidth of spatial frequency channels (e.g., Blakmore and Campbell, 1969; Stromeyer and Julesz, 1972; Sachs, Nachmias and Robson, 1971). The exact number of channels is also not at issue here; the three channels depicted in Figure 1 are hypothetical and six could have been drawn with as much theoretical ease. It is also assumed that a number of channels sensitive to different frequencies exist at any one retinal location and that spatial frequency effects should be fairly constant across the lateral extent of the visual field (8 degrees in the studies reported below). This "homogeneity of effect" assumption is in agreement with Weisstein, et. al., (1977) and with Graham, et. al., (1978). In an adaptation study using small grating patches and full field grating with a magnitude estimation procedure, Weisstein, et. al., found extensive spread of masking: regardless of where in the visual field the grating patch appeared (within a total 10 degree extent), a bar, which is a very broad band pattern in the frequency domain, would mask that grating patch. In a similar vein, Graham, et. al.,

found little or no difference in the detectability of gratings at or near threshold as a function of retinal eccentricity. While these results are counter to the results of others (e.g. Limb and Rubenstein, 1977), they do make the "homogeneity of effect" assumption a reasonable one for the model.

Up to this point, then, it is assumed that the stimulus pattern, such as a grating, impinges on the retina, is transformed by optical factors (the MTF) and retinal factors (the state of light or dark adaptation) and is filtered by a stage of medium band (or narrow band) spatial frequency channels. The next stage is the most important for the research reported here. It is assumed that relative phase information is obtained from the combined outputs of the channels and further, that there are a number of phase sensitive channels, each sensitive to a relatively narrow band of phases. The rationale for the phase channels being placed after the frequency channels is that relative, not absolute, phase information is being processed. For example, if a complex pattern, such as a human face, is presented and then shifted to the left or right, the relative phase information among the frequency components stays constant: all the frequency components at their respective phases have been shifted by a constant amount. It is only the relative phase information (i.e., between the Fourier

components rather than where the whole pattern lies on the retina) that is needed to synthesize or analyze the pattern in the frequency domain.

The relative phase information is combined with the magnitude of the frequency at the next stage. The final response stage consists of an additive summing of the response of the phase/magnitude (hereafter called phase) and frequency channels. This summed response will result in the perceived stimulus. If the output of either a frequency or phase channel is diminished (e.g., due to saturation), the perceived stimulus will be altered.

Now that the main model has been described, some of the assumptions that are not made will be presented. First of all, it is explicitly not assumed that the spatial frequency channels inhibit one another within the context of the experiments conducted here. There has been some evidence (Tolhurst, 1972; Dealy and Tolhurst, 1974) that spatial frequency channels inhibit each other when the adaptation paradigm has been used. On the other hand, the evidence has not been consistent. Stromeyer, Klein and Sternheim (1977) theorize that, at least at threshold, the apparent inhibitory effects can be explained by a probability summation model (e.g., Stecher, Segal and Lange, 1973; Graham and Rogowitz, 1976). Likewise, it is not assumed that the phase channels inhibit each other.

It is also not assumed that the extraction of the phase information from the pattern occurs after the extraction of the frequency information. Although the phase channels are drawn in Figure 1 after the frequency channels, the case may be that both types of information (frequency and phase) are obtained in a parallel fashion.

Finally, it is assumed that the principle of superposition is tenable at suprathreshold levels. It is almost certain that at threshold the visual system is fairly linear (Davidson, 1965). There is also psychophysical evidence that Fourier techniques predict adaptation effects at suprathreshold levels (Weisstein and Bisaha, 1972; Weisstein, et. al., 1977). If there are non-linearities it is assumed that they are small relative to the adaptation effects. Those studies using threshold level gratings typically find no phase effects (Graham and Nachmias, 1971). Those studies that do find phase effects have used suprathreshold stimuli (Stromeyer, et. al., 1974). Thus it seems likely that the use of suprathreshold stimuli in this series of experiments will enhance the possibility of obtaining phase effects.

Although the next set of assumptions depend on the nature of the specified model, they have more to do with the nature of the paradigm and with the subjects' task as used in this series of experiments. When a stimulus, such

as a grating, is presented for a relatively long period of time, the channels that are sensitive to the frequency components in the pattern will begin to respond. When the channels respond for that period of time they will become fatigued so that the presentation of a second stimulus with similar spectral characteristics will not elicit a response. In terms of the model, the saturation of the adapted channels will cause the perceived stimulus to change. The experiments here assume that grating contrast is the sum of responses from the individual channels and such saturation will result in a reduction in apparent contrast. This is the general adaptation paradigm assumption (Weisstein, 1968).

Now that the working model for the adaptation studies has been outlined, some tentative predictions can be made with regard to the first four experiments. The first four experiments were exploratory in nature. They were conducted to examine some of the conditions under which phase-specific adaptation might be obtained. In this sense, they are conceptually related, although they do not follow a structural sequence. The first experiment was simple attempt to examine adaptation effects as a function of phase/position using full-field sinusoidal gratings containing only one or two frequency components. It was hypothesized that a simple sinusoidal grating would not be as effective a mask as a grating containing the same frequency components

as the target gratings. From the model in Figure 1, it can be seen that the channels are assumed to sum the response, so that a pattern that fatigues two channels should produce more adaptation than a grating that fatigues only one channel, given that the target gratings are all two component gratings. It was further hypothesized that the composite grating, containing two frequency components at 0 degrees phase, would result in maximal adaptation for targets with the same frequency and phase components with decreasing adaptation for the non-zero phase targets. This prediction stems from the model shown in Figure 1. The model assumes that the frequency and phase information is combined in determining the response. The zero phase, two component mask would result in the greatest fatigue in the two frequency zero phase channel with the non-zero phases being relatively free of fatigue. The exact form of the adaptation curve (i.e., least adaptation at 90 degrees phase with slightly more at 45 and 135 degrees) would depend on the exact weights that may be attributable to each phase channel. The main prediction for the first experiment is that the simple 5 cycle grating should result in the least adaptation while the two component grating should result in the most, with the greatest amount of adaptation for the 0 degrees phase target.

The second experiment was an exact replication of the

first at a lower contrast level. As stated previously, those studies that have used threshold gratings typically find no phase effects, while those studies using supra-threshold gratings do. If the change in contrast reduced the phase-specific adaptation, the model shown in Figure 1 would have to be augmented to take contrast level into account.

The third experiment was conducted as one direct test of the space domain model as opposed to the frequency domain model. The two masks of interest were sinusoidal gratings whose bar widths varied across the lateral extent of the visual field (frequency gradients). In the frequency domain, however, the masks contain essentially an infinite number of frequency components. At the same time one of the masks contained a constant phase relationship of 90 degrees among frequency components. In the space domain the bar widths and the relative bar positions (i.e., the relative distance between a peak and the trough of the bars) varied. The targets were gratings at 4 different frequencies and 3 different phases. It was hypothesized, in accordance with a Fourier model, that all the target gratings would be masked equally well by the mask, and that those gratings with a phase relationship of 90 degrees would be masked more than gratings with other phase terms by the phase mask. A space domain model would predict



no appreciable masking since the targets are not physically similar to the masks. Moreover, the space domain model would predict no differential adaptation due to phase since the relative peak to trough distance, or bar position, varies with the lateral extent of the mask. This would presumably involve different size detecting units across the visual field.

The fourth adaptation study was conducted to examine whether effects due to the Fourier components explicitly present in the mask but forming a pattern that does not resemble the target could be obtained. It differed from the third experiment in that the contrast in the mask was not uniform but varied in irregular ways across the extent of the visual field. It thus represented a control study for the use of one of the dependent measures (the uniformity rating described in the next chapter) as well as a test of phase and frequency effects.

The fifth and sixth experiments were both backward masking studies. The model depicted in Figure 1 would need to be elaborated somewhat before predictions for these studies can be generated. Whereas the adaptation paradigm used here assumes the fatiguing or the saturation of frequency and phase channels, backward masking has to make some assumptions about the temporal course of processing. As stated previously, some neurophysiological work (Pollen, Lee, and Taylor, 1971;

Maffei and Fiorentini, 1973) has suggested that phase, at least within a channel maybe encoded by temporal latency of firing. Another line of neurophysiological research has identified cells, the sustained and the transient cells, that have very different but easily identified temporal parameters. This work has inspired and informed some psychophysical work that has identified similar channels in human vision. In particular, the same temporal relationships have been found in human "sustained" and "transient" channels that have been suggested by neurophysiological work (Breitmeyer, 1975). Clearly, human psychophysics is not another form of single unit recording; but such work with animals has inspired some of the work in human vision. There have been a number of parallels in the findings from both areas as well.

For the purposes of the masking experiments, it will be assumed that the extraction of information will take different amounts of time in the visual system. If there is inhibition between the various phase channels as there seems to be for frequency channels in backward masking paradigms, then the backward masking studies should result in differences in the ISI at which maximum masking takes place. If the inhibition assumption is dropped the backward masking predictions would be slightly different. If there is no inhibition between phase channels, then masking should occur for

both targets and masks in Experiment 5 at the same time interval because the effects would be determined largely by the frequency composition of the gratings and not the phase. If there is no inhibition between frequency and phase channels, then there should be no masking at all except perhaps at an ISI of zero; in this case, the masking would not necessarily be determined by the spatial frequency content of the mask or the target (see Breitmeyer and Ganz, 1976, for a discussion of the various types of masking functions that can be obtained and their relationship to the spatial frequency information available). In short, the prediction of backward masking results depends on the postulating of inhibitory interactions among the various components in the model.

Experiment 5 used masks and targets of identical spatial frequency content but differing phases. The predictions were that the phase information in the target would result in differences in the time interval at which the maximum masking would take place. Experiment 6 used a very broad band mask containing a number of frequencies, all having the same phase relationships among each other (the same phase shift in the frequency domain). If there is inhibition between phase channels, then gratings of different frequencies but similar phases should be masked at the same ISI, while different phases should be masked at different ISIs. One problem in doing backward masking research is that psychophysical

evidence has been obtained that supports the existence of sustained and transient channels in human vision using backward masking techniques (Breitmeyer, 1975; Breitmeyer and Ganz, 1976). Thus there does exist the possibility that temporal effects in the experiments reported here might be due to the activity of the sustained and the transient channels; these channels are thought to possess different temporal latencies (Breitmeyer, 1975; Victor, Shapley and Knight, 1977) as well as inhibit each other (Tolhurst, 1972). The potential effects of the sustained/transient dichotomy on the backward masking experiments will be considered in greater detail in the summary discussion.

It should be stated at this point that the experiments in general did not find effects that could be attributable to phase within the general context of the Fourier model. As will be seen in the discussion of Experiments 1, 2 and 4, some positive results were obtained but none that could be attributable to phase alone. While the evidence obtained here can be summarized with the statement that phase effects were not found, certain frequency effects were found that could not be explained by a simple space domain model (see Experiment 4). The combination of these results leads to a number of speculation concerning the adequacy of the model that was postulated in the previous sections and depicted in Figure 1. For the purposes of the discussion here, the most important postulates of the model were that

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the frequency and the phase information is combined and results in a reduction in the perceived contrast of the target gratings. An ancillary assumption of the model was that the frequency and the phase channels do not inhibit each other, although they interact in order to extract the relative phase information. Both of these assumptions and their tenability are examined at length in the General Summary chapter at the end of the dissertation.

## GENERAL METHODOLOGY

Prior to describing the results of the experiments, the creation of the stimuli will be described as well as the points of method and procedure that are common to all the experiments. Any aspects of procedure unique to a particular experiment will be described in the appropriate section.

### Stimuli

All the experiments used gratings that had luminance profiles that followed that of either a simple sine wave or the sum of two sine waves(except for Experiments 3,4 and 6).

In order to create gratings, a Fortran program was written which generated a vector of 1024 points that corresponded to the values necessary to generate the desired function. The program was written to automatically compute the correct intervals to represent a sinusoidal function of any frequency and phase. The original function values were then scaled to conform to a range from 0 to 255. The vector was then plotted via a xerographic process, and, if it were judged suitable, copied to a magnetic tape.

The information on the tape was input to a program resident on a PDP 11/20 computer, interfaced with a photographic drum device capable of emitting a rectangular raster of light in any one of 255 different densities.

The size of the area illuminated by the raster was .001 by .0008 inches. The computer read the function values from the tape and drove the photographic drum so that the raster would expose the film a small area at a time, with the intensity of the exposure corresponding to the function values. When the raster scan was complete, the film would be removed from the drum and developed at conditions to keep the photographic gamma close to one. The film was extremely high grain with sensitivity toward the red end of the spectrum. The preparation of one photographic transparency from the magnetic tape took approximately 1.5 hours. All the gratings were prepared initially in the above manner. The gratings on these transparencies were then enlarged onto 5 inch by 7 inch sheet film, once again taking care that the photographic gamma close to one. For use in the experiment, the transparencies were mounted in black cardboard mounts in order to stay rigid in the tachistoscope which was used for presentation.

It should be noted at this point that no attempt was made to normalize the gratings so that they all had the same peak to trough distance. Thus, the contrast of the gratings varied as a function of phase and as a function of whether it was a "simple" (one sinusoid) or a "complex" (two sinusoids) grating.

The contrast of the stimuli is defined by:

$$\frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

where  $L_{\max}$  is the maximum luminance of the grating and  $L_{\min}$  is the minimum luminance of the grating. The gratings were scanned with a microdensitometer; the resulting density readings were converted to contrast levels using the above formula. Using the above definition, the contrasts of the various grating stimuli were as follows:

<u>Type of Grating</u>	<u>Contrast</u>
Simple: 1 frequency	58%
Composite: 0° phase	65%
Composite: 45° phase	72%
Composite: 90° phase	70%
Composite: 135° phase	69%

### Apparatus

All of the experiments were conducted using a three-channel Scientific Prototype tachistoscope, Model N-1000. A solid state controller allowed the setting of the luminance and the duration for each channel independently. Each of the three channels was illuminated by two neon bulbs that had rise times between 2 to 5 microseconds. The optical path length from the stimulus plane to the eye of the



subject subtended by the mask and the target fields was approximately 6 by 8.3 degrees visual angle, although the gratings subtended a slightly smaller (by about one degree) field of view due to the black cardboard mounts used for the transparencies.

The luminances of the fields in all the adaptation experiments were 11.2 ft. L. for the mask, 7.25 ft. L. for the target, and 1 ft. L. for the background fields. For the backward masking studies, the luminance of the target field was lowered to 5.0 ft. L. For the adaptation studies, the mask duration was 15 seconds, and the target duration was 50 milliseconds. For backward masking, the duration of both mask and target was 50 milliseconds.

### Procedure

The dependent variables of interest were the apparent contrast of the test grating and its uniformity in appearance, both relative to the test grating flashed alone. The actual measures used were magnitude estimations of the apparent contrast of the test gratings, and a simple yes/no response for its uniformity. Magnitude estimation procedures have been used in studies of this type (Growney, 1976; Weisstein, 1971; 1972; Cannon, 1979; Tangney, Weisstein, and Berbaum, 1979) typically using the number 10 as modulus. In one study which used a free modulus procedure (Cannon, 1979), subjects used numbers in the range of 0 through 12.

Thus, the number 10 was selected as the modulus in these experiments.

Apparent contrast was defined as the difference between the light and the dark striations of the test pattern. Care was taken to ensure that each observer understood this definition, and that each did not confuse his or her task with rating the overall brightness or dimness of the pattern. Uniformity was defined for each observer as the homogeneity of the contrast with the spatial extent of the test grating.

Prior to beginning each experiment, each subject was given instructions as to his or her rating tasks. The instructions were as follows:

First, examine this pattern. (At this point, the experimenter flashed the target grating.) You will notice that this pattern is composed of alternating dark and light bars. This difference is called the contrast of the pattern, and this pattern is called target grating. As the dark bars get darker or the light bars get lighter, we say that the contrast of the grating increases. As both types of bars get grey, we say that the contrast decreases. I want you to take note of the contrast of this grating because you will be using it as a comparison later on. I want you to mentally assign the number 10 to this pattern.

In the actual experimental trial, a grating will come on in the field of view after I say "Ready". That grating will stay on for approximately 10 seconds. When it goes off, the test grating will come on for a brief time as when you saw it alone. I want you to give me a number that is a comparison of the grating shown alone with the contrast of the test grating in the trial. What I want you to do is to form a scale in your head, so that if the test grating in the trial had half as much contrast, I want you to say "Five". If it had twice the contrast I want

you to say "Twenty". There might be times when you may not see the trial grating at all. If that happens, I want you to say "Zero". It is important that you (1) make sure that you are rating the contrast of the test grating and not the overall brightness or dimness of the pattern; and that (2) you try to build that scale inside your head as I described. It is also important to try and use all the numbers on the scale, or at least as many different ones to reflect the relative changes in contrast that you see.

At this point, the experimenter answered any questions that the subject may have had on the experimental procedure or on the rating task. After the questions, a number of trials were conducted to give the subject some familiarity with the procedure and with their task. Each trial was preceded by the flashing target alone, or the standard. After these preliminary trials, more instructions were given to the subject:

There is an additional rating that I want you to give along with the contrast of the target grating compared to its contrast when flashed alone. After you give me the contrast rating, I want you to tell me a simple "yes" or "no" as to whether the contrast was uniform across the whole field or whether it varied in different parts of the test grating. In other words, the test grating might appear splotchy with the light and dark bars having more contrast in one part of the grating than in another part. If this is true, I want you to say "no". If, however, the grating appears uniform I want you to say "yes". Do you have any questions?

If the subject had any questions they were answered at this time. Then a series of experimental trials were begun. For the very naive subjects, the experimenter asked the

subject to verbally describe their percept, without necessarily giving either of the two ratings. As the subjects became more comfortable with the visual phenomena and with the experimental procedure, the verbal descriptions were replaced by magnitude estimations of apparent contrast and by the judgments of uniformity. For the naive subjects, these practice sessions were conducted for two to four hours before actual data collection commenced.

All of the experiments were conducted with three subjects who had 20/20 corrected or uncorrected vision. Different observers worked at different speeds so that any one experiment took two to four sessions, each lasting from one and one-half to three hours to complete.

#### Possible Implications of Using Magnitude Estimates

The one basic assumption behind the use of the magnitude estimation procedure is that the subject follows the instructions so that the estimates will reflect the ratio of perceived target contrast to the perceived contrast of the standard (Uttal, 1973). If the subjects do not develop this interior ratio scale the resulting magnitude estimations are ambiguous. Cannon (1979) and Hamerly, Quick and Reichert (1977) found that the mean log magnitude estimates of contrast were a linear function of the log physical contrast of sine-wave gratings over a variety of frequencies and contrasts of the gratings. This is consistent with the

notion that the use of magnitude estimation results in a power function of stimulus magnitude. But the use of such a procedure is not necessarily universally accepted and has been shown to result in significant differences at the individual subject level (see the discussion in Uttal, 1973). A direct way of examining individual subject biases in their ratings would involve independently varying the contrast of the target grating in a control condition and having subjects rate its contrast relative to the standard used in a particular experiment. This, however, was not possible with the equipment and the gratings available. It is necessary, then, to consider the type of scale that the subjects may have actually used and the implications of that scale for the data analysis and the reporting of the results.

Following Stevens' terminology (1951) four types of scales may be distinguished: nominal or categorical, which preserve the categories of judgements; ordinal which preserve the order of magnitude of judgements; interval, in which the order of magnitude as well as the difference between two judgements is maintained (i.e.,  $n - (n-1) = (n-1) - (n-2)$ ); and ratio scales possess the above properties and an absolute zero point as well. For the experiments reported here, there was an absolute zero point when the subject saw a homogeneous grey field in those trials

involving a grating target and grating mask. All of the subjects experienced trials where they apparently did not see the target since every subject had occasion to use the number zero as their rating. More difficulty lies in trying to ascertain the type of scale when the subjects used numbers other than zero.

The first possibility is that the subjects followed the instructions properly and used a ratio scale. In this case, the analysis of variance is appropriate and the data curves presented in the graphs are (apart from subject variability) reliable estimates of the perceptual effects of the masks on the targets. That the subject may have used an equal interval scale is not possible since there was an absolute zero point in the ratings, both theoretically and empirically. If the subjects' ratings reflected equal intervals (with an appropriate log transformation) they were necessarily the outcome of a ratio scaling operation.

The remaining possibility is that the subjects' ratings reflected an ordinal scale of masking magnitude. If this was the case, then Friedman analysis of variance on ranks would be more appropriate as a statistical tool and the data curves would not necessarily be indicative of magnitude of effects but only of the order of the effect. There is no direct answer to this dilemma because of the inability to independently vary the physical contrast of

of the target gratings. The use of a ratio scale would predict a linear relationship between the geometric mean of the subjects ratings and the log of the degree of masking. An ordinal scale would necessarily predict a monotonic one where increased masking would be related to the use of lower magnitude estimates.

In light of the possibility that ratio scales were not used by the subjects, it is necessary to interpret the results with some degree of caution. In the chapters that follow ratio scales are assumed for the purposes of statistical analysis; this permits the use of log transformation and the plotting of the data as geometric means, in keeping with the studies of Cannon (1979) and Hamerly, Quick, and Reichert (1977). At the same time, interpretation of the data will be somewhat conservative; where both the statistics and the plots of the data show meaningful effects the interpretation will be mutually reinforced. When the data graphs exhibit large standard errors or small effects, the interpretation will be appropriately conservative.

## ADAPTATION STUDIES

Experiment 1: Identification of the PhenomenonIntroduction

The purpose of this experiment was to establish that differential adaptation due to phase could be obtained. That such adaptation could be obtained was highlighted by the results of Stromeyer, et. al., (1973) cited above, although they used color saturation with a McCullough effect paradigm as their dependent measure. This experiment differs from theirs in that it uses the magnitude estimation of the apparent contrast of the test grating as the dependent measure.

In order to establish differential phase adaptation, it is necessary to use targets that differ only with respect to phase relationships among their components. The stimuli used in this experiment were:

Masks

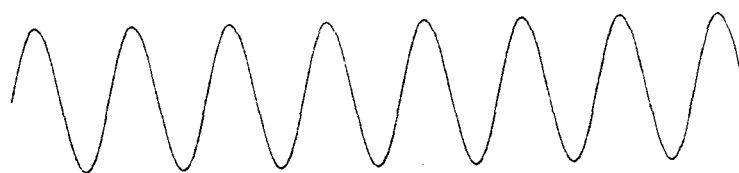
- 5 cycle per degree simple sine wave grating
- 5 + 15 cycle per degree grating, 0° phase
- homogeneous grey field as a luminance control

Targets

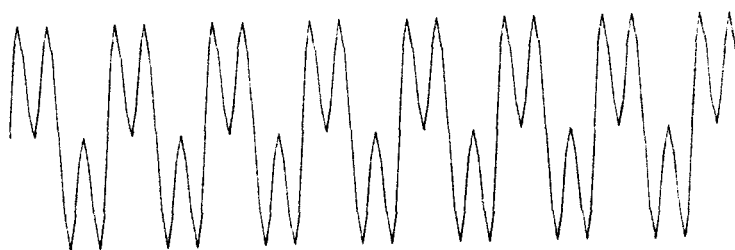
- 5 + 15 cycle per degree grating, 0° phase
- 5 + 15 cycle per degree grating, 45° phase
- 5 + 15 cycle per degree grating, 90° phase
- 5 + 15 cycle per degree grating, 135° phase

Figure 2 shows the luminance profiles of the grating





$\sin 5x$



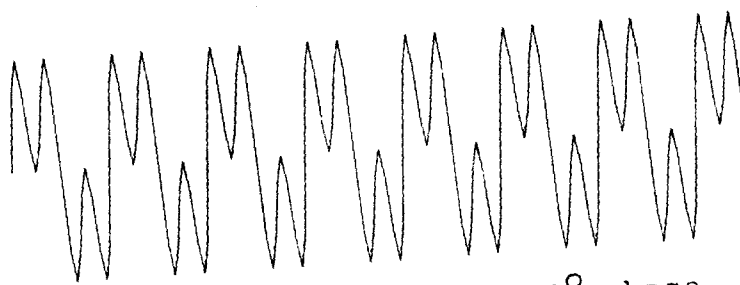
$\sin 5x + \sin 15 x, 0^\circ \text{ phase}$

Figure 2. Luminance Profiles of Grating Masks

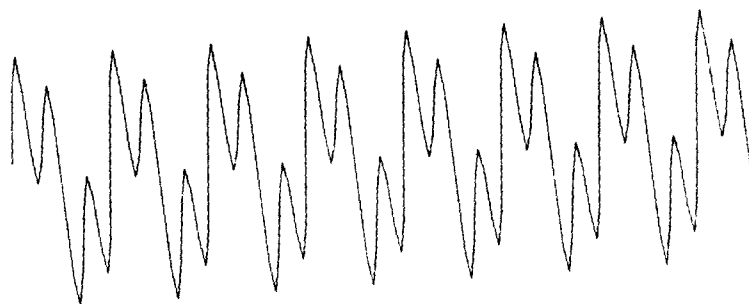
masks and Figure 3 shows the luminance profiles of the grating targets. In Fourier terms, the spectra for all targets is identical with the exception of the phase term. The expectation from Fourier theory would be that maximum adaptation would occur for the  $0^{\circ}$  phase mask and target combination; less adaptation should take place for the non-zero phase targets and the  $0^{\circ}$  phase mask. The least adaptation should occur for the simple 5 cycle per degree mask and all the targets because that mask only has one component while the composite mask has two. The grey field, acting as a control for luminance, should result in no appreciable adaptation.

### Results

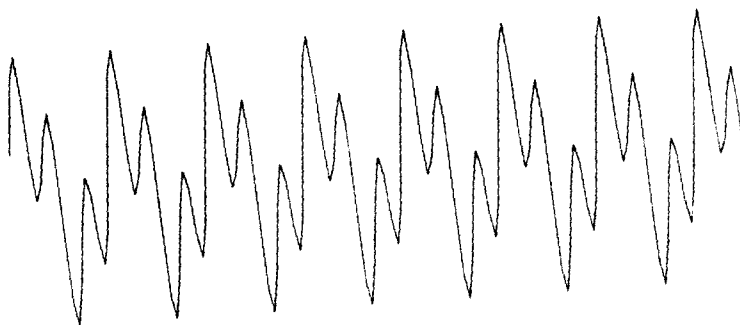
An analysis of variance was computed on the common logarithm of the magnitude estimates because they are log normally distributed (Stevens, 1957). This was a 3 (Subjects) by 10 (Replications) by 3 (Masks) by 4 (Targets) complete within subjects design. All of the effects were statistically significant; the Mask main effect ( $F(2,54)=44.20, p<.05$ ); the Target main effect ( $F(3,81)=11.72, p<.05$ ); and the Mask by Target interaction ( $F(6,162)=6.82, p<.05$ ). Figure 4 displays the results for each of the three subjects. The vertical bars at each data point represent plus or minus one standard error (S.E.). Each point in Figure 4 represents the mean of 10 observa-



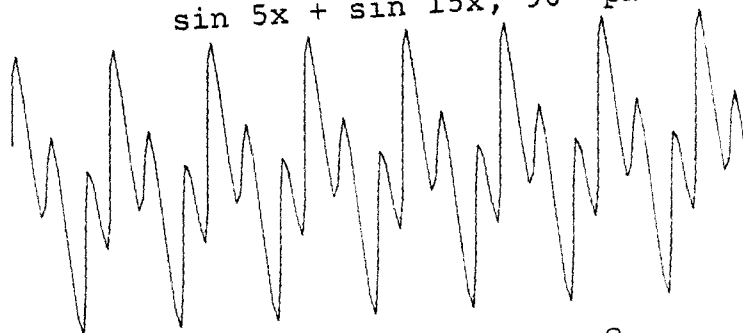
$\sin 5x + \sin 15x$ ,  $0^\circ$  phase



$\sin 5x + \sin 15x$ ,  $45^\circ$  phase



$\sin 5x + \sin 15x$ ,  $90^\circ$  phase



$\sin 5x + \sin 15x$ ,  $135^\circ$  phase

Figure 3. Luminance Profiles of Grating Targets

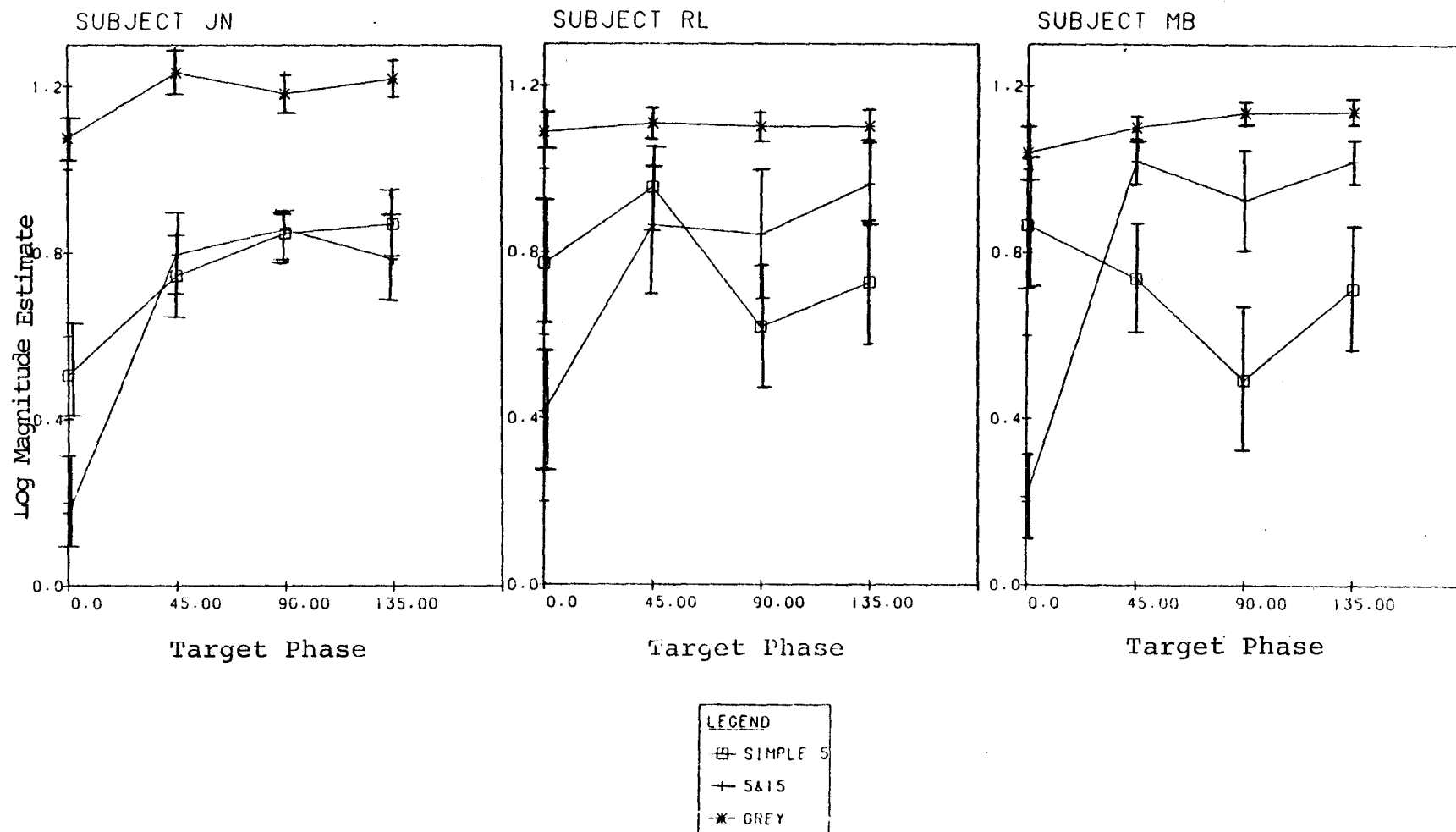


Figure 4. Log Magnitude Estimates of Grating Contrast, Experiment 1

tions.

Post hoc analyses (Duncan's range test, all tests being performed at the .05 level) revealed that the mask main effect was due to the grey field being significantly less powerful than either of the two grating masks as an effective adaptation stimulus. It was also found that the Target main effect was due to the  $0^{\circ}$  phase target being the most susceptible to adaptation. Post hoc analyses of the interaction term revealed that the  $0^{\circ}$  phase target and mask combination resulted in the most adaptation. The differences between the effects of the 5 cycles per degree and the 5 + 15 cycles per degree masks on each target were not significant otherwise. The grey adaptation field resulted in significantly less adaptation for each target than either of the grating masks.

Table 1 presents the percentages that the target was seen as uniform as a function of the mask and the target for each subject. Chi-squares computed for these tables showed that the effect of masks alone on the perceived uniformity of the target was statistically significant ( $\chi^2(2)=17.30, p<.05$ ).

Inspection of Figure 4 will show that the 0 degrees phase target was masked the most by the 0 degrees phase mask. All subjects exhibited enhancement for the grey field mask and all of the targets. Subjects RL and MB

exhibit a slight tendency for the simple 5 c/degree mask to cause more masking than the composite 5 + 15 c/degree grating. For Subject MB this difference was significant. None of the subjects showed more adaptation being caused by the composite mask than the simple sine grating.

### Brief Discussion

The original expectations for this experiment were:

(1) that the grey field should result in no appreciable masking; (2) that the 5 cycle per degree grating should result in adaptation evenly at all phases since it contains only one component and phase should be largely irrelevant within a frequency channel; (3) the  $0^{\circ}$  phase mask should result in the greatest adaptation at  $0^{\circ}$  phase, intermediate adaptation at  $45^{\circ}$  and  $135^{\circ}$ , and minimal adaptation at  $90^{\circ}$ . Clearly these expectations were not fulfilled.

Maximal adaptation did take place for the 0 degree phase target and there was a slight unexpected enhancement effect for the grey field mask condition, but none of the main predictions were fulfilled. Especially surprising was the fact that the simple 5 cycle grating resulted in as much or slightly more adaptation than the composite mask. The fact that only one data point for each subject follows the predictions makes the interpretation of this finding ambiguous since the two competing models (space domain and frequency domain) can be used to explain the results with

Table 1  
 Percentage of Trials That Target Was  
 Perceived as Being Uniform

## Subject JN

## Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	60%	70%	90%
45° Phase	60%	50%	100%
90° Phase	20%	80%	100%
135° Phase	50%	40%	100%

## Subject RL

## Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	90%	70%	80%
45° Phase	100%	90%	100%
90° Phase	70%	80%	90%
135° Phase	90%	80%	90%

## Subject MB

## Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	100%	100%	100%
45° Phase	100%	100%	100%
90° Phase	100%	100%	100%
135° Phase	100%	100%	100%

equal effectiveness.

Within the context of the frequency model, speculation can be made that the phase channels are very narrowly tuned such that only a target with identical (within the limits of phase present in these target gratings) phase as the mask becomes susceptible to adaptation effects. The non-zero phase gratings would then be adapted an equivalent amount based only on their similarity to the magnitude of the frequency components present in the mask. The fact that the simple one-component grating caused as much as the adaptation of the two-component grating for the non-zero phase gratings would argue against this latter possibility.

Within the context of other possible models, such as a space domain or a feature similarity model (see Weisstein, 1968, for a general discussion of such feature analytic models) the results can be explained by the simple fact that zero phase mask and target are identical patterns stimulating identical channels (feature channels) within the visual system. The fact that the grey field mask resulted in no adaptation but a small amount of enhancement may reflect a general pattern vs. no pattern adaptation effect. A third possible explanation is that the adaptation paradigm with magnitude estimates of apparent contrast is not sensitive or appropriate to capture any effects due to phase even if the phase information is being processed by the visual system.



Experiment 2: Replication of Experiment 1 at  
a Lower Contrast

Introduction

Experiment 1 was performed using gratings whose contrasts were suprathreshold. A number of studies ( Graham and Nachmias, 1971; Wilson and Giese, 1976 ) have found no phase specific effects using stimuli at threshold. One study varied the contrasts of sinusoidal gratings in a discrimination task and resulted in no phase effects near threshold, but some phase effects above threshold (Nachmias and Weber, 1976). It is possible that phase adaptation, as found in Experiment 1 is obtainable only at suprathreshold contrasts and deteriorates as the contrast is lowered. In order to answer this question, Experiment 2 was conducted.

Because the stimuli used for this series of studies are photographic transparencies, the contrasts of the various masks and targets cannot be manipulated independently. The alternative method used to lower the contrast did so at the expense of increasing the overall luminance level. In this experiment, all of the experimental conditions were identical with those of the previous experiment: the masks and the targets were the same; the duration of the mask was 15 seconds and the duration of the target was 50 milliseconds. The luminance of the target and the mask fields was identical. The only difference was that the

luminance of the background was increased from 1 ft. L. to approximately 10 ft. L. The increase in background luminance was, in effect, added optically to the luminance of the targets and the masks equally. Inspection of the formula for contrast given previously will show that adding luminance to the target and the mask fields will mathematically reduce the contrast of the gratings. With the luminances used for the mask and the target fields, this increase will reduce the contrast by about 60%. In all other respects, Experiment 2 was conducted in the same manner as Experiment 1.

### Results

An analysis of variance was computed for the log transforms of the magnitude estimates. The design was identical to that of Experiment 1 with the exception that the number of replications here was 5 rather than 10. Once again, all effects were statistically significant; the Mask main effect (  $F(2,24)=26.13, p<.05$  ); the Target main effect (  $F(3,36)=3.34, p<.05$  ); and the Mask by Target interaction (  $F(6,72)=3.38, p<.05$  ). Figure 5 displays the results for each of the subjects. Each data point is the mean across 5 observations, with the vertical bar representing plus or minus 1 Standard Error.

The individual subjects, who were the same in Experiment 1, showed distinct and statistically significant

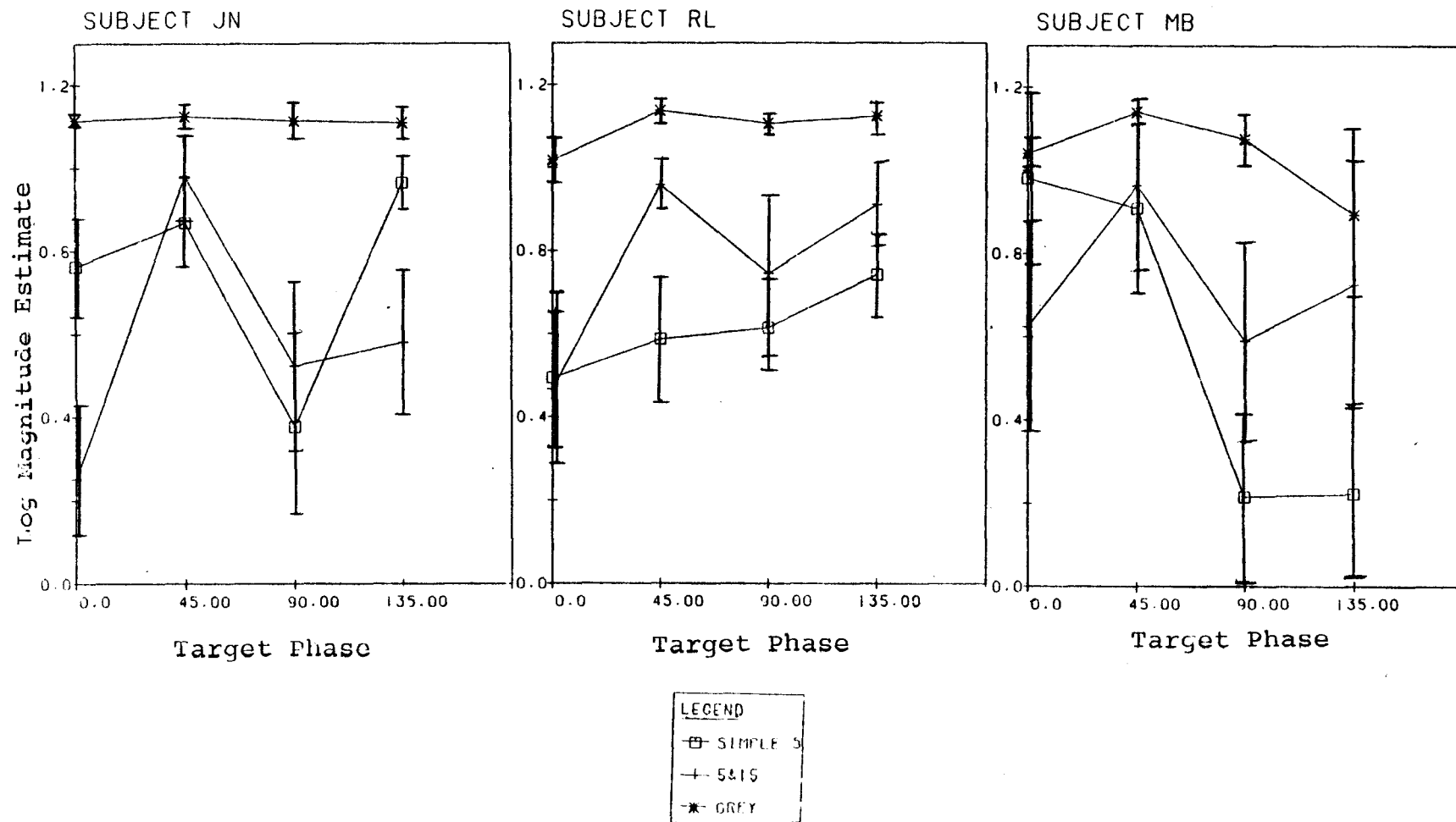


Figure 5. Log Magnitude Estimates of Grating Contrast, Experiment 2

differences in their curves between the two experiments. Subject JN showed as much adaptation for the  $90^{\circ}$  phase target and simple 5 cycle per degree mask as for the  $0^{\circ}$  phase mask and target. Subject RL shows more adaptation for the 5 cycle per degree for all non-zero phase targets while subject MB shows the most adaptation with the 5 cycle per degree mask and the  $90^{\circ}$  and  $135^{\circ}$  phase targets. For subjects JN and MB, the  $0^{\circ}$  phase mask was equally effective for the  $0^{\circ}$ ,  $90^{\circ}$  and  $135^{\circ}$  phase targets.

Table 2 shows the percentage that the target was perceived uniformly as a function of mask, of target, and of mask and target. There were no statistically significant effects. It is apparent that the targets were seen more uniformly than in Experiment 1.

## Discussion

Inspection of Figure 4 shows that Subject JN and Subject RL once again showed the most masking of the 0 degrees phase target. Subject MB shows the most adaptation with 90 degrees and the 135 degrees phase target inexplicably. For all subjects there is essentially no difference in effect for the two grating masks. Both grating masks, however, resulted in more adaptation than the homogeneous grey field thus indicating that the effects present are

Table 2

Percentage of Trials That Target Was  
Perceived as Being Uniform

Subject JN

Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	60%	100%	80%
45° Phase	80%	80%	100%
90° Phase	100%	100%	100%
135° Phase	100%	100%	80%

Subject RL

Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	80%	100%	100%
45° Phase	80%	80%	100%
90° Phase	80%	80%	100%
135° Phase	100%	100%	100%

Subject MB

Masks

<u>Targets</u>	<u>Simple</u>	<u>Complex, 0° Phase</u>	<u>Grey Field</u>
0° Phase	100%	100%	100%
45° Phase	100%	100%	100%
90° Phase	100%	100%	100%
135° Phase	100%	100%	100%

due to the gratings rather than to the average luminance of the field as was found in Experiment 1. In general, the enhancement effect is approximately the same and the two pattern masks resulted in more overall adaptation than in the first experiment.

Most importantly, however, there was no effect that can be ascribed exclusively to the target and mask phase relationships. These results do not contradict those of the first experiment. They are less clear for Subjects RL and MB; Subject RL exhibited virtually identical masking effects for both of the pattern masks and the zero phase target, while Subject MB showed similar level of adaptation for all the targets and both pattern masks (the Standard Error lines overlap across all the targets for both pattern masks).

The fact that the targets were seen more uniformly in Experiment 2 than in Experiment 1 may seem paradoxical at first because it might be thought that a lower contrast would result in a smaller just noticeable difference (jnd). But it must be remembered that the contrast in Experiment 2 was lowered at the expense of raising the background level of luminance, thus bringing the photopic system into play (as opposed to the mesopic) and resulting in more uniformity.

### Experiment 3: Adaptation Phase Effects With Aperiodic Mask Gratings

#### Introduction

One of difficulties in interpreting the results of

previous research is that periodic stimuli are often used. Stromeyer, et. al., (1974) Atkinson and Campbell (1974), and de Valois (1977) all used periodic gratings or patterns in studying the potential effects of phase. Thus, there is an essential ambiguity to their interpretation since the results can be predicted by both space domain and frequency domain models. Space domain models would make predictions based on the individual bars in the grating while frequency models would make predictions based on the spectral characteristics of the patterns. Since frequency and bar width are perfectly correlated in periodic patterns, no theoretical differentiation can be made. With aperiodic stimuli, however, the predictions of space domain and frequency domain models begin to diverge because the space domain model is essentially one based on local adaptation effects while the frequency domain model integrates information over a much wider retinal area. For example, it was previously noted that Weisstein and Bisaha (1972) found that a bar masked a grating uniformly over the visual field and that a bar masked a bar more than a grating masked a bar. These results illustrate the utility of the use of aperiodic patterns in providing evidence for frequency selective mechanisms as opposed to local size detecting mechanisms.

With regard to phase, a periodic composite grating (such as the targets used in Experiments 1 and 2) will have a fixed bar width (or distance between the maxima and the minima of a grating) that is constant across the visual field. Thus any phase effects found might be predicted from a consideration of the response of a single "unit" (such as that proposed by Macleod and Rosenfeld, 1972a) to the bar pattern. Variations in the relative phase of the two components of a composite grating change the distance between the maxima and the minima of major and minor bars of a grating. At this level, phase effects would merely result from the differential effects of the excitatory and inhibitory parts of that unit's "receptive field." The Fourier hypothesis, however, dictates that the salient variable is the relative phase between the two components in the frequency domain, not the space domain. Therefore, in order to decide between these two models, a mask (or target) is necessary in which the relative bar widths vary in the pattern, while the relative phase among the spectral components is constant. Experiment 3 was conducted to investigate whether an aperiodic mask with differing bar widths but constant phase among its spectral components would result in phase specific adaptation.

In this experiment, the following masks and targets were used:



### Masks

simple  $\sin x^2$  grating  
 $\sin x^2 + \sin 3x^2$  composite grating,  $90^\circ$  phase  
 homogeneous grey field as a luminance control

### Targets

$\sin 3x + \sin 9x$  grating,  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  phase  
 $\sin 5x + \sin 15x$  grating at the three phases  
 $\sin 8x + \sin 24x$  grating at the three phases  
 $\sin 10x + \sin 30x$  grating at the three phases

Figures 6 and 7 show the luminance profiles of the masks and the targets, respectively. The Fourier transforms of the targets are identical to those given for the composite gratings used in Experiments 1 and 2 above with the appropriate changes to reflect the different frequencies of these target gratings. The transform of the simple  $\sin x^2$  mask (ignoring various luminance constants) is:

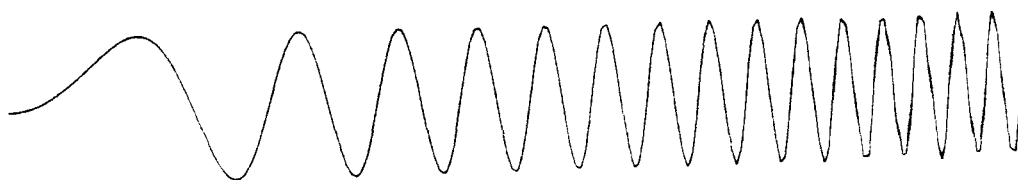
$$F(w) = \cos(w^2/4 + \pi/4)$$

where  $w$  is the variable indicating the frequency spectrum.

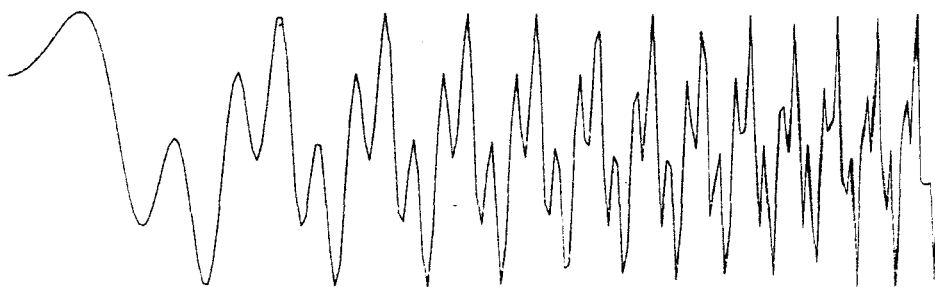
The transform of the composite mask grating is

$$F(w) = \cos(w^2/12 + \pi/4) + \cos(w^2/4 + \pi/4)e^{-j\theta}$$

The rationale for choosing this particular mask, then, was that it had local displacement variations with a constant phase. The expectation from Fourier theory would be that maximum adaptation would take place for the  $90^\circ$  phase mask and all of the  $90^\circ$  phase targets, regardless of frequency, since the phase is constant for all



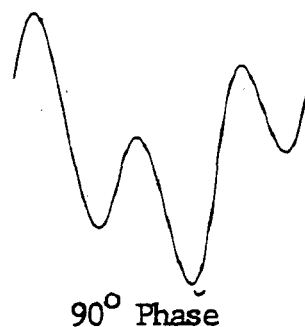
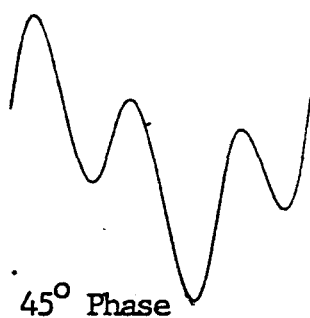
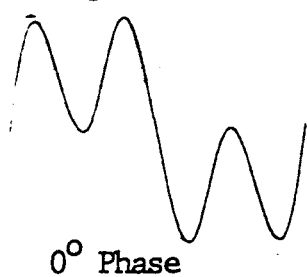
(a)  $\sin x^2$  grating



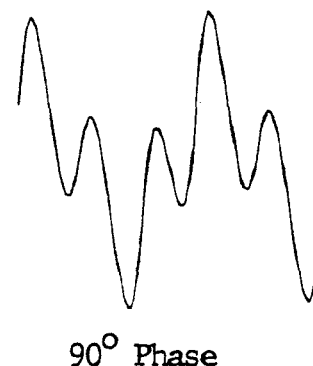
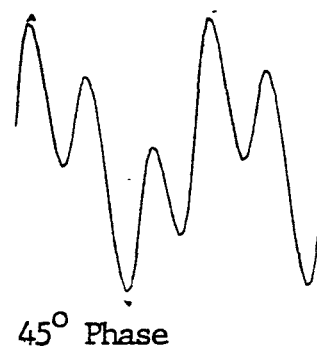
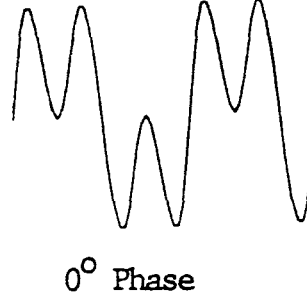
(b)  $\sin x^2 + \sin 3x^2$ ,  $90^\circ$  phase grating

Figure 6. Luminance profiles of masks in Experiment 3.

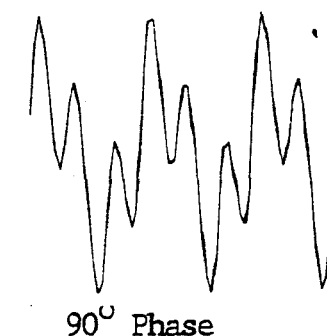
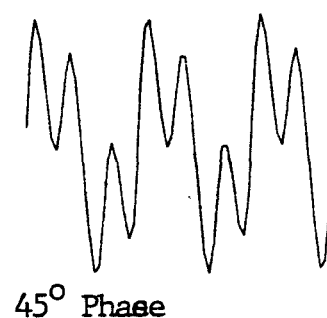
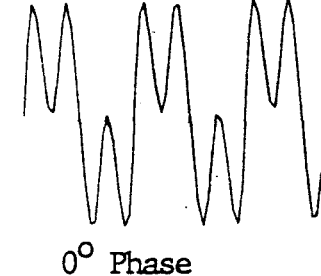
3 c/deg fundamental



5 c/deg fundamental



8 c/deg fundamental



10 c/deg fundamental

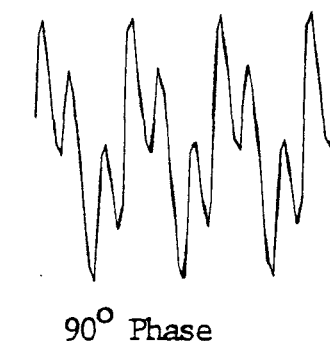
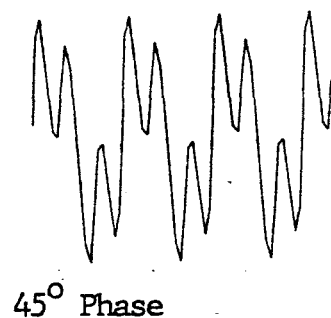
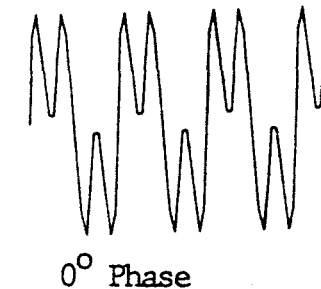


Figure 7. Luminance Profiles of Targets in Experiment 3.

of the frequencies in the spectrum. In addition, the  $\sin x^2$  mask should result in less adaptation than the composite since it would share less of the energy in the targets. A space domain model would predict no significant adaptation as a function of phase. It might predict slightly more adaptation caused by the composite mask because of its greater contrast relative to the  $\sin x^2$  mask. Finally, a space domain model would predict non-uniform adaptation because the bar widths vary across the lateral extent of the viewing field in the masks but not the targets.

### Results

An analysis of variance was computed on the log transforms of the magnitude estimations. This was a 3(Subjects) by 4 (Frequencies) by 3 (Masks) by 3 (Targets) by 5 (Replications) design. The analysis showed the following significant effects: the Mask main effect (  $F(2,28)=47.07$ ,  $p < .05$  ), a significant Frequency effect (  $F(3,42)=15.66$ ,  $p < .05$  ), significant Frequency by Mask, Frequency by Target, and Frequency by Mask by Target interaction (  $F(6,84)=4.41$ ,  $F(6,84)=3.0$ , and  $F(12,168)=2.32$ ; all  $p < .05$  ). Inspection of, and post hoc tests on, the cell means for the various effects showed that the frequency effect was due to the 3 cycle grating being less susceptible to adaptation effects than the gratings at other

frequencies. The Mask main effect was due to the blank control field causing enhancement of the target gratings. Figures 8, 9, and 10 display the resulting adaptation curves for each of the subjects, each mask being represented by one figure. An examination of these figures will show that, in accordance with the analysis of variance results, there is enhancement, or an increase in perceived contrast at all phases and frequencies of the target gratings for the grey field mask.

While there are individual data points in Figures 8 and 9 that are significantly different from other data points, there is no overall pattern of phase-specific data that is established. For example, for the composite masks no subject showed significant adaptation to 90 degree phase, regardless of frequency. Clearly, the expectations initially developed from consideration of the Fourier spectra and their phase relationships were not fulfilled.

### Discussion

The data do not show clear or consistent phase-specific adaptation effects. Both the simple and the composite grating masks resulted in an equivalent amount of adaptation. As noted previously, the composite grating had Fourier components that were in a 90 degree phase relationship across all frequencies although the cues varied with the lateral extent of the grating. The data do not show the expected phase adaptation.

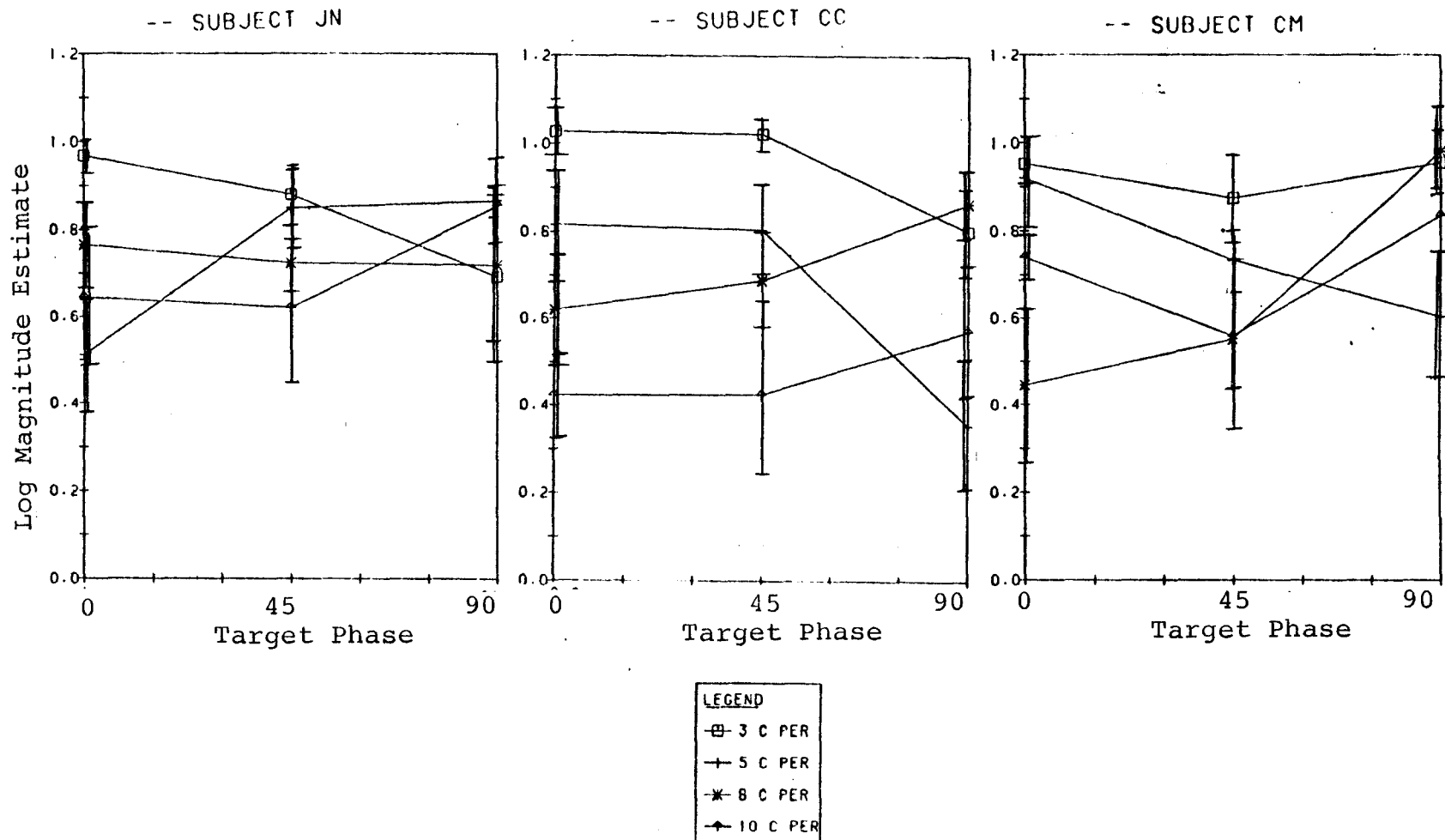


Figure 8. Log Magnitude Estimates of Grating Contrast for Sin  $x^2$  Mask, Experiment 3.

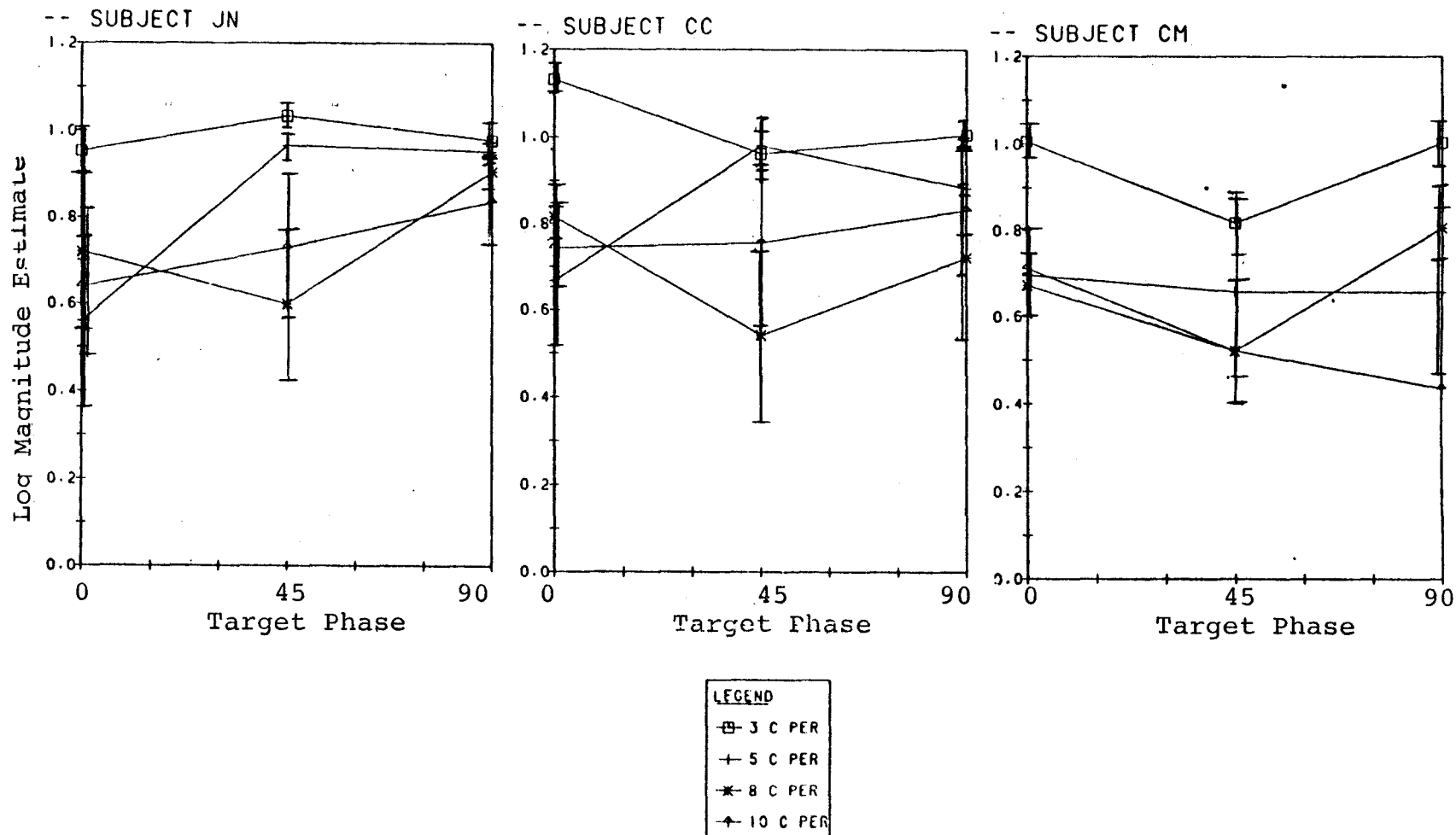


Figure 9. Log Magnitude Estimates of Grating Contrast for 90° Phase Mask, Experiment 3

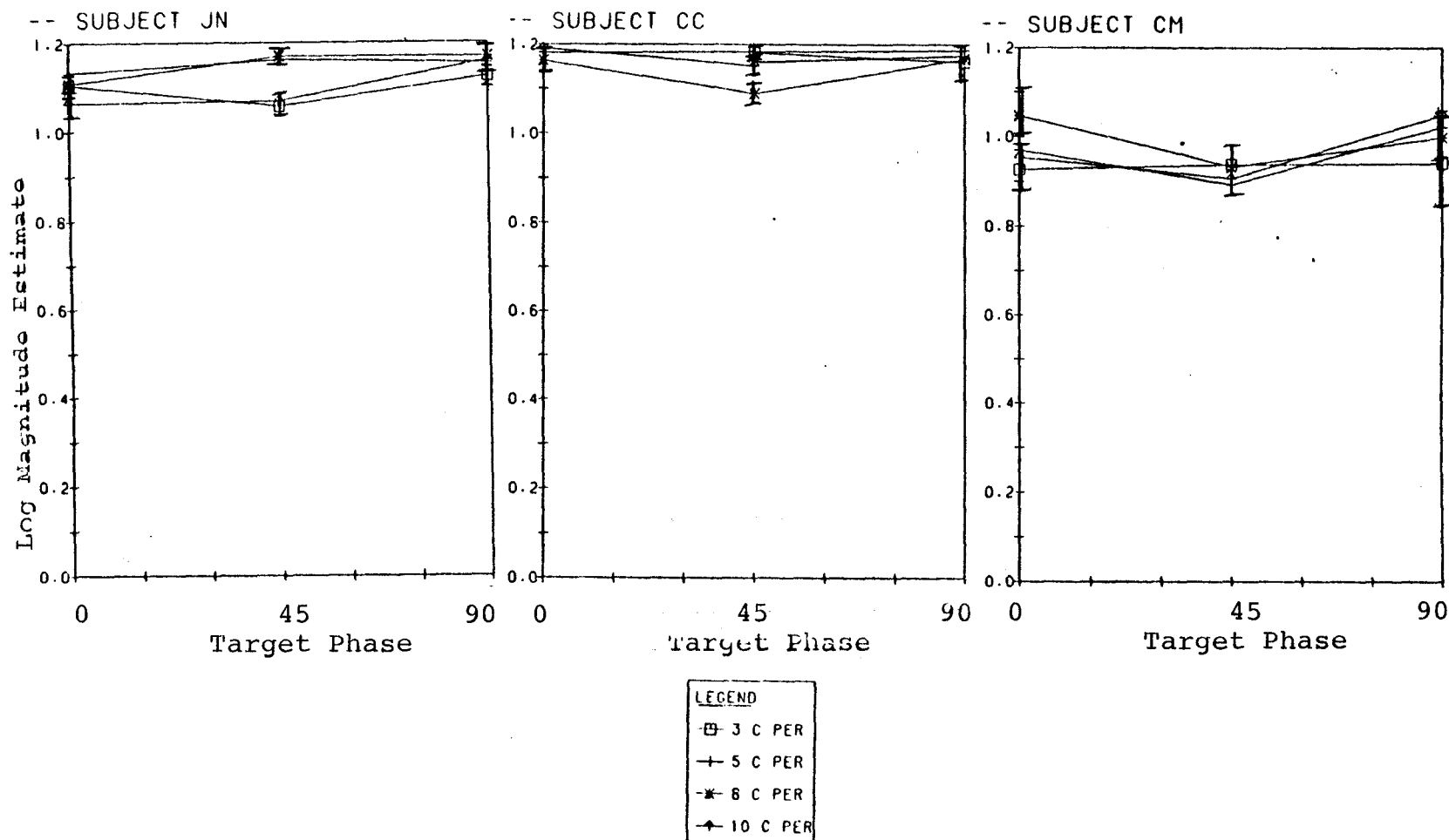


Figure 10. Log Magnitude Estimates of Grating Contrast for Grey Field Mask, Experiment 3



On the other hand, if the adaptations were purely local (or that usually associated with retinal effects), the there would have been a large number of non-uniform judgments for all the targets because the bar width of the mask is not constant across the visual field. This was not obtained. The test gratings were seen as uniform virtually one-hundred percent of the time across all experimental conditions.

An additional consideration mentioned in the discussion of Experiment 1 has to do with the relative weakness of the adaptation effect. A casual inspection of Figures 8 and 9 will reveal that the strength of the masking effect seldom gets larger than .5 log units. The weakness of the masking and the overlap of the Standard Error bars leads to the speculation that perhaps an adaptation paradigm such as that used here might be relatively insensitive to phase; or that phase sensitivity, in the Fourier sense, does not exist in the visual system.

It is unlikely that this lack of sensitivity would still permit a reasonable model of Fourier pattern processing. An easily demonstrable fact is that human observers can readily discriminate between gratings with similar frequency components and dissimilar phase relationships at suprathreshold levels. Thus, experience in the visual world dictates that phase processing must exist.

#### Experiment 4: A Test of the Uniformity Criterion

All of the experiments reported here involved uniformity ratings of the target grating contrast. This measure was used in order to ascertain the validity of one of the initial assumptions of the model described in the introduction: that a number of spatial frequency channels of narrow to medium bandwidth exist and that their distribution does not vary within the retinal eccentricities used here (8 degrees centered at the fovea). This assumption is in accord with a particular class of models, the space-invariant class as discussed in the introductory chapters. This assumption is contrary to the space-variant class of spatial frequency models.

The uniformity measure is especially important with the frequency gradient masks which do not have a uniform bar width across the visual field. A space-variant model would predict differential adaptation as a function of retinal eccentricity while a space-invariant model would predict no such differential adaptation. It was felt that a more direct test of these two types of models would be in order. If a stimulus were presented with local contrast non-uniformities, the space-variant models would predict very non-uniform adaptation taking place. The type of space-invariant model assumed in the introduction would predict uniform adaptation in accord with the frequency components making up the stimulus.

The following masks and targets were used in this experiment and are displayed in Figures 10 and 11:

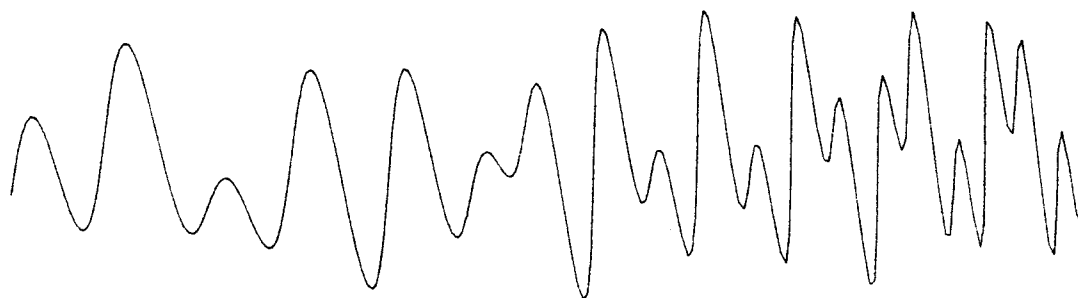
### Masks

$\sin x^2 + \sin 5x$  grating,  $0^\circ$  phase  
 $\sin x^2 + \sin 5x$  grating,  $90^\circ$  phase  
 homogeneous grey field control

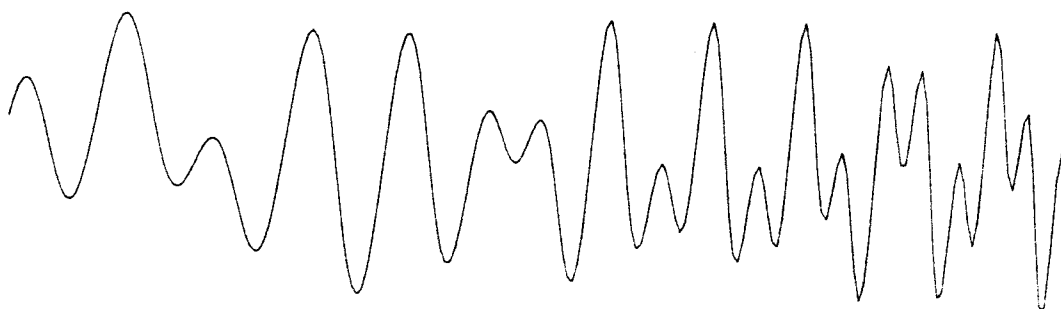
### Targets

$\sin 5x + \sin 15x$  grating,  $0^\circ$  phase  
 $\sin 5x + \sin 15x$  grating,  $90^\circ$  phase  
 $\sin 5x$  grating  
 $\sin 15x$  grating

The addition of a simple 5 cycle grating to a frequency gradient has the net effect of creating local contrast non-uniformities although the space average contrast and luminance stays the same. By including the two components (5 cycle per degree and 15 cycle per degree) of a composite grating along with the two phased versions of those gratings (5 + 15 cycle per degree,  $0^\circ$  and  $90^\circ$  phase), the experiment will be able to assess the relative strength of the effects due to frequency and due to phase. In light of the fact that this experiment is a test of the uniformity of the adaptation effect, the uniformity data is of paramount importance. If a Fourier type of process were not going on in the human visual system, the expectation would be that

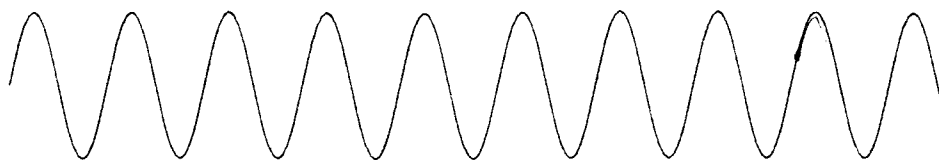


$\sin x^2 + \sin 5x$ ,  $0^\circ$  phase

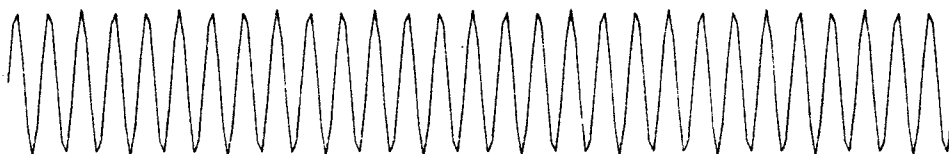


$\sin x^2 + \sin 5x$ ,  $90^\circ$  phase

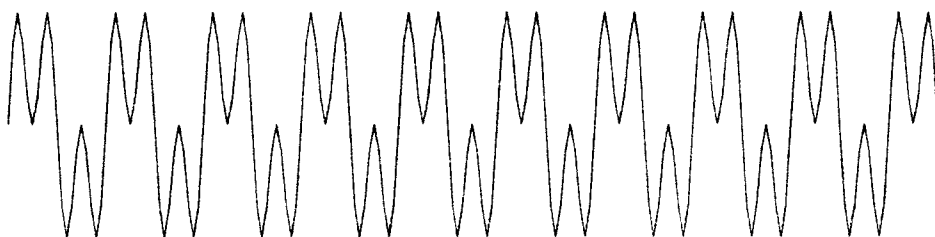
Figure 11. Luminance Profiles of Masks Used in Experiment 4



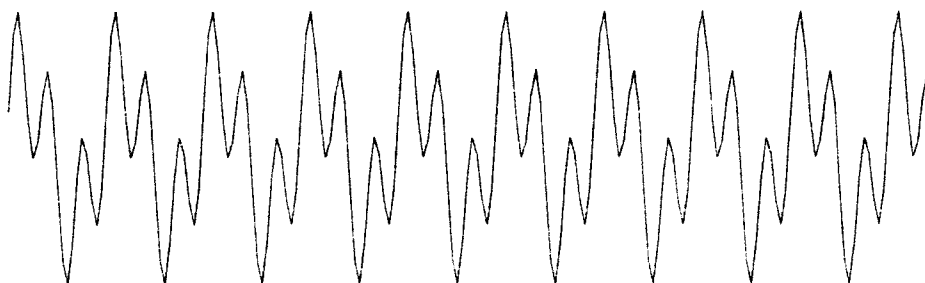
$\sin 5x$



$\sin 15x$



$\sin 5x + \sin 15x, 0^\circ \text{ phase}$



$\sin 5x + \sin 15x, 90^\circ \text{ phase}$

Figure 12. Luminance Profiles of Targets Used in Experiment 4.

most of the trials would result in the target not being seen uniformly. The subject should see "patches" of the target with little or no contrast and other patches with moderate to high contrast. Moreover, the patches in the target grating would match the contrast non-uniformities in the mask. Expectations from Fourier theory would predict that the simple 5 cycles per degree would be masked the most since it was explicitly added to the frequency gradient mask. Additionally, the masking should be uniform across the visual field since the key mediating variables would be the frequency spectra of the targets and the masks rather than the local bar width or contrast non-uniformities. The 90 degree phase composite targets should be masked less than the simple 5 cycle per degree grating but more than the remaining two targets since it shares the 5 cycle component in the same phase relationship as present in the mask. Finally, the 0 degree phase composite target and the simple 15 cycle per degree target should be masked since they share fewer components with the masks than the other two targets.

### Results

An analysis of variance was computed on the log transforms of the magnitude estimations of the apparent contrast of the target gratings. This was a 3 (Subjects) by 3 (Masks) by 4 (Targets) within subjects design with 10 replication for each unique combination of the indepen-

dent variables. This analysis revealed both main effects of Mask and Target as well as their interaction to be significant (  $F(2,54)=83.37$ ,  $F(2,81)=11.30$ , and  $F(6,162)=2.56$ , all at  $p < .05$  ). Chi-squares were computed for the uniformity data. These revealed a significant mask effect (  $\chi^2_{(2)}=58.86$ ,  $p < .05$  ) and a significant target effect (  $\chi^2_{(3)}=8.81$ ,  $p < .05$  ); the interaction term for the uniformity data was not significant.

The adaptation results are displayed in Figure 13 for each subject. Post hoc analysis of the data (Duncan's range test, all at  $p < .05$  ) revealed that the grey field mask caused significantly less adaptation than either of the two grating masks. The two grating masks, while causing a significant amount of adaptation, did not differ significantly from each other. Of the targets, the simple 5 cycle per degree grating was masked the most; furthermore, it was masked equally well by both mask gratings. The other targets were masked less well than the simple 5 cycle per degree grating, and about equally well by either of the mask gratings.

Figure 14 graphically displays the uniformity data for each subject. One subject saw all the targets as being uniform under all the experimental conditions. The other two subjects perceived the 5 cycle per degree grating much more uniformly than any other of the other target gratings.

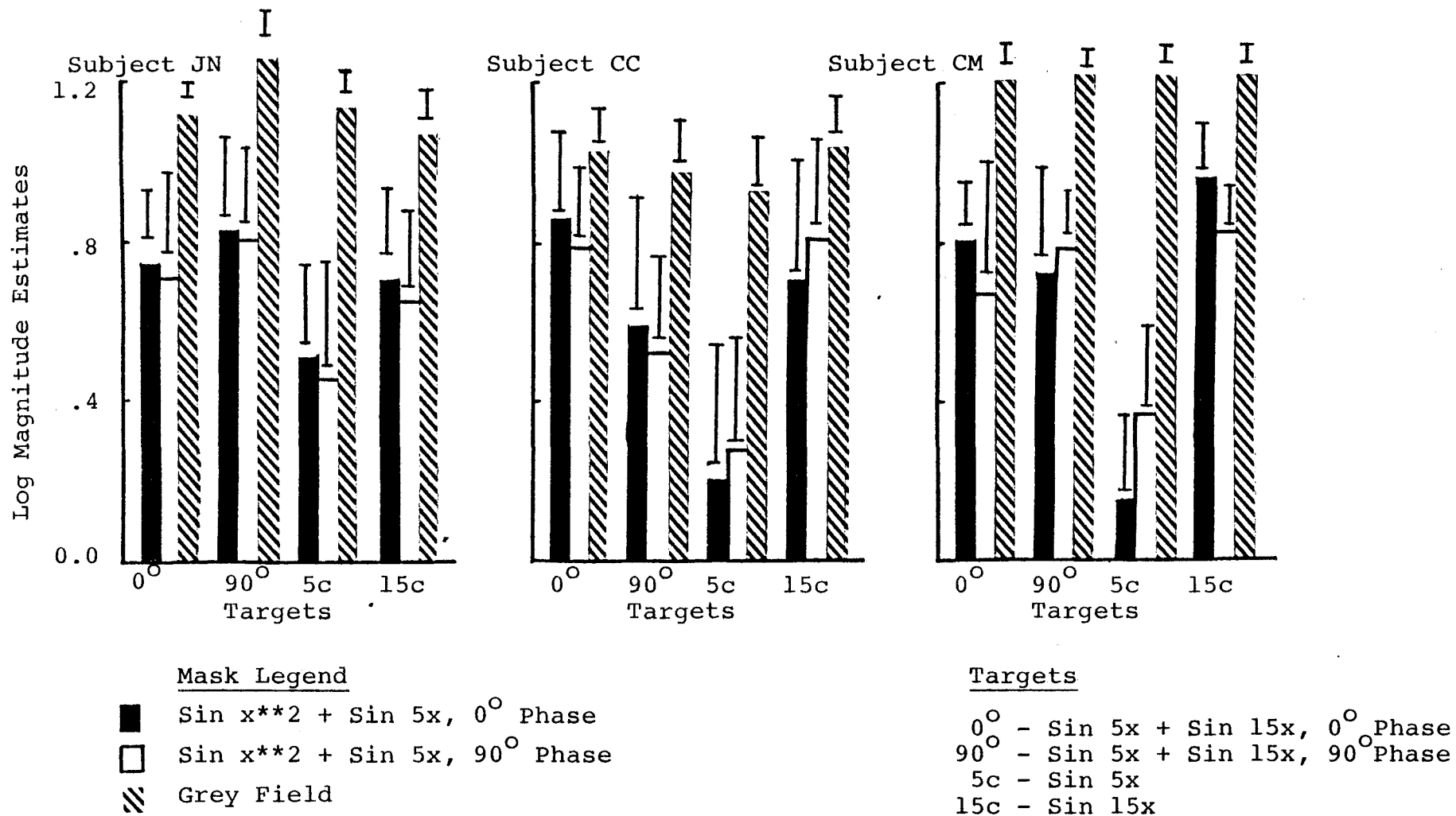


Figure 13. Log Magnitude Estimates of Grating Contrast, Experiment 4



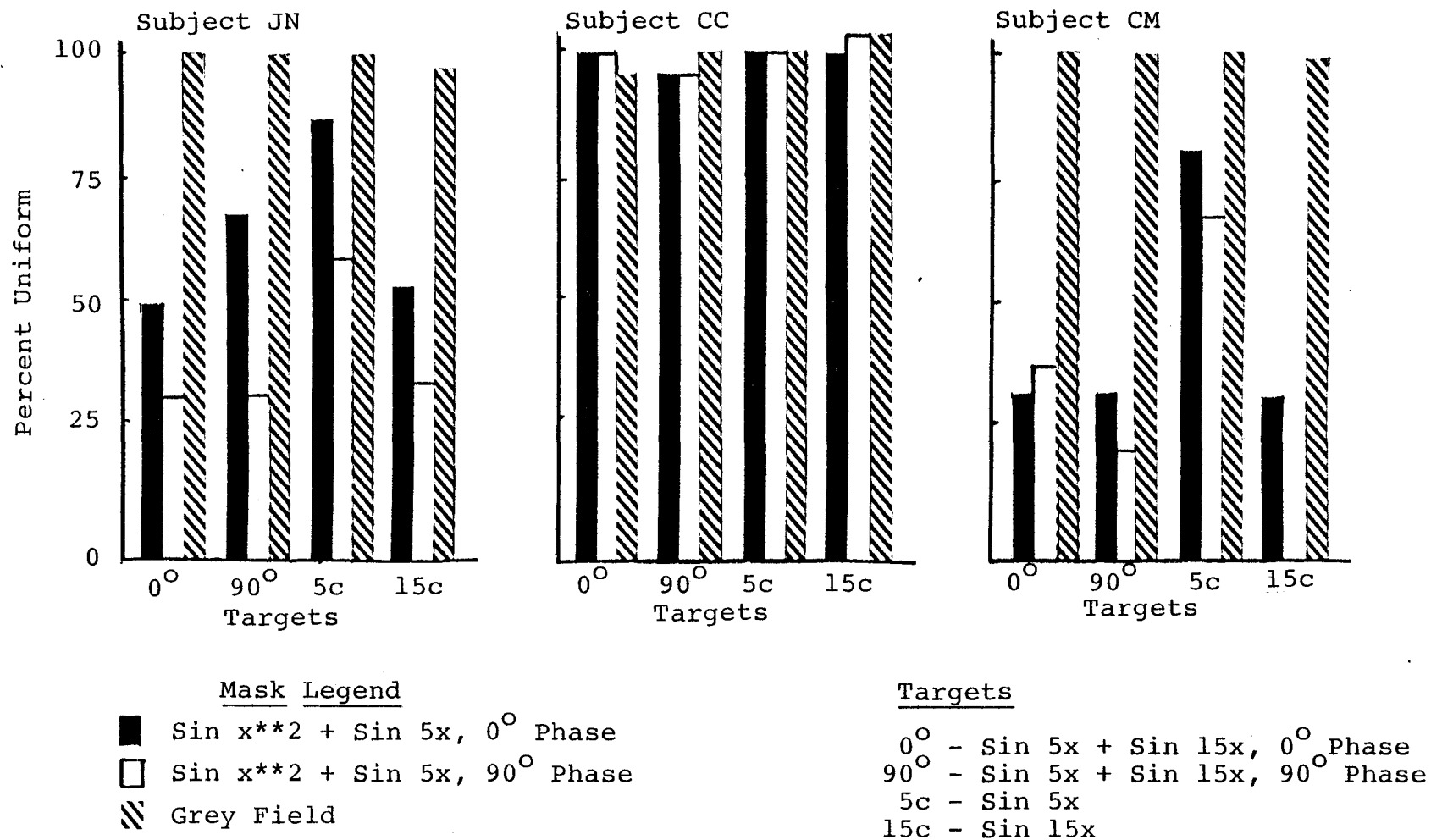


Figure 14. Percent That Grating Targets Were Seen As Uniform, Experiment 4

The two subjects reported that when non-uniformity did occur (as in the other three targets), it corresponded to those areas of the mask gratings where the contrast was the lowest.

### Discussion

There are two main findings in this experiment. First, there was no adaptation that could be attributable to phase relationships among the Fourier spectra of the targets and the mask. Second, the five cycle target underwent the greatest degree of masking and it was more uniformly masked than any other target.

The phase shift for the 5 cycle grating was not constructed with respect to a 15 cycle component as it was in Experiments 1 and 2 but with respect to the starting edge of the  $\sin x^2$  grating. The lack of phase (or position) adaptation reinforces the findings from the previous experiment in which a constant phase difference in the frequency domain also resulted in the lack of phase-specific adaptation. This experiment did find frequency specific adaptation that was uniform across the visual field. That the simple 5 cycle per degree grating was masked the most might be initially attributed to the fact that it had a lower physical contrast than any of the composite gratings. If adaptation were due to contrast, however, then the simple 15 cycle grating should have been masked at least as much

as or even more than the 5 cycle grating. This did not occur. These results also have some bearing on the previous speculation raised with regard to Experiments 1 and 2 about the sensitivity of the adaptation paradigm to spatial frequency phenomena. Here the local bar widths varied across the visual field. In addition, the local contrast also varied across the visual field independently of bar width. The maximum adaptation at 5 cycles cannot be explained by a space domain model which would be sensitive to local irregularities. This result can be explained by consideration of the Fourier spectra of the masks and the targets. The results here also have some impact on the interpretation of the findings in Experiment 1. But the discussion of this will be reserved for the concluding chapter.

#### Summary of the Adaptation Studies

These four adaptation experiments investigated the sensitivity of the human visual system to phase differences in sinusoidal gratings. Experiment 1 showed that adaptation to a composite (two component) grating will reduce sensitivity to a target grating of that phase and frequency but not to gratings of different phases. Experiment 2 showed that this finding is somewhat dependent on the contrast of the mask and the target gratings. Experiment 3 failed to show any effects due to phase or position: the level of

masking was small and the inter-subject variability was somewhat high. There was a slight tendency exhibited by all the subjects for adaptation to increase with increased frequency of the target grating although this had no bearing on the main predictions deduced from a Fourier phase model. Experiment 4 showed that the uniformity criterion used in the other experiments is an adequate measure of the subjects perceptions of homogeneous effects. More importantly, it showed that the adaptation paradigm is sensitive enough to use in obtaining frequency specific effects that cannot be explained by a local feature or a space domain model.

In all of the adaptation studies, none of the phase effects predicted by the Fourier model posited in the introduction were obtained. This leads to a number of questions having to do with the assumptions included in the model. A fundamental assumption of the model is that adaptation fatigues or saturates a set of independent frequency and phase channels. A number of ancillary assumptions were made (e.g., the lack of inhibition between both types of channels) that could have predicted a reduction in the apparent contrast of the test gratings as a function of phase. Since these results were not obtained, it is clear that the model and its assumptions need to be re-evaluated. The key assumptions that need to be questioned have to do

with inhibitory relations between channels and with the exact nature of phase adaptation, as opposed to frequency adaptation. These questions will be discussed in the concluding chapter, after the results of the backward masking studies are presented.

## BACKWARD MASKING STUDIES

### Experiment 5: Temporal Aspects of Phase

Backward masking is a tool that permits the investigation of temporal relationships among stimuli. If a particular mask causes masking of a target, then it is assumed that some aspect of the target and the mask interacted to create the result. At the same time, since one of the variables in masking is the relative temporal latency between the two stimuli, the paradigm permits the inference of when psychophysical events occur.

The introduction discussed some of the neurophysiological data (Pollen, Lee, and Taylor, 1971; Fiorentini and Maffei, 1973) that implies that phase, or position of a bar within a spatial frequency channel or with respect to the center of a neural cell, results in a change in latency of a firing of that cell. Since backward masking is sensitive to the spatial frequency content of the target and mask (Breitmeyer and Ganz, 1976; Growney, 1977), it is possible that phase or position will result in differences within the limitations established in the masking functions. In other words, it is possible that the time at which maximum masking takes place will differ depending on the phase/position differences in the target and mask. Accordingly, this experiment was conducted to examine whether such peak shifts occur.

The stimuli used for this experiment were:

### Masks

sin 5x + sin 15x grating, 0° phase  
 sin 5x + sin 15x grating, 90° phase  
 homogeneous grey field control

### Targets

sin 5x + sin 15x grating, 0° phase  
 sin 5x + sin 15x grating, 90° phase

There were 10 inter-stimulus-intervals (ISIs): -40, -20, 0, 20, 40, 60, 80, 100, 150, 200 all in milliseconds (msec.), where a negative sign signifies that the mask preceded the target, otherwise the target preceded the mask. The duration of both the target and the mask was 50 msec.

### Results

This was a 3 (Subject) by 3 (Mask) by 2 (Target) design with 10 replications per unique mask/target combination. An analysis of variance was computed on the log transformed magnitude estimations of the apparent contrast of the grating. The following significant effects were obtained: Mask,  $F(2,58)=18.26$ ,  $p < .05$ ; Target,  $F(1,29)=4.55$ ,  $p < .05$ ; and Mask by Target by ISI,  $f(18,522)=2.23$ ,  $p < .05$ . The uniformity data showed no variation among the experimental conditions so they will not be reported here.

The masking curves are presented in Figures 15 and 16 for the individual subjects. The curves for the 0 degree phase target are presented in Figure 15 and the curves for

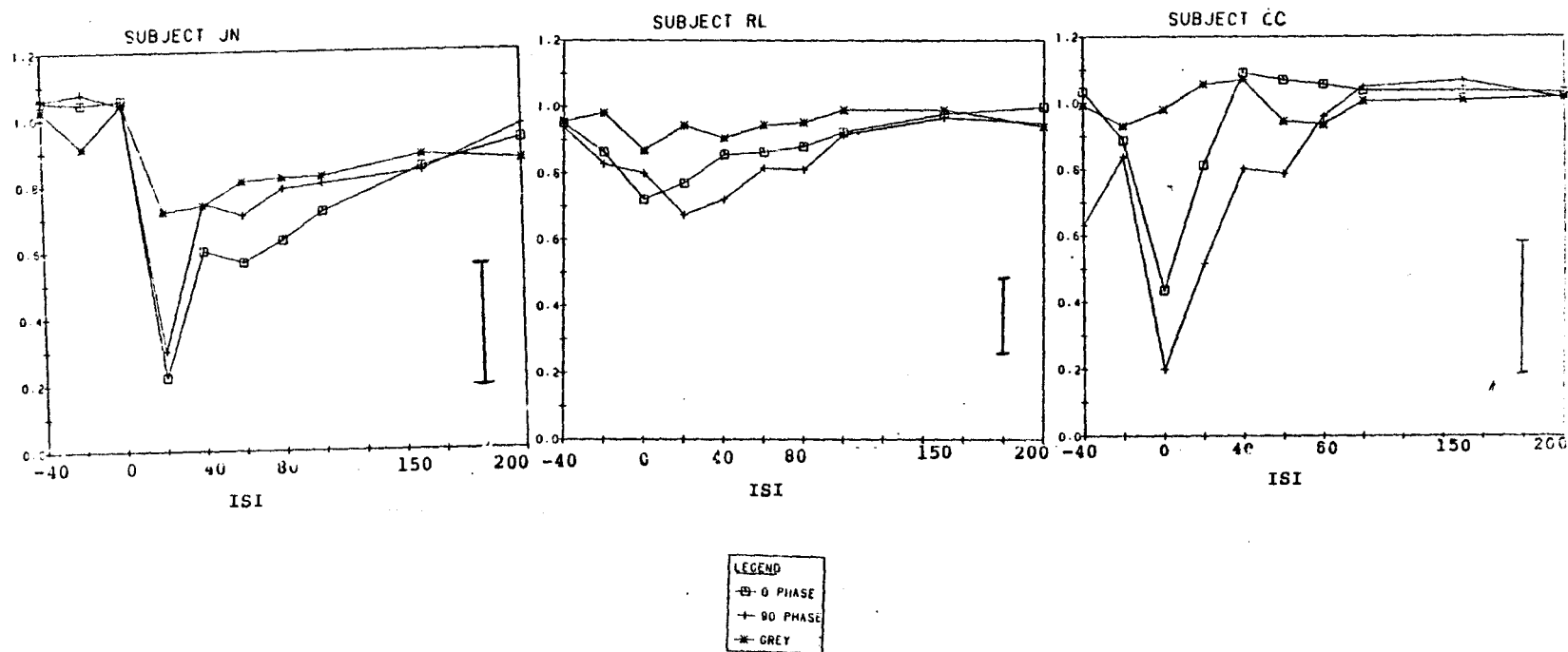


Figure 15. Log Magnitude Estimates for 0° Phase Targets, Experiment 5.



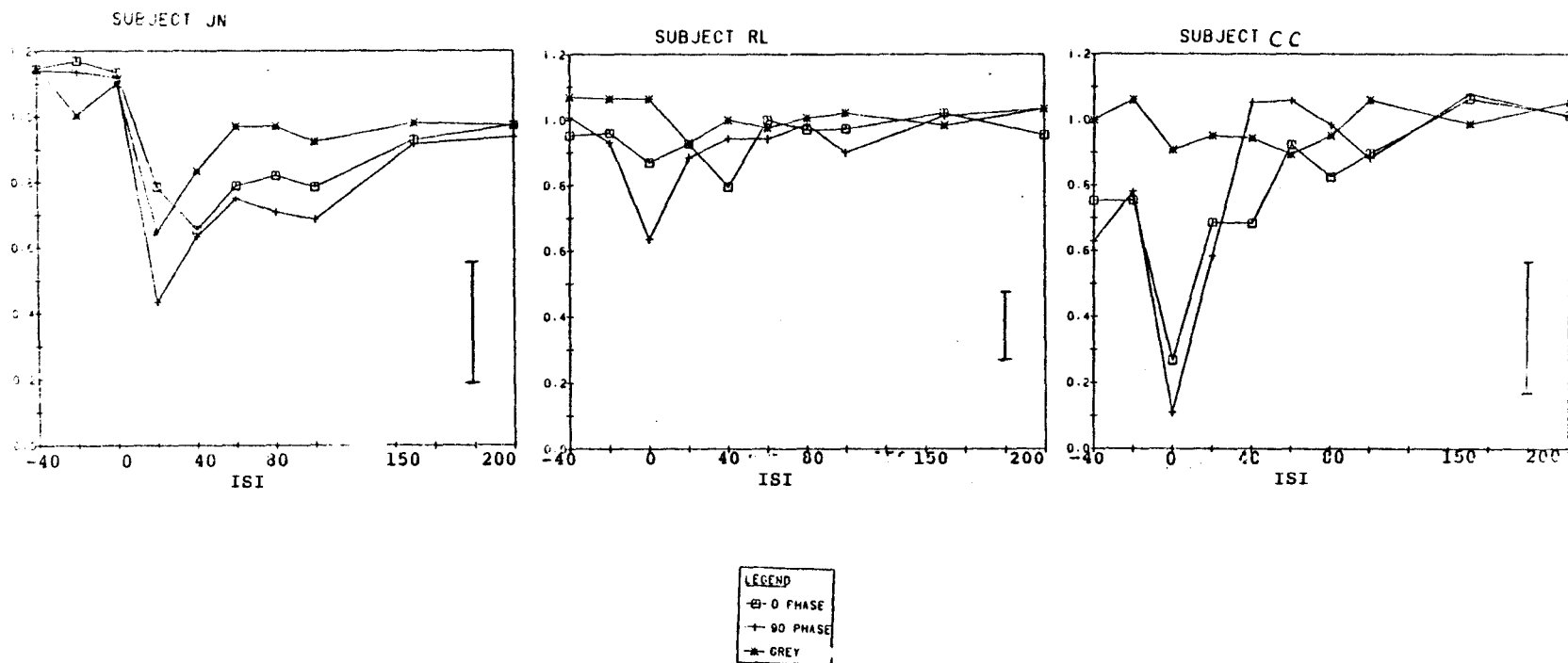


Figure 16. Log Magnitude Estimates for 90° Phase Targets, Experiment 5.

the 90 degree phase targets are presented in Figure 16. The masking for subject RL was not as great as for the other two subjects, although the magnitude of the mask effects for all three subjects is consistent with that found by others (Growney, 1973; Growney, Cox, and Weisstein, 1977; Breitmeyer, 1975). It can be seen that masking is a U-shaped function of ISI with the point at which maximum masking takes place differing depending on the target and mask for two of the three subjects (subject CC does not show this peak shift).

Subject JN shows maximum masking taking place at 20 msec. ISI for the for the 0 degree target and both 0 degree and 90 degree phase mask (Figure 15). For the 90 degree phase target, subject JN shows maximum masking taking place at 20 msec. ISI with the 0 degree phase mask and 40 msec. ISI for the 90 degree mask (Figure 16).

Subject RL shows maximum masking taking place at 0 msec. ISI for the 0 degree phase mask and target, and at 20 msec. ISI for the 90 degree phase mask and 0 degree phase target (Figure 15). For the 90 degree phase target she shows maximum masking at 0 msec. ISI with the 90 degree phase mask and at 40 msec. ISI for the 0 degree phase mask. For all three subjects there is more masking for same-

phased targets and masks (i.e., the 0 degree phase mask and target combination) than for different phased targets and masks. The grey field resulted in little or no masking taking place. This would imply that masking was due to the grating patterns rather than average luminance. The variability for all subjects averaged between .1 and .2 log units. Since the ISI shift occurs for both grating masks for only one subject, and does not occur at all for another, not much confidence should be placed in these data.

### Discussion

If the shifts in ISI at which maximum masking takes place were more consistent across subjects, they would be within the temporal range suggested by Pollen, Lee and Taylor (1971), on the order of about 10 msec. Given the lack of consistency, a more conservative interpretation would state that no differential masking was obtained as a function of the phase targets and the masks.

### Experiment 6: Temporal Aspects of Phase and Spatial Frequency

If the impact of Experiment 3 was that no phase/position information was being processed with those masks, then backward masking curves with the frequency gradient mask should result in no shifts in the ISIs at which maximum masking takes place. On the other hand, adaptation is not equiva-

lent to backward masking. For example, in Experiment 1 the 0 degree phase mask only adapted itself but not any other phase target grating. But Experiment 5 showed that about the same masking functions could be obtained with dissimilar phase targets and masks. This experiment was conducted to examine whether phase effects could be obtained with the frequency gradient masks and a number of different frequency and phase targets. A Fourier model, in conjunction with the neurophysiological data discussed above would predict temporal shifts in peak masking as a function of the phase similarity between the frequency components of the targets and masks.

The masks and the targets were:

#### Masks

sin  $x^2$  + sin  $3x^2$  grating,  $0^\circ$  phase  
 sin  $x^2$  + sin  $3x^2$  grating,  $90^\circ$  phase  
 homogeneous grey field as a luminance control

#### Targets

sin  $3x$  +  $9x$  grating,  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  phases  
 sin  $5x$  +  $15x$  grating,  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  phases  
 sin  $10x$  +  $30x$  grating,  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  phases

The durations of the masks and the targets were the same as in Experiment 5. The ISIs were also the same. From an inspection of the list of masks and targets, it is apparent that this experiment is meant to be similar to Experiment 3, which also varied the phase and the frequency with similar but not identical masks and targets.

## Results

An analysis of variance was performed using the log transforms of the resulting magnitude estimations. This was a 3 (Subjects) by 3 (Frequencies) by 3 (Masks) by 3 (Targets) by 10 (ISIs) completely within subjects design with 5 replications at each unique stimulus combination resulting in 1350 trials per subject. Due to the relatively large number of testable effects, the analysis results are presented in tabular form in Table 3. It can be seen from that table that only the Frequency by Mask, Mask by Target, and Mask by Target by ISI were not significant.

The data are displayed in Figures 17 through 25. Each figure presents the data for a single target/mask combination across all three frequencies used. Each data point is the mean of the logs of the magnitude estimations. In order not to obscure the masking curves themselves, the average standard error is indicated by the vertical bar at the upper right hand side of each graph. In general, more variability was obtained for those data points that show more masking. The confidence intervals for the two grating masks in general are larger than the intervals for the grey field mask.

None of the subjects exhibited temporal shifts at which maximum masking took place for any combinations of target and mask phase. In general, maximum masking took place at

Table 3

## Analysis of Variance Results

<u>Source of Variation</u>	<u>Sums of Squares</u>	<u>df</u>	<u>Mean Squares</u>	<u>F</u>
Frequency (F)	11.26	2	5.63	28.86**
Error	4.68	24	.19	
Mask (M)	9.09	2	4.55	37.33**
Error	2.93	24	.12	
Target (T)	1.14	2	.56	12.73**
Error	1.06	24	.04	
ISI (I)	70.68	9	7.85	122.91**
Error	6.90	108	.06	
F x M	1.88	4	.47	2.20
Error	10.22	48	.21	
F x T	.98	4	.24	4.55**
Error	2.24	48	.04	
F x I	3.60	18	.20	3.72**
Error	11.63	216	.05	
M x T	.29	4	.07	2.03
Error	1.76	48	.04	
M x I	16.21	18	.90	25.73**
Error	7.56	216	.04	
T x I	.70	18	.04	2.13**
Error	3.97	216	.02	
F x M x T	.80	8	.10	2.62**
Error	3.66	96	.04	
F x M x I	2.32	36	.06	1.71**
Error	16.31	432	.04	
F x T x I	2.03	36	.06	2.45**
Error	9.93	432	.02	
M x T x I	1.02	36	.03	1.20
Error	10.15	432	.02	
F x M x T x I	2.46	72	.03	1.45**
Error	20.39	864	.02	

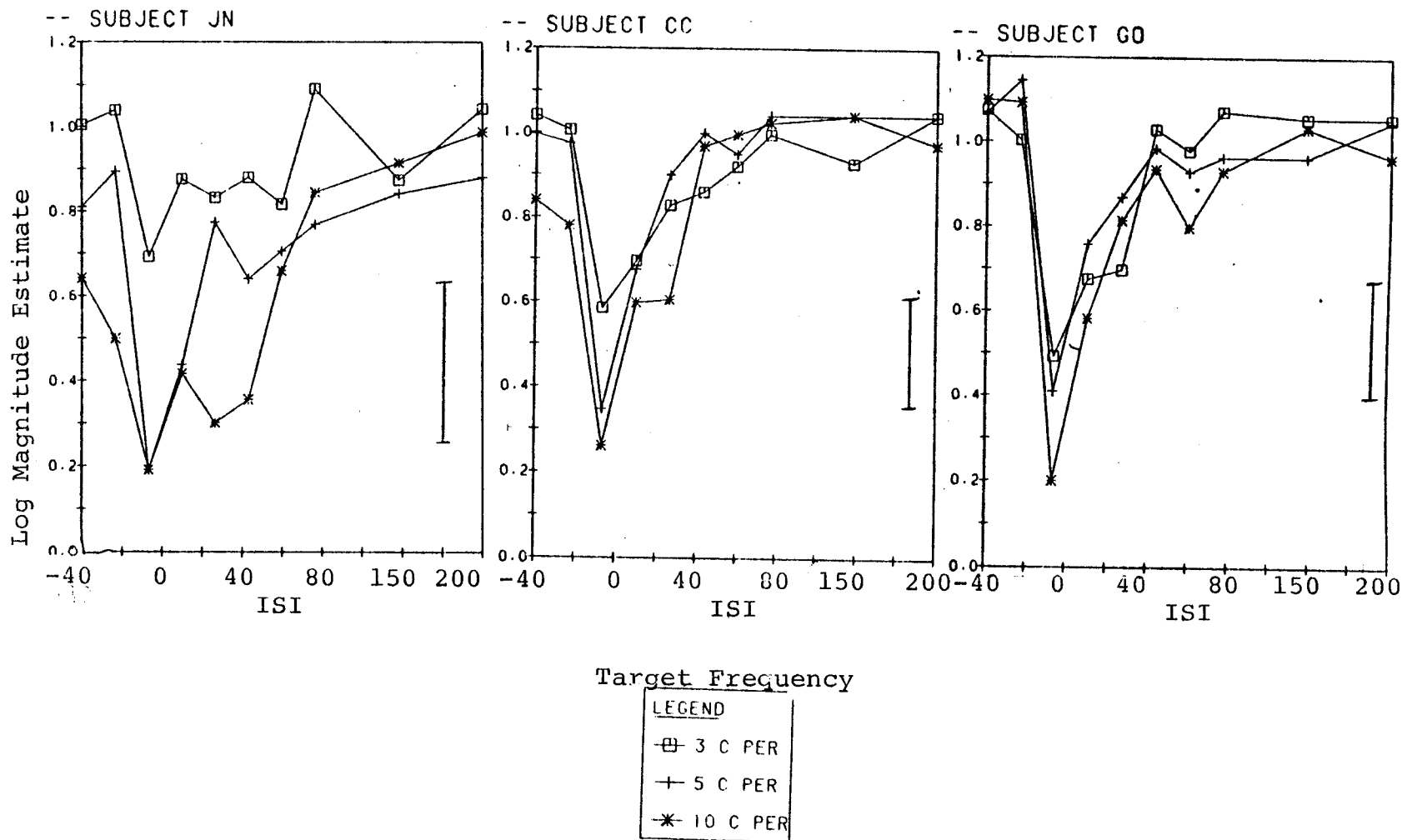


Figure 17. Log Magnitude Estimates of Grating Contrast for  $0^\circ$  Phase Mask and  $0^\circ$  Phase Targets, Experiment 6

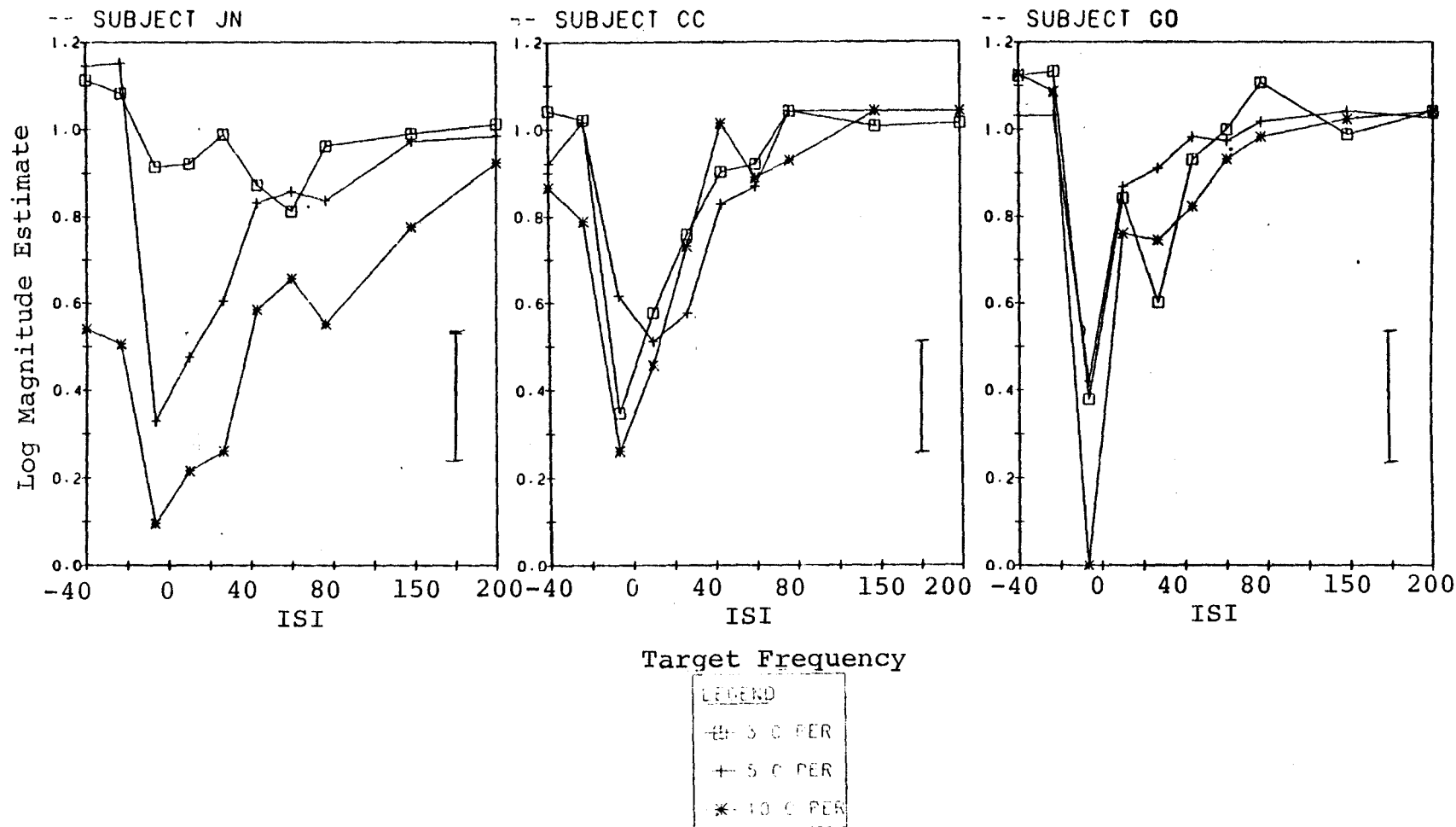


Figure 18. Log Magnitude Estimates of Grating contrast for  $0^{\circ}$  Phase Mask and  $45^{\circ}$  Targets, Experiment 6.



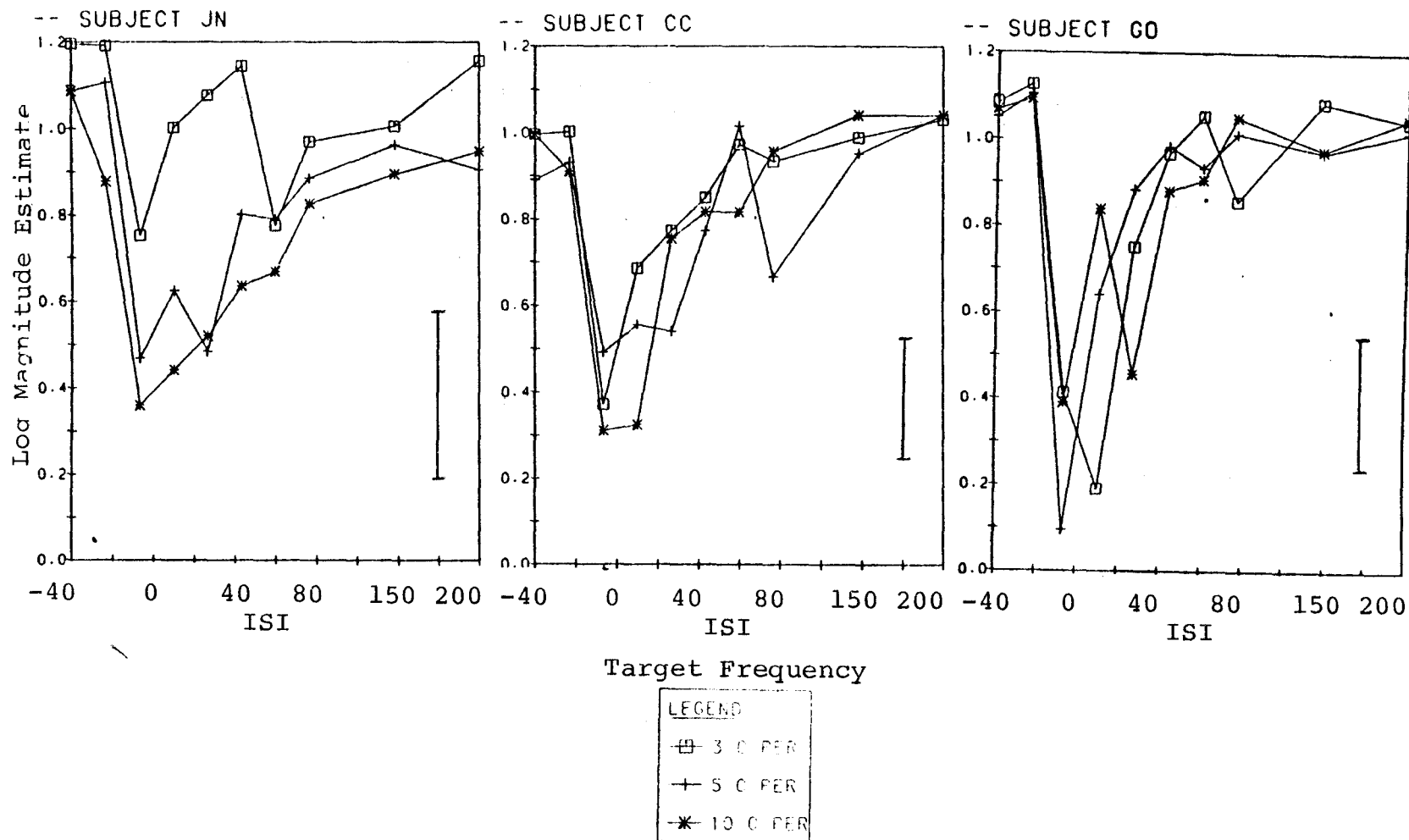


Figure 19. Log Magnitude Estimates of Grating Contrast for 0° Mask and 90° Targets, Experiment 6.

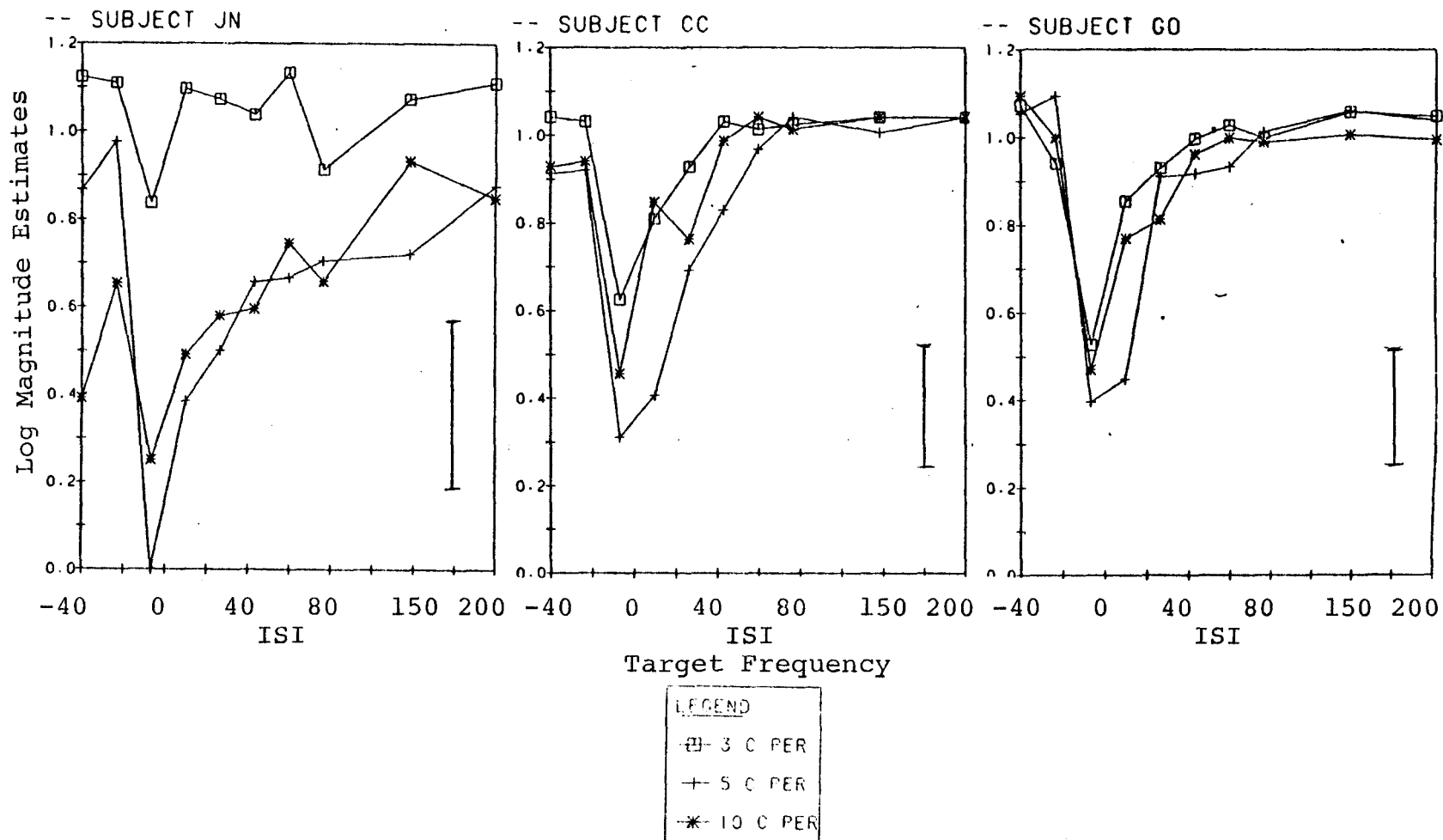


Figure 20. Log Magnitude Estimates of Grating Contrast for 90° Phase Mask and 0° Phase Targets, Experiment 6.

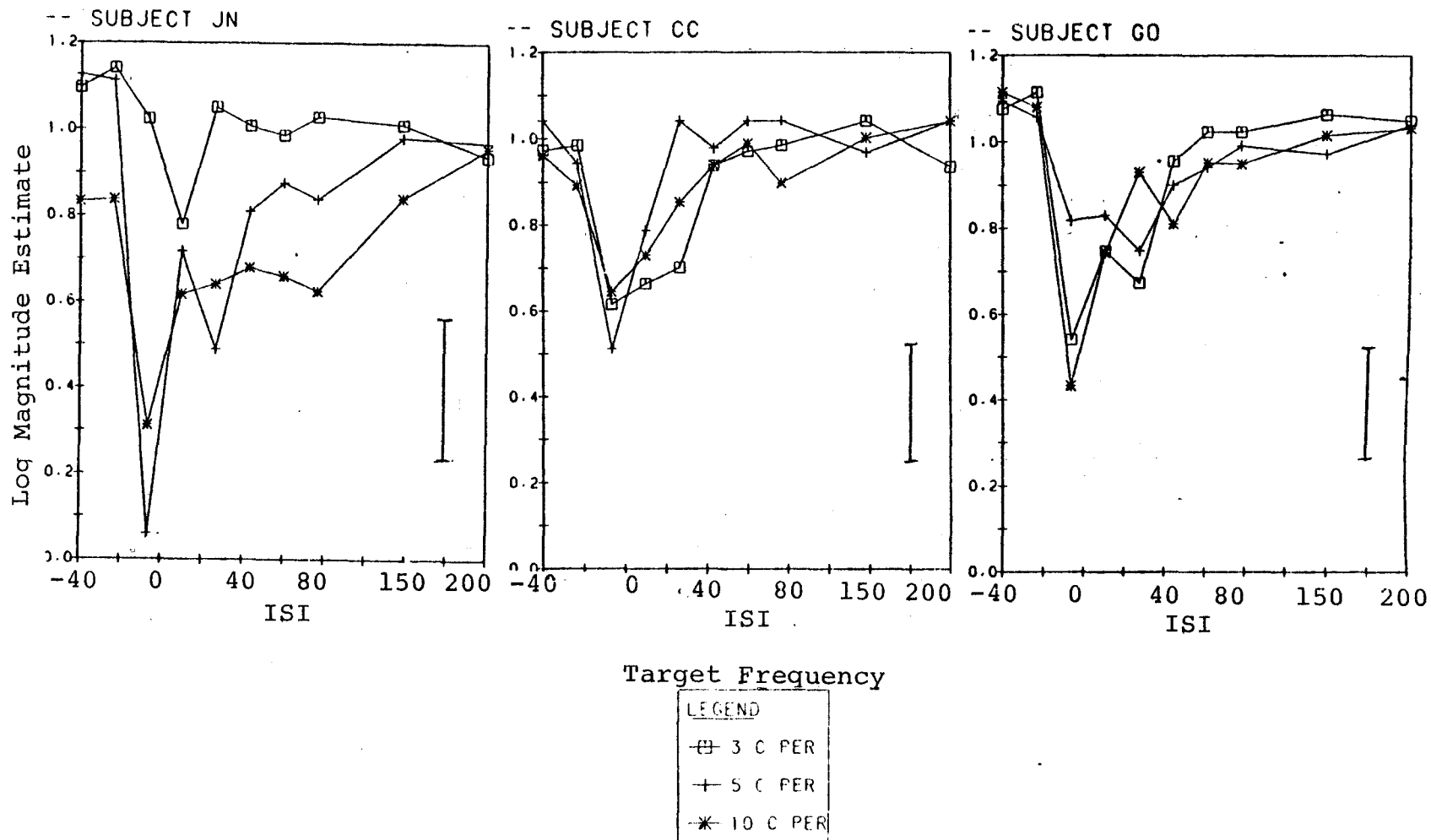


Figure 21. Log Magnitude Estimates of Grating Contrast for  $90^{\circ}$  Phase Mask and  $45^{\circ}$  Phase Targets, Experiment 6.

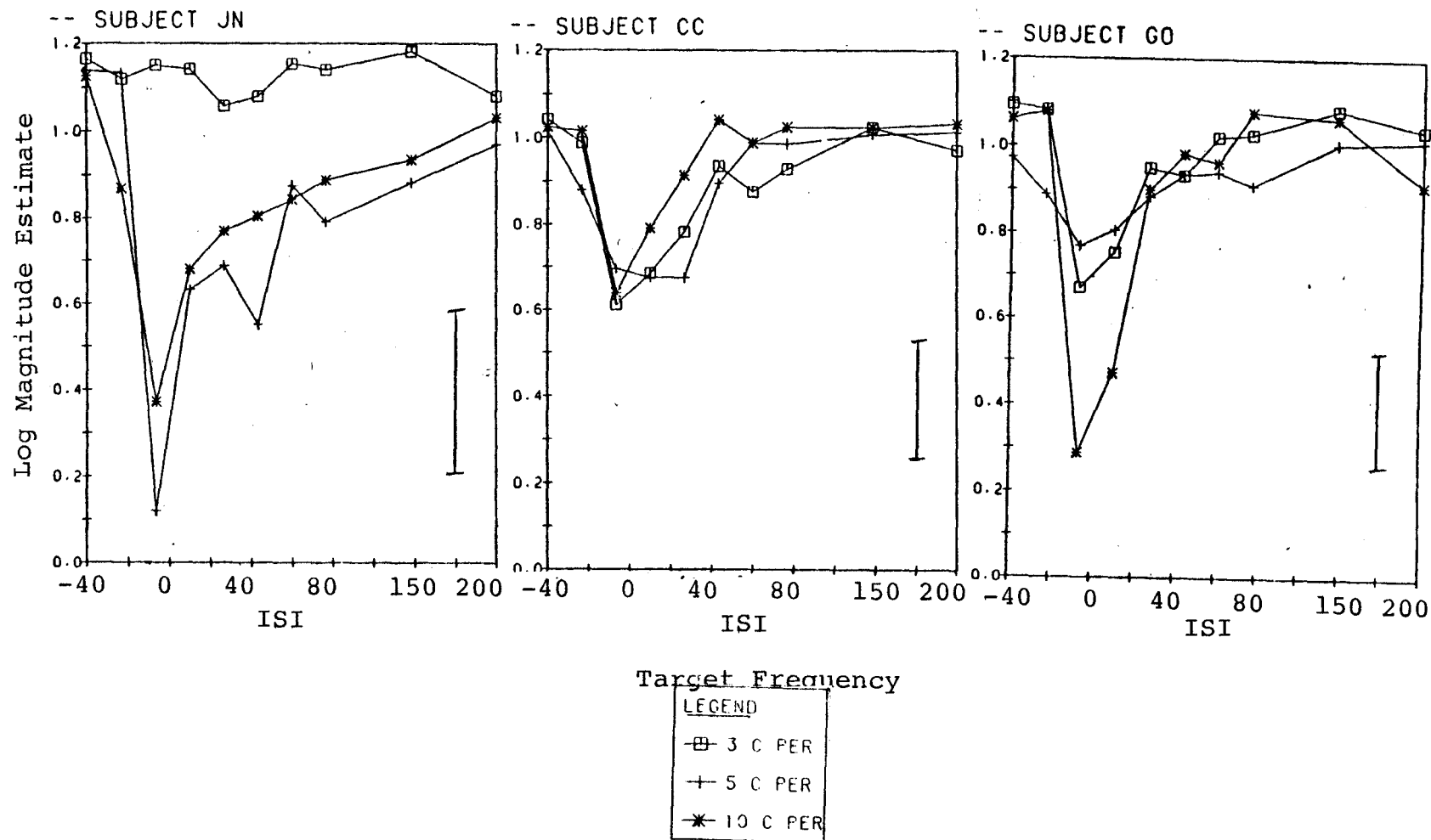


Figure 22. Log Magnitude Estimates of Grating Contrast for  $90^\circ$  Mask and  $90^\circ$  Phase Targets, Experiment 6.

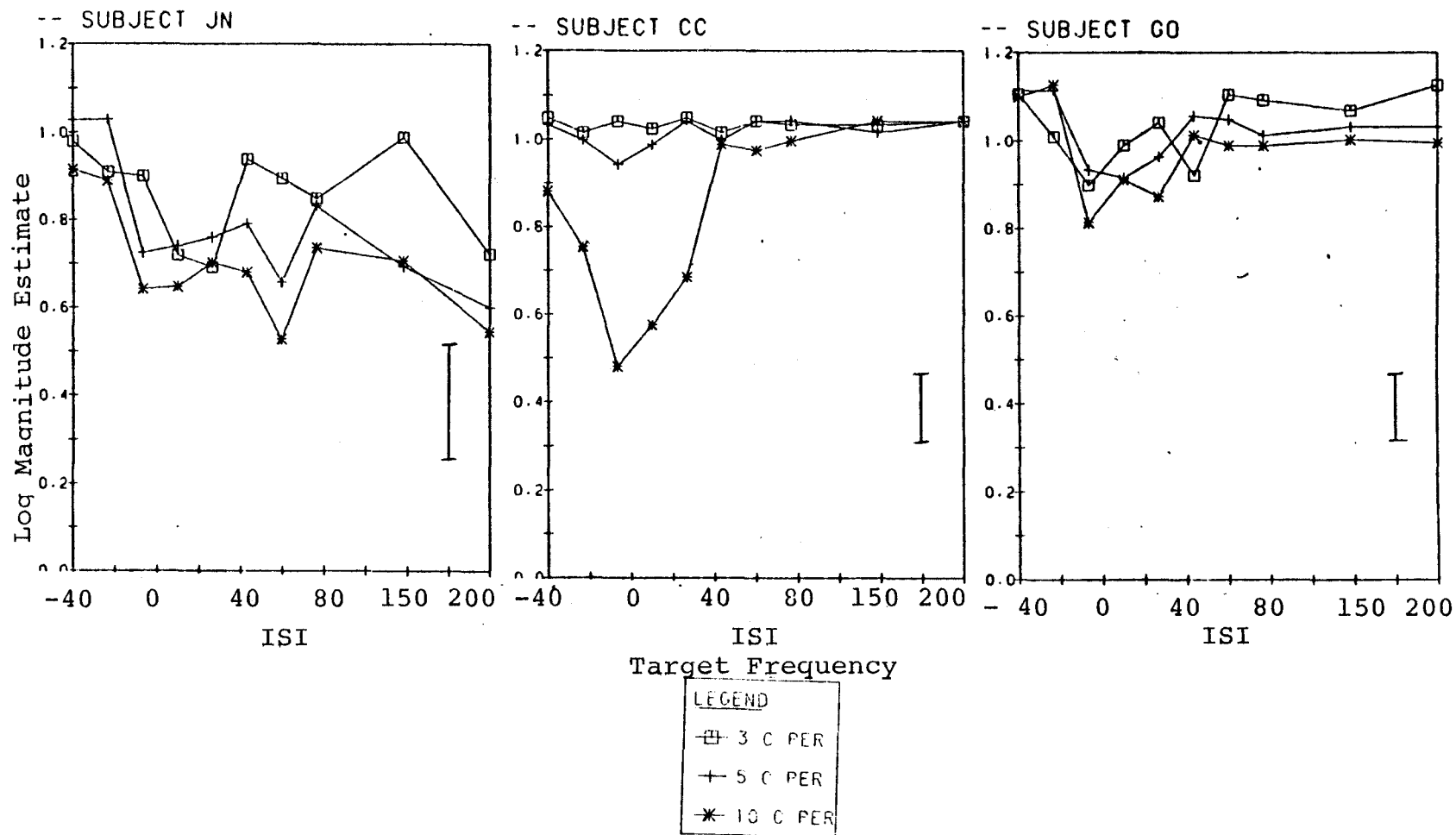


Figure 23. Log Magnitude Estimates of Grating Contrast for Grey Field Mask  
0° Phase Target

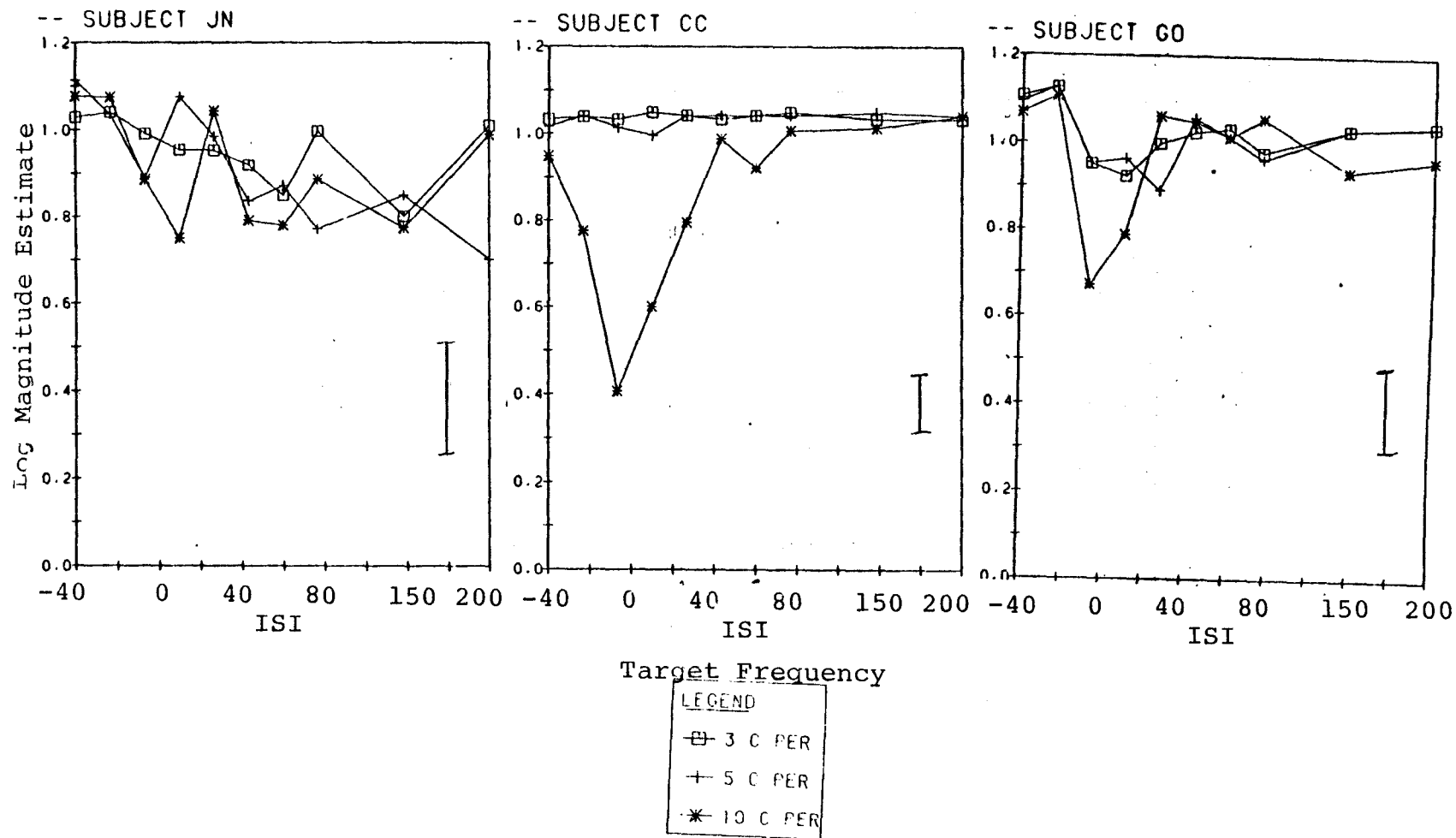


Figure 24. Log Magnitude Estimates of Grating Contrast for Grey Field Mask and 45° Phase Targets

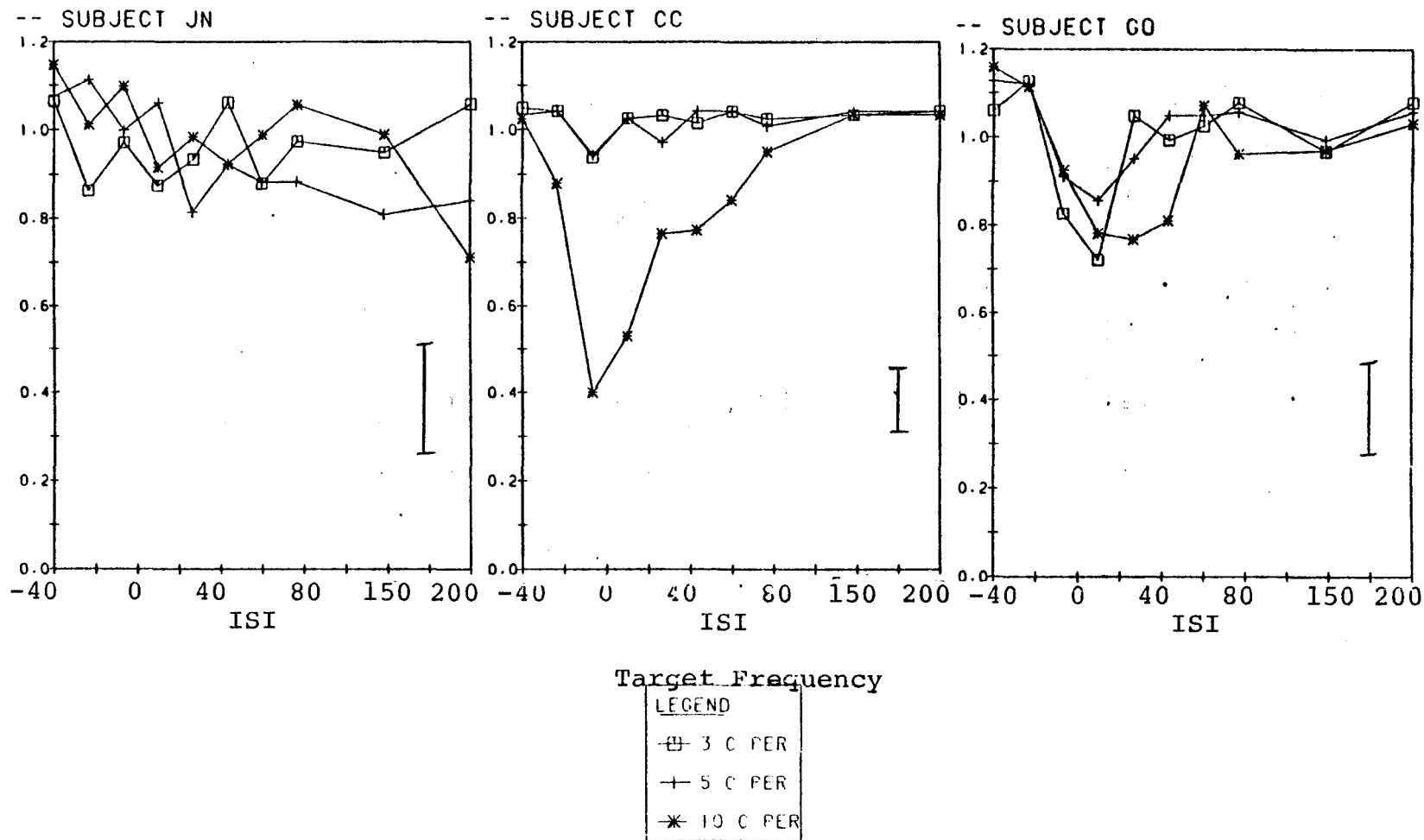


Figure 25. Log Magnitude Estimates of Grating Contrast for Grey Field Mask and 90° Targets, Experiment 6.

0 ISI with a few exceptions (Subject GO, 3 cycle 90 degree phase target and 0 degree phase mask in Figure 18; Subject CC, 5 cycle 90 degree phase target and 90 degree phase mask in Figure 21). Thus, the phase variations in the targets and masks did not result in temporal shifts in the masking curves as was found in Experiment 5.

### Summary of Backward Masking Studies

Neither of the two backward masking experiments resulted in shifts in the ISI at which peak masking occurs. Thus, the general hypotheses concerning maximum masking shifts as a function of phase in the stimuli were not supported. Typical masking curves were obtained with maximum masking occurring at 0 ISI. Such curves have been termed "Type A" masking functions and are thought to be the result of some type of integration of sensory formation (Erikson, 1966). Breitmeyer and Ganz (1976), in considering the possible implications of the existence of sustained and transient channels in human vision, have theorized that Type A masking curves result from the integration of sustained channel information without including transient channel information.

One potential confound in the backward masking studies is that both target and mask were present in an abrupt "on-off" manner. If sustained and transient channels do exist in human vision (Breitmeyer, 1975; Legge, 1978) with



properties similar to sustained and transient cells found in cat (Enroth-Cugell and Robson, 1966), it is possible that such abrupt stimulus onset and offset excites the transient channels. Some researchers have used a temporal Gaussian envelope in presenting stimuli in order to minimize transient affects (e.g., Wilson and Berger, 1979; Graham, et. al., 1978). It is possible that, in the backward masking studies here, the method of mask and target presentation resulted in the excitation of transient channels which, in turn, are thought to inhibit sustained channels (Legge, 1978). If this were true, then any phase effects in terms of the time at which maximum masking would take place would have been obscured through the simultaneous temporal differences due to phase (if any) and those due to transient stimulation.

The notion of sustained and transient channels were not incorporated in the original model shown in Figure 1. It is apparent that this distinction may be an important point for elaboration in the original model. Since the transient method of presentation may have also affected the outcome of the adaptation studies, this point will be discussed at greater length in the next chapter which summarizes all of the studies conducted.

## GENERAL SUMMARY AND DISCUSSION

This summary and discussion chapter will focus first on potential sources of artifactual variation in the data. It will then attempt to integrate the findings of the previous experiments and discuss their implications for Fourier models of pattern processing.

### Contrast Artifacts

As noted earlier, the gratings varied in contrast along with phase. From the standpoint of Fourier theory, the peak-to-trough distance (i.e., the difference between local luminance maxima and minima) is not the critical variable so much as the relative amplitudes of the individual sinusoidal components. From the standpoint of local, space domain models, the bar width or peak-to-trough distance is the critical variable, and any differential adaptation or masking due to phase may be explained by the variations in the relative contrast of the gratings. In the methodology chapter, it was noted that the grating with the greatest contrast was the 45 degree phase gratings followed in decreasing order by the 90 degree phase, the 135 degree phase, the 0 degree phase, and finally, by the simple one component gratings. Thus, if the adaptation for the target gratings followed this order, the results would be attributable solely to contrast differences. An examination of

Figure 4, giving the results of Experiment 1, shows that this is clearly not what was obtained. The greatest adaptation was obtained with the 0 degree phase target and mask combination. Furthermore, the mask showing the greatest overall adaptation was the simple 5 cycle grating, the one with the lowest overall contrast. An inspection of the results of Cannon (1979), who used a magnitude estimation procedure in assessing contrast sensitivity, shows that the difference in estimations for the small range of contrasts used in these experiments would be greater than .05 or .1 log unit. If this indirect estimate of contrast effects is accurate, then the variation in adaptation due to contrast would not be very substantial.

Methodologically, a more rigorous test of the effects of contrast would have involved the normalizing of the gratings to the same physical contrast levels, although such a procedure would change the relative amplitudes of the components in the Fourier domain. Interestingly enough, the studies cited in the literature review that dealt with phase specific effects did not equate the stimuli for contrast.

#### Inhomogeneity of the retina

The point has been made (Wilson and Giese, 1977;

Koenderink, van de Grind, and Bouman, 1971) that the inhomogeneity of the retina results in variations in spatial frequency sensitivity as a function of retinal eccentricity. This point is certainly valid for stimuli at threshold, but remains unclear for suprathreshold stimuli. Differential frequency sensitivity can be effectively discounted in these studies for a number of reasons. First of all, the target gratings were invariably seen as uniform except in Experiment 4. Inhomogeneity effects would ostensibly show up as non-uniform contrast variations at the edges of the target gratings. Furthermore, the  $\sin^2$  mask that was used varied in frequency, with the largest frequencies on the subject's left and the smallest frequencies on the subject's right. If retinal inhomogeneity were a problem, the use of such a mask would have resulted in non-uniform adaptation and masking. But in Experiment 4, where non-uniformity was explicitly manipulated, subjects reported seeing the target gratings as uniform. This is in agreement with the findings of Weisstein, et. al., (1977) who found uniform adaptation effects throughout the 8 degrees lateral extent of the viewing field. In a more general sense, Davidson (1965) has shown that inhomogeneity does not present analytical problems for Fourier approaches to pattern processing.

### Grating apertures

As was noted in the discussion of Experiment 3, the target gratings in the experiments involving the frequency gradient masks were mounted such that the spatial extent of the target gratings were less than that of the mask gratings. This was true in Experiments 3 and 6. The potential artifact that the aperture could introduce is the addition of high frequency components in the Fourier spectra of the target gratings. (Technically, apertures result in the convolution of a  $(\sin x)/x$  function spectrum with the spectrum of the grating itself.) This may have resulted in some attenuation of effects for the higher frequency gratings. This is not likely because all gratings had at least 18 cycles of that grating for that frequency. This is well within the number of cycles required in order to represent the grating within the visual system (Hoekstra, et. al., 1974).

### Subjective Scaling and Magnitude Effects

The possibility was raised in the introductory chapter that perhaps the subjects did not actually use a ratio scale in giving their magnitude estimations. If this is true, interpretation of the results, especially in Experiments 1 and 4, has some constraints. In this section the potential impact of other possible scales will be considered.

The first possibility is that the subjects used an ordinal rating scale in judging the apparent contrast of the target gratings. While no direct measurement of physical contrast and subject contrast was possible, some inferences can be made from the distributions of the subjects ratings. If the ratings were ordinal, then the ratings represent the rank of perceived contrast (i.e., the targets contrast is "less than" or "greater than" the standard) rather than the amount of contrast reduction. In order to examine the impact of an ordinal scale the ratings in Experiment 1 were transformed into rank scores within each replication. Such a transformation perceives the order of effects. Depending on the actual numbers used, it may eliminate the experimental differences obtained because it eliminates outliers. Since any one replication had a total of 12 conditions (3 masks x 4 targets), the ranks could range from 1 through 12. The mean rank was then calculated for each of the 12 experimental conditions. Table 4 shows the results for Subject JN (the other subjects showed similar results). A comparison of the mean ranks in Table 4 with data for subject JN in Figure 4 will show that the main findings for that experiment are essentially unchanged. This does not show that the subjects did not resort to an ordinal scale in making their ratings; it only supports the premise

TABLE 4

Mean Ranks for the Experimental Conditions in  
Experiment 1, Subject JN

<u>Targets</u>	<u>Simple 5 cycle</u>	<u>5 + 15 Phase</u>	<u>Grey Field</u>
0° Phase	3.35 (.21)	1.6 (.06)	8.6 (.08)
45° Phase	5.4 (.23)	4.7 (.19)	11.1 (.07)
90° Phase	5.05 (.23)	5.2 (.21)	10.6 (.73)
135° Phase	5.95 (.21)	5.2 (.21)	11.2 (.94)

Standard Errors are in parentheses.

that the results and their interpretation are not fundamentally differed in such circumstances.

Another possibility is that the subjects used an interval scale in judging their contrast. This would make use of the log transformations inappropriate. In order to ascertain the impact of this on the statistical analysis of variance computations were redone using the raw data rather than the log transformed data. Except for a few isolated instances, the results, in terms of significant main effects and interactions, were replicated with the raw data.

Finally, the main findings that will be discussed below, those from Experiment 1 and 4, do not depend on absolute magnitude of effect for their interpretation. The ordinal nature of the effect is, of course, critical. There is support in the studies of Cannon (1979) and Hamerly, et. al. (1977), that log magnitude estimations do follow a linear function of contrast. Kulikowski (1976) has found evidence for linearity of supracontrast sensation using indirect psychophysical methods. With the possible constraints of problems with magnitude estimations in mind, the following discussion will be presented with the assumption that ratio scales were employed by the subjects.

Inspection of Figures 4 and 13 indicates that the magnitude of the adaptation effect is on the order of



pattern masking with maximum masking occurring at 0 ISI did not find minima shifts as a function of phase. The effect of contrast (Experiment 2) seems to be that of obscuring the very specific adaptation found in Experiment 1. Experiment 3, which varied frequency and phase, found no consistent adaptation due to phase and some effects due to frequency (the adaptation tended to be greater for the higher frequencies for all the subjects). Experiment 4 clearly showed a frequency selective effect. The next section discusses these results and their implications for Fourier models of pattern processing.

### Interpretation and Implication of Results

In order to fully and uniquely describe a pattern with Fourier techniques, the magnitude and the phase of the spectral components of that pattern must be known. For the visual system to exhibit Fourier processing properties, it must be sensitive to the magnitude and the phase of the spectral components of the visual input. There has been an overwhelming literature developed during the past ten years supporting the hypothesis that the visual system responds selectively to the frequency components themselves. Current prevailing models, for example, typically specify a number of frequency channels in the visual system, each responding to a relatively narrow band of frequencies. Under only one condition was a phase effect obtained: when the mask and

the target were identical. Of course, this can be predicted by a number of various models, none of which require assumptions of a Fourier process. A natural question, then, concerns whether the adaptation paradigm as employed here was sensitive enough to obtain any frequency or phase effects.

The data from Experiment 4 (Figure 13) support a frequency hypothesis. In this experiment a 5 cycle per degree sine wave was added to a  $\sin x^2$  grating in constructing the mask. The resulting pattern was not similar to a simple 5 cycle per degree grating and yet was masked more than any other test grating. The width of the individual bars varied across the lateral extent of the grating and the local contrast varied in a random fashion. Thus the results cannot be explained by postulating size or bar width detecting units. The results cannot be attributable to differences in contrast among the test gratings (the composite gratings have more contrast than the single component gratings) because the simple 15 cycle grating was masked less than the 5 cycle even though it had the same contrast. These results indicate that the adaptation paradigm as used here is sensitive enough to obtain frequency effects.

Another question which arises in the context of Experiment 4 is as follows: if frequency effects are obtainable, why were not all of the test gratings masked since the two

grating masks are broad band stimuli with an infinite number of components. A preliminary answer can be obtained from inspection of Figures 26 and 27 which give the amplitude spectrum and the magnitude spectrum of the  $\sin x^2 + \sin 5x$  mask. The abscissa is the frequency and the ordinate is drawn in arbitrary units. It can be seen that the magnitude of the 5 cycle grating is about eight times that of a 5 cycle component in the  $\sin x^2$  grating alone. In previous studies using adaptation paradigms (see, for example, Weisstein and Bisaha, 1972; and Tangney, et. al., 1977) it is unclear whether it is the spectral overlap or the magnitude itself that is the critical variable. Weisstein and Bisaha found that a bar masked a square wave grating. For any one component of the grating, the energy of the bar is relatively low, yet masking was still obtained, although it was not as great as that for a grating masking a bar. In Figure 13 there was masking for all 4 test gratings; it was greater for the 5 cycle grating. The grey field resulted in either no masking or slight enhancement. It would seem that the masking shown in Figure 13 is consistent with the order of magnitudes in Figure 26. The 15 cycle grating is masked less well, but the magnitude at the 15 cycle component is much less in the  $\sin x^2$  mask. The composite (two component) test gratings are masked by about the same

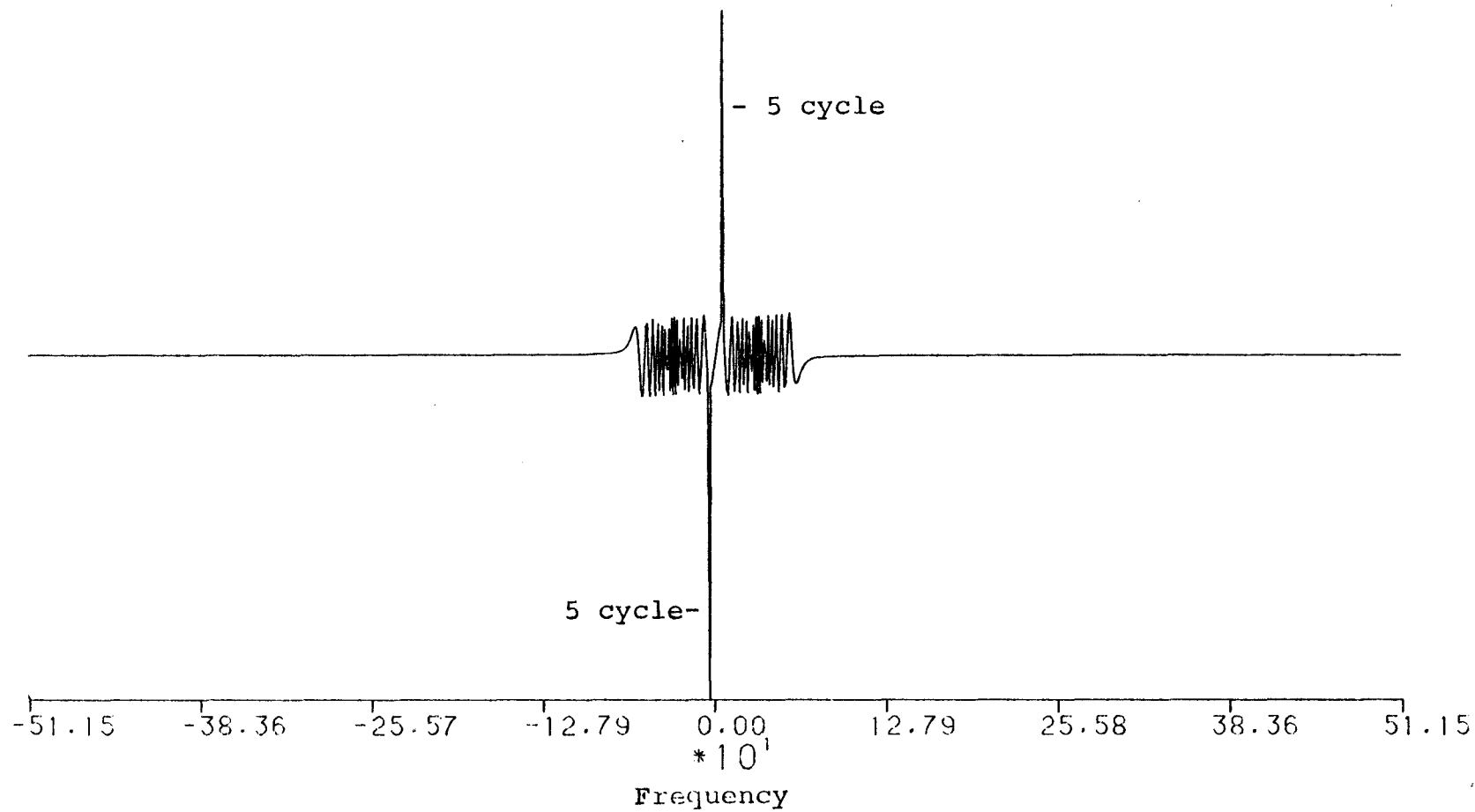


Figure 26. Amplitude Spectrum of  $\sin x^2 + \sin 5x$ ,  $0^\circ$  Phase Mask

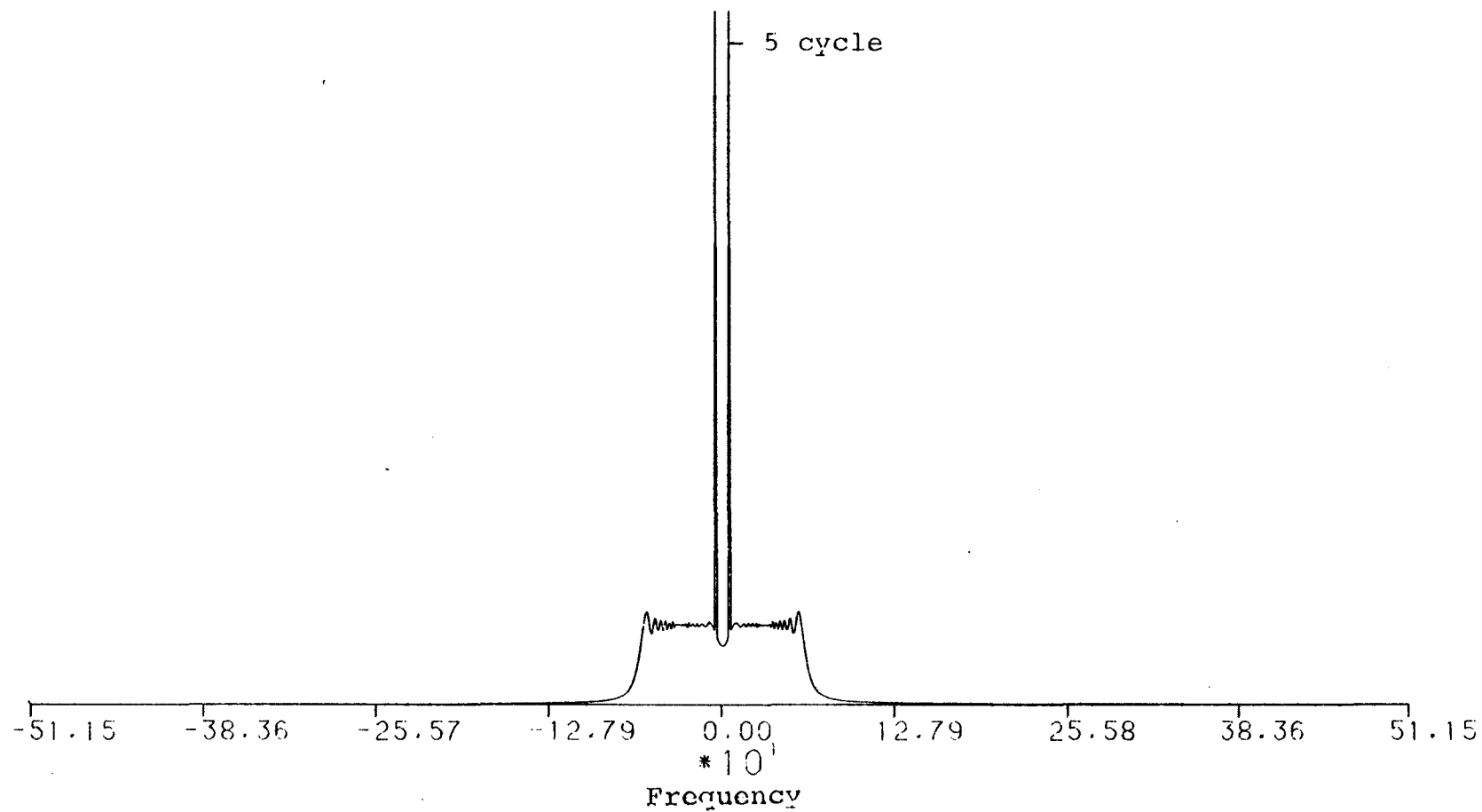


Figure 27. Magnitude Spectrum of  $\sin x^2 + \sin 5x$ ,  $0^\circ$  Phase Mask

amount as the 15 cycle, leading to the speculation that the 5 cycle component of the test grating is adapted out leaving the 15 cycle component to be slightly masked by the corresponding component in the mask.

If the adaptation paradigm is sensitive enough for frequency effects, can the results of Experiment 1 be interpreted as evidence for phase effects, or is it another example of pattern similarity at work? The most parsimonious explanation for Experiment 1 is that the observed effects are more in line with a local bar detecting or a space domain model than a frequency model. First of all, phase effects, if they exist, may be small relative to frequency effects because Experiment 4 found no effects due to phase. Secondly, the 5 cycle grating caused as much adaptation as the composite mask for the non-zero phase targets. If frequency effects were responsible, the 5 cycle mask should have caused less masking since it does not share the 15 cycle component in the targets. This was not obtained. Thirdly, a simple pattern matching or correlation can be ruled out because correlations computed between the waveforms of the two masks and the four targets do not fit the data at all (except for the target that is identical to the mask). Table 5 present these correlations. Fourthly, Experiment 3, which varied local bar width in the mask but kept phase constant, did not result in any

TABLE 5  
Correlations of the Two Mask Gratings  
with the Test Gratings

<u>Targets</u>	<u>Masks</u>	
	<u>Simple 5 cycle</u>	<u>5 + 15 cycle, 0°Phase</u>
0° Phase	.707	1.000
45° Phase	.500	.854
90° Phase	.000	.500
135° Phase	-.707	.000

effects due to phase.

One possible conclusion that can be drawn from the six studies together is that phase information is lost by the visual system. This would be equivalent to dropping the phase channels from the model in Figure 1. The fact that human observers can readily discriminate between supra-threshold gratings having different phases would argue against such a position. Another possible conclusion is that the model, as originally formulated in the introductory chapters, is inadequate either due to untenable assumptions or to assumptions that need to be made. To recapitulate, the main assumptions of the model were as follows:

- (1) There are multiple frequency channels, each sensitive to a narrow to medium band of frequencies.
- (2) There are multiple phase channels, each sensitive to a narrow band of spatial phases.
- (3) The frequency and phase channels are space invariant.
- (4) There is no inhibition between channels.
- (5) The frequency and the phase information is combined to determine the response to a particular frequency and phase.
- (6) Adaptation is the result of saturation or fatigue of a particular set of frequency and phase channels.

It is clear that some of these assumptions need to be recon-



sidered. The uniformity data generally support the space invariance assumption since most of the target gratings were adapted or masked uniformly across the visual field. The multiple frequency channel assumption has received an enormous amount of support in the literature and partially from the results of Experiment 4. Thus, both assumptions (1) and (3) can be retained without further modifications. For the time being, the multiple phase channels assumptions can also be retained. The remaining assumptions need to be replaced or elaborated.

A logical alternative to the assumption of no inter-channel inhibition is one suggested by the research on sustained and transient properties in human vision. From neurophysiology (Victor, Shapley, and Knight, 1977) and human psychophysics (Breitmeyer, 1975; Legge, 1978), it is suggested that frequency channels can be classified as transient or sustained. Transient channels are sensitive to lower spatial frequencies and react to stimulus onsets and offsets, but not to steady presentation. Sustained channels are sensitive to higher spatial frequencies, are linear in their response, and respond optimally to steady-state stimulus presentation. It is thought that transient channels inhibit sustained channels (Breitmeyer, 1975), although there is some evidence for sustained channels inhibiting transient channels under certain conditions (Breitmeyer, 1978).

Another complementary assumption is that adaptation may be the result of prolonged inhibition, as discussed by Dealy and Tolhurst (1974) who found that adaptation to a 4 cycle per degree sine wave grating increased the threshold of a subsequently presented 6.7 cycle per degree grating by as much as 100 per cent.

Given this new set of assumptions, how may the adaptation results be interpreted? Consider the results of Experiment 1 which found that a simple 5 cycle grating was as powerful adapting stimulus as a composite 5 + 15 cycle grating. These results could be reinterpreted in terms of the simple 5 cycle grating inhibiting the 15 cycle channel as well as adapting the 5 cycle per degree channel. In this case, both masks (the simple and the composite gratings) would result in the same amount of adaptation. Alternatively, it is possible that the offset of the simple 5 cycle component in either mask could be exciting a transient channel that, in turn, would inhibit the response of the sustained channel that would be more sensitive to the 15 cycle component in the test gratings.

The inhibitory relationships between sustained and transient channels that are assumed to exist could also explain some of the failure in obtaining the masking functions that were predicted. The fact that both the masks and the targets were presented in a way that optimally stimulates transient channels leads to the speculation that any

temporal changes stemming from the phase of the stimuli could have been obscured by the undesired activity of the transient (low-frequency) channels.

That remaining assumption in the model, namely that frequency and phase information is combined to affect the apparent contrast of a grating appears to be untenable since no differential adaptation due to phase was obtained under a wide variety of conditions. If, however, it is assumed that the phase information is extracted the grating patterns and processed differently from frequency information, then the appropriateness of the subjects task (rating apparent contrast) becomes questionable. In terms of the model depicted in Figure 1, this assumption would be equivalent to drawing the lines from the phase channel to a separate stage to bypass the combined responses stage. Thus, a task that more directly taps the phase information available would be more appropriate to obtaining psychophysical phase effects. In the experiments reported here, the phase information present in the masks and the targets may have affected the perceived stimulus, but not in a way that affected the apparent contrast of the target gratings.

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