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SPATIAL FREQUENCY UNCERTAINTY EFFECTS IN THE DETECTION OF SINUSOIDAL GRATINGS

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Abstract—A sinusoidal grating is less detectable when it is randomly intermixed in a block of trials with gratings of other spatial frequencies than when it is the only grating presented in a block of trials. This spatial-frequency uncertainty effect is expected if observers have attentional control over multiple spatial-frequency channels. When intermixed blocks contain a preponderance of one spatial frequency, the *primary*, the uncertainty effect is smaller for frequencies near the primary than for frequencies further away. Both the tuning of the uncertainty effect and the analysis of sequential conditional probabilities suggest that observers can employ different attention strategies.

INTRODUCTION

According to prevalent theories of information processing in the human visual system, the spatial frequencies composing a particular stimulus are detected and transmitted by multiple channels; each channel is maximally sensitive to a different spatial frequency and responds only to a restricted range of frequencies (Graham, 1980a, b, reviews the psychophysical evidence for spatial-frequency channels). If multiple spatial-frequency channels exist and if an observer has attentional control over these channels, one might expect to find an uncertainty effect; that is, a sinusoidal grating would be less detectable when an observer is uncertain about his spatial frequency than when he is certain about it. Such spatial-frequency uncertainty effects have been reported (Graham *et al.*, 1978; Martens and Blake, 1980; Sekuler and Tynan, 1978).

Attention strategies, as we are using the term, describe how the observer selectively monitors (not necessarily consciously) the outputs of different sensory channels. Three different attention strategies which might produce an uncertainty effect are investigated here. These strategies are analogous to the auditory psychophysical models (Green and Swets, 1966). Two are *single-band* and the third is a *multiple-band* attention strategy.

The technique used here is similar to the probe technique used in auditory psychophysics (Greenberg and Larkin, 1968; MacMillan and Schwartz, 1975). The detectability of a sinusoidal grating when it was the only stimulus presented on each trial (and thus, the observer was certain about the spatial frequency) was compared to its detectability when one of several sinusoidal gratings was randomly presented on each trial (and thus, the observer was uncertain about the spatial frequency). In each intermixed block of trials, one spatial frequency was called the primary frequency and was usually presented on a majority of the trials; a number of secondary frequencies of other spatial frequencies were randomly presented on the remaining trials. In order to investigate the spatial-frequency tuning of the uncertainty effect, the primary spatial frequency was varied as well as the proportion of trials on which it was presented. We also examined the trial-to-trial sequential conditional probabilities to determine whether attentional control over multiple spatial-frequency channels was an adequate explanation of the results and, if it was, to determine which attention strategy was used in each condition.

METHODS

Stimuli

The stimuli were vertically oriented sinusoidal gratings. The primary spatial frequency was 1.5, 4.0 or 10.0 c/deg. Six secondary spatial frequencies, equally spaced on a logarithmic frequency scale, were ordinarily used, three higher and three lower than the primary frequency. The secondary spatial frequencies were the following: 0.375, 0.60, 1.0, 2.5, 4.0 and 6.0 c/deg for the 1.5 c/deg primary; 1.0, 1.5, 2.5, 6.5, 10.0 and 16.0 c/deg for the 4.0 c/deg primary; and 2.5, 4.0, 6.5, 14.0, 20.0 and 26.0 c/deg for the 10.0 c/deg primary.

Details of the stimuli. The vertically-oriented sinusoidal gratings were produced on the face of a Tektronix 5103N oscilloscope by a conventional Z-axis modulation technique (Campbell and Green, 1965). The P31 phosphor produces a desaturated green hue. A 31.75 cm diameter annular surround of approximately the same hue framed the scope. Both had a mean luminance of 1.9 ft-L. All contrasts used in these experiments were within the linear range of equipment operation.

The viewing distance was usually 145 cm (at which distance the stimulus subtended 4° vertically and 5.25° horizontally) but was 72.5 cm for a primary

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stimulus of 1.5 c/deg in order to ensure that at least three cycles of any stimulus were presented.

Each stimulus was presented for 100 msec with abrupt onsets and offsets. When no stimulus was present, the screen was a blank field at the same mean luminance.

Experimental conditions

There were five experimental conditions. In one condition the primary spatial frequency was 4.0 c/deg and the proportion of trials on which it was presented was 80%. In the other four conditions, the primary frequency and the proportions were the following: 1.5 c/deg and 80%; 10.0 c/deg and 80%; 4.0 c/deg and 95%; 4.0 c/deg and 14.3%. This last condition, where the proportion was 14.3%, was also called the uniform condition since each of the seven stimuli (one primary and six secondaries) was presented equally often.

In each experimental condition there were both *intermixed* and *alone* sessions. In an intermixed session the primary stimulus and secondary stimuli were randomly presented on the prescribed proportions of trials; all secondary stimuli were presented equally often within a block. In any block of trials in an alone session, however, gratings of only one spatial frequency were presented. In each alone session, there was one block of trials for each spatial frequency used. Intermixed and alone sessions were conducted on separate days.

To produce enough trials to yield a reliable sensitivity measure at each secondary stimulus in the 95% condition, only three secondary spatial frequencies were used. The three were lower than the primary frequency for one observer and higher than the primary frequency for another observer.

In all experimental conditions tested, a two-interval, forced choice procedure without feedback was used—the observer had to report which of the two temporal intervals contained the grating. The two 100 msec intervals were marked by tones and separated by approximately 200 msec. The observer initiated the beginning of each trial so the intertrial interval was variable, being approximately 2 sec. On the basis of previous testing, the contrasts of different frequencies had been adjusted so that the percentage of correct detection in alone blocks would not be too close to 50% or to 100%.

Details of intermixed sessions. At the beginning of each intermixed session there was one practice block. (The practice block contained five high contrast samples of the primary stimulus followed by twenty-five practice trials of the primary stimulus with feedback, which encouraged the observer to attend to the primary spatial frequency.) Following the practice block there were three experimental blocks Each experimental block began with five high contrast samples of the primary stimulus and ten practice trials (without feedback) of the primary stimulus. The main part of each experimental block consisted of 300 experimental trials except in the uniform condition when it consisted of 280.

Details of alone sessions. In an alone session, each block began with five high contrast samples of the tested stimulus followed by twenty practice trials with feedback. The main part of each block was 120 experimental trials. The order of the spatial frequency blocks within an alone session was counterbalanced across sessions.

Instructions to the observers. To encourage observers to attend to the appropriate spatial frequency and to be as accurate as possible, they were told at the beginning of each session: "I want you to attend very carefully to the spatial frequency of the high contrast samples at the beginning of each block. You can pause between trials as long as you wish . . . I want you to be as accurate as you can in detecting each stimulus."

Observers

Observer E.D., the first author, participated in all the experimental conditions tested. The other two observers, T.S. and R.D., were initially naive and participated in selected conditions. The observers had normal vision after correction for myopia.

SPATIAL FREQUENCY TUNING RESULTS

Difference curves

The upper portion of Fig. 1 shows an example of results from intermixed and alone sessions. (These results are from the 4.0 c/deg primary, 80% condition for observer T.S.) The spatial frequency of the stimulus is plotted along the horizontal axis. Percent correct is plotted on the right vertical axis, and the d' value derived from percent correct is plotted on the left vertical axis. (See Green and Swets, 1966, pp. 408–411 and also Elliott, Appendix I, in Swets, 1964, for details of the d' calculation.) The vertical bars represent plus and minus one standard error of the mean of the d' values.

The lower portion of Fig. 1 shows the *difference curve* derived from the results in the upper portion. The difference between the d' values from the alone and intermixed sessions ($\Delta d' = d'$ Alone $- d'$ Intermixed) is plotted. The largest differences, representing the biggest uncertainty effects, are plotted toward the bottom. The vertical bars represent ±1 SE. The standard error shown is the standard error of the difference between the mean of the d' values from the intermixed sessions and the mean of the d' values from the alone sessions.

The use of d' *as the response measure.* The response measure used is d' rather than percent correct because with d' the size of the uncertainty effect is much less dependent on the particular contrasts used. It is less dependent because percent correct saturates near 100% for high-contrast stimuli, but d' continues to grow.

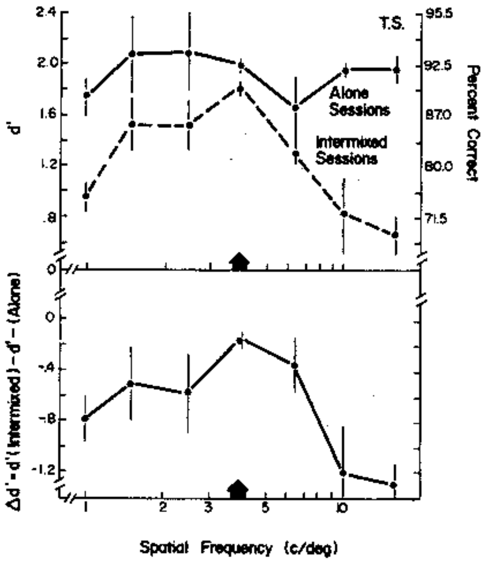

Fig. 1. *Upper portion*: Data obtained for observer T.S. in the 4.0 c/deg primary, 80% condition from intermixed sessions (dashed line) and alone sessions (solid line). The spatial frequency of the stimulus is plotted along the horizontal axis; an arrow marks the spatial frequency of the primary. Percent correct and d' values are plotted on the right and left vertical axes, respectively. *Lower portion*: The difference curve obtained from the results above shows the difference between the d' values for the alone and intermixed sessions as a function of spatial frequency.

The data were examined for any response interval bias. Observer T.S. showed no response interval bias; observers E.D. and R.D., however, did show a small bias in reporting the second interval more often than the first. Nevertheless, the response bias is ignored here since, when this bias was taken into account, the effect on the difference curves was negligible (Davis, 1979).

Effects of the primary spatial frequency

Figure 2 shows difference curves for the three primary spatial-frequencies, 1.5 c/deg (circles), 4.0 c/deg (triangles) and 10.0 c/deg (squares). The primary was presented on 80% of the intermixed trials. The upper and lower portions show observer E.D.'s and observer R.D.'s data, respectively. The arrows on the horizontal axes mark the primary frequencies.

The shapes of the difference curves are somewhat irregular due to variability in the data. In general, however, the range of frequencies for which the uncertainty effect is least (the highest points in the figure) does shift to higher spatial frequencies as the primary frequency is increased and tends to surround the primary frequency.

Effects of the proportion of primary stimulus trials

Figure 3 shows the difference curves obtained for various proportions of primary stimulus trials, 95% (circles), 80% (squares), and the uniform condition (triangles). The primary frequency was 4.0 c/deg. Ob-

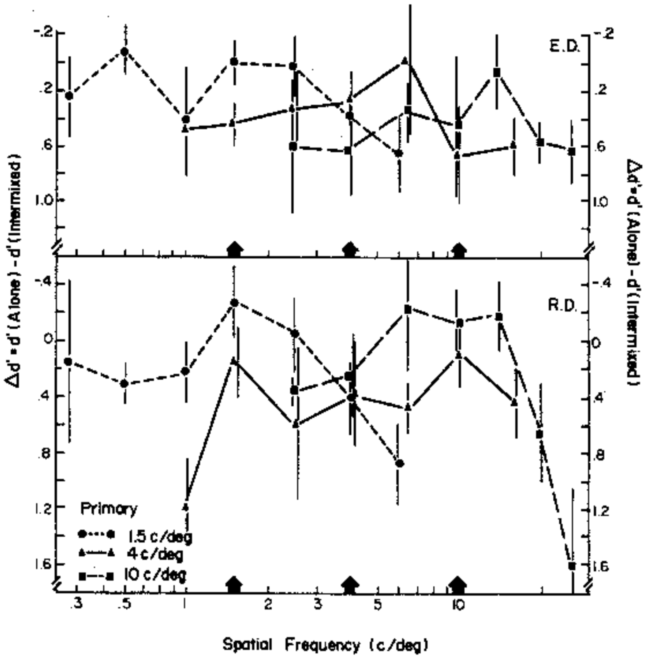

Fig. 2. Difference curves for the 1.5 c/deg primary (circles), the 4.0 c/deg primary (triangles), and the 10.0 c/deg primary (squares) for observers E.D. (upper portion) and R.D. (lower portion) in the 80% condition. Arrows along the horizontal axis indicate the spatial frequencies of the primaries.

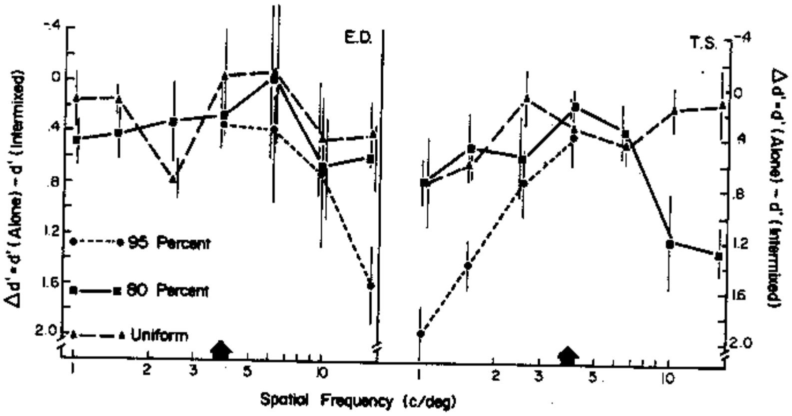

Fig. 3. Difference curves for the 95% condition (circles), 80% condition (squares), and the uniform condition (triangles) for observers E.D. (left portion) and T.S. (right portion) with a 4.0 c/deg primary.

server E.D.'s and observer T.S.'s results are plotted in the left and right portions of the figure, respectively.

There were two effects of increasing the proportion of primary trials in intermixed sessions. First, tuning in the uncertainty effect became sharper and more centered at the primary spatial frequency. Second, the magnitude of the uncertainty effect increased, especially for secondary spatial frequencies very different from the primary.

DISCUSSION OF TUNING CURVES RESULTS

Two very different interpretations of the uncertainty effects are considered here. An interpretation based on errors in accommodation of the lens is unlikely and cannot explain all of the results obtained. The other possible interpretation is based on attentional control of spatial-frequency channels and can explain all of the results obtained.

An interpretation in terms of accommodation

Could systematic errors in accommodation possibly explain the uncertainty effects? An error in accommodation could reduce the contrast in the retinal image of a sinusoidal grating and therefore reduce the observer's sensitivity to that grating. Suppose that for each secondary stimulus the error in accommodation was *less* in an alone block than in an intermixed block. Suppose, however, that for the primary stimulus the error in accommodation was the *same* in the alone and intermixed blocks because the observer always accommodated to the primary stimulus. Secondary stimuli would then be less detectable in intermixed blocks than in alone blocks. The primary stimulus, however, would be just as detectable in intermixed blocks as in alone blocks. The uncertainty effect would, therefore, be tuned to the primary frequency as it tends to be in the results.

At first glance, such an interpretation based upon errors in accommodation appears plausible. Green and Campbell (1965) as well as Charman and Tucker (1977), for instance, have found that sinusoidal gratings viewed monocularly from a fixed distance without fixation targets elicited accommodation that was not constant; instead, accommodation varied as a function of spatial frequency. There are several difficulties, however, that an accommodation interpretation encounters in explaining the results obtained in these experiments.

There are cues for accommodation available in the present experiments which can reduce or eliminate errors in accommodation. First, convergence of the two eyes resulting from binocular viewing can serve as a cue to accommodation (Duke-Elder, 1963). Second, the edges between the aperture of the annular surround and the face of the display oscilloscope can stabilize the observer's accommodation.

Even if there were errors in accommodation, they probably could not account for uncertainty effects obtained at low spatial frequencies. Green and Campbell (1965) found, for example, that the observer's sensitivity for a 1.5 c/deg grating was not decreased when the retinal image of the grating was defocused over a range of two diopters. Therefore, uncertainty effects obtained in the present experiments at low spatial frequencies, especially in the 95% condition, cannot be explained by errors in accommodation.

Interpretation in terms of spatial-frequency channels

Models that assume both the existence of multiple channels and attentional control over these channels can explain the experimental results. We will first make explicit the assumptions about the channels themselves and then the assumptions about three possible attention strategies.

Assumptions about the multiple channels

(1) There is no one spatial-frequency channel sensitive to the full range of visible spatial frequencies.

Rather, there are many channels; each channel is maximally sensitive to a different spatial frequency; the response of a channel is a monotonically increasing function of contrast; and the noise (i.e. variability) in different channels is uncorrelated.

(2) In a two-interval forced-choice experiment, each channel responds twice on every trial, once in each interval. The observer reports the interval which produces the largest response in any one of the monitored channels.

There are other possible assumptions about how the observer selects which interval contained the stimulus that would also predict an uncertainty effect. For instance, the observer could somehow combine the outputs of all the monitored channels in each interval and select the interval containing the largest combined response. The differences in predictions between these various assumptions is small (viz, Creelman, 1960), however, and the variability in the data is probably too large to choose among them.

Assumptions about attention strategies

The two single-band attention strategies assume that on each trial the observer only attends to the channel, or small subset of contiguous channels, most sensitive to the spatial frequency of the stimulus presented on a majority of the trials or which the observer expects to be presented. This channel or small subset of contiguous channels will be referred to as a single band.

Specific assumptions about the two single-band strategies are the following:

(3) According to the *stationary single-band* attention strategy, the observer monitors the same single band of channels on all trials.

(4) According to the *switching single-band* attention strategy, the observer switches his attention from one single band to another. Switching is assumed to occur rather slowly—requiring longer, on the average, than the duration of a single trial to change the location and/or size of the monitored single band. (One rule that might govern whether the band is switched from one trial to the next is, "If you have a winning bet, stay with it; if not, switch." For our purposes, the only assumption is that the switching is slow).

The multiple-band attention strategy is an attention-sharing strategy in which all relevant channels are simultaneously monitored. The specific assumption follows:

(5) According to a *multiple-band* attention strategy, in an alone block of trials the observer monitors the channel most sensitive to the spatial frequency of the one stimulus presented. In an intermixed block of trials, however, the observer simultaneously monitors every channel that is sensitive to any frequency within the entire range of spatial frequencies presented. He monitors all these channels on every trial.

The multiple-band attention strategy could be considered a switching single-band attention strategy in which the switching is extremely fast (contrary to our above assumption of slow switching) and all channels are monitored equally often within a trial.

Predictions. When the observer attends only to a single band of spatial frequencies on any trial, in an intermixed block he will sometimes be attending to the "wrong" single band (i.e. one insensitive to the stimulus) because a number of different spatial frequencies are presented. In an alone block, however, the observer can attend to the correct single band on all trials. Therefore, some stimuli will be less detectable in intermixed than in alone blocks. That is, there will be an uncertainty effect for some stimuli. This is true whether the observer uses a stationary or switching single-band attention strategy.

Whether or not the uncertainty effect is tuned, however, may depend on whether the single band is stationary or switching. If it is stationary, centered at the primary frequency, then the uncertainty effect will be tuned. In particular, it will be smallest at the primary frequency and greatest for the spatial frequencies furthest away from the primary. If the single band is a switching single band, however, there may or may not be tuning depending on what proportion of trials the observer attends to each band of frequencies.

According to the multiple-band attention strategy, more channels are monitored in an intermixed than in an alone block of trials. The more channels that are being monitored, the more likely it is that the largest response will be produced by noise in a channel insensitive to the stimulus and, thus, since the observer's report is based on the largest response (by assumption 2), the worse the observer's performance. In short, performance will be worse in intermixed than in alone blocks. Further, since all relevant channels are assumed to be monitored equally well during intermixed blocks, there should be no tuning of the uncertainty effect.

Comparison of tuning results with the attention strategies

When the primary stimulus is presented on a majority of the intermixed trials (80 and 95% intermixed conditions), tuning is found for the uncertainty effect. The switching and stationary single-band attention strategies can predict the tuning in the uncertainty effect, but the multiple-band attention strategy cannot. When each stimulus is presented with equal probability in an intermixed block of trials (uniform condition), there is little or no tuning in the uncertainty effect. Either the multiple-band or the switching single-band attention strategy could explain these data; the stationary single-band attention strategy cannot. In order to distinguish more finely among these three attention strategies, we will examine trial-by-trial sequential conditional probabilities.

SEQUENTIAL CONDITIONAL PROBABILITIES

Sequential conditional probabilities were analyzed for two experimental conditions which would represent the two most different attention strategies used: (1) the 4.0 c/deg primary, uniform condition and (2) the 4.0 c/deg primary, 95% condition.

Definitions of sequential conditional probabilities

Three kinds of conditional probabilities were computed because they are useful in distinguishing among the attention strategies.

Same-correct probability. The probability of correctly reporting the interval of a particular stimulus on the present trial given that the interval of the same stimulus had been correctly reported on the previous trial will be named the *same–correct* probability.

Different–correct probability. The probability of correctly reporting the interval of a particular stimulus on the present trial given that the interval of a *different* stimulus had been correctly reported on the previous trial will be named the *different–correct* probability.

Same-error probability. The probability of correctly reporting the interval of a particular stimulus on the present trial given that the interval of the same stimulus had been incorrectly reported on the previous trial will be named the *same-error* probability.

Results

Figures 4 and 5 show the sequential conditional probabilities for the uniform and 95% conditions, respectively. On the vertical axis is plotted the conditional probability of being correct. The *same–correct* probability is shown by a square, as well as the extended dashed line. The dashed line is there to facilitate comparison with the *different–correct* probabilities, which are shown by circles. The *same–error* probability is shown by a triangle. On the horizontal axis is plotted the difference between the logarithm of the spatial frequency on the present trial and the logarithm of the spatial frequency on the previous trial. The results for two observers are presented; the upper and lower panels show observer E.D.'s and T.S.'s results, respectively. Vertical bars drawn through the symbols represent plus and minus one standard error. If no bar is shown, the standard error is the same as the symbol size or smaller. The standard errors shown are conventional standard errors for proportions.

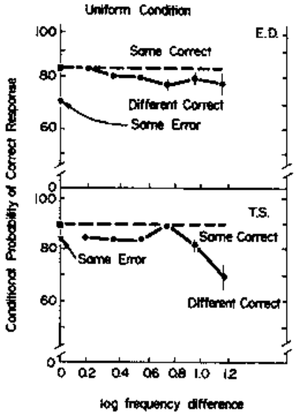

Fig. 4. Three kinds of conditional probabilities of being correct—same-correct (square), different-correct (circles) and same-error (triangle)—for observers E.D. (upper portion) and T.S. (lower portion) for the uniform, 4.0 c/deg condition. On the horizontal axis is plotted the difference between the logarithm of the spatial frequency on the present trial and the logarithm of the spatial frequency on the previous trial.

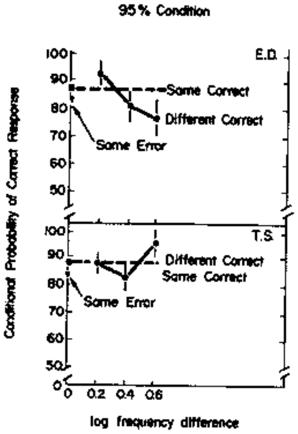

Fig. 5. Conditional probabilities for the 95%, 4.0 c/deg condition. Symbols as in Fig. 4.

In the uniform condition shown in Fig. 4, there is evidence of sequential conditional probabilities. The *same–correct* probability is larger than the *same–error* probability for both observers, but especially for observer E.D. The *different–correct* probabilities for both observers are less than the *same–correct* probability for large log frequency differences, but especially for observer T.S.

In the 95% condition shown in Fig. 5, the differences between the three kinds of conditional probabilities are not as large and the pattern of differences is not as systematic as in the uniform condition.

Interpretations in terms of attention strategies

Both the stationary single-band and the multiple-band attention strategies predict that the probability of being correct does *not* depend upon what happened on the previous trial. This is because the set of monitored channels does not change from one trial to another.

The switching single-band attention strategy, however, predicts that the probability of being correct *does* depend upon what happened on the previous trial. This is because the set of monitored channels does change. Since the switching is assumed to be slow, the *same–correct* probability is predicted to be greater than the *same–error* probability and also greater than the *different-correct* probabilities for relatively large spatial frequency differences (Davis, 1979).

In the uniform condition the lack of tuning of the uncertainty effect (see Fig. 3) could be explained by a switching single-band or by a multiple-band (but not by a stationary single-band) attention strategy. The existence of at least some strong sequential dependencies in this condition, however, rules out the multiple-band strategy. Thus the complete results for this condition can best be explained by observers' using a switching single-band attention strategy (of the three strategies we are considering).

In the 95% condition, the tuning of the uncertainty effect (see Fig. 3) could be explained by either a stationary or a switching single-band (but not a multiple-band) attention strategy. A stationary single-band attention strategy leads to better overall performance in this condition than a switching band. Moreover, the lack of convincing sequential dependencies in this condition is evidence against the switching single-band strategy. The complete results for this condition, therefore, can best be explained by the stationary single-band strategy.

CONCLUSIONS

Spatial-frequency uncertainty effects were obtained for an experienced observer as well as for two initially naive observers. The range of spatial frequencies for which the uncertainty effect was smallest shifted to higher spatial frequencies as the primary spatial frequency was increased. Furthermore, the tuning in the uncertainty effect became sharper and more centered at the primary spatial frequency as the proportion of primary stimuli in the intermixed blocks increased.

Attentional control over multiple spatial frequency channels can account for these results. The tuning of the uncertainty effect and the sequential conditional probabilities suggest that which attention strategy is employed depends at least partially on the proportion of primary stimuli in the intermixed block of trials. In the uniform condition, for instance, the observers used a *switching* single-band attention strategy. Moreover, this single band appeared to be broader (i.e. composed of more contiguous spatial-frequency channels) for observer E.D. than for observer T.S. In the 95% condition, however, the observers may use a *stationary* single-band attention strategy; this stationary single band was centered on the primary spatial frequency.

A single band may represent the action of one or more contiguous spatial-frequency channels. The narrowest bandwidth estimates based on these data, therefore, should be at least as broad as those obtained using other psychophysical paradigms such as masking, adaptation, and subthreshold summation (see Graham, 1980a, b, for reviews of this literature). Bandwidth estimates obtained from these uncertainty data involve a number of assumptions (e.g. d' grows linearly with contrast for the range of contrasts used here). For the tuning obtained with the present data, bandwidth estimates would appear to be at least as broad as those obtained in other paradigms (i.e. two plus or minus one octave at half-amplitude full-bandwidth).

The existence of uncertainty effects poses a problem to psychophysicists studying small effects with gratings of different spatial frequencies. At the least, the degree of uncertainty should be the same in conditions that are compared one to another.

Both psychophysicists and cognitive psychologists have studied uncertainty effects and/or selective attention and some have developed theories to account for them (e.g. Graham *et al.*, 1978; Green and Swets, 1966; Egeth, 1977; Erderlyi, 1975; Cohn and Lasley, 1974; Martens and Blake, 1980; Sekuler and Ball, 1977; Shaw and Shaw, 1977; and Sperling and Melchner, 1978); most of these theories utilize the notions of information transmission by a multiprocess system of some sort and selective attention for certain kinds of stimuli over other kinds of stimuli. Psychophysicists often emphasize the sensory level of information processing in interpreting their data. As Erderlyi (1975) has observed, however, selectivity is pervasive throughout the entire information processing system and no single site is likely to provide an exhaustive explanation of any substantial selective phenomenon. The selective attention in the present experiments, therefore, may be occurring at both sensory and higher cognitive levels of information processing.

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