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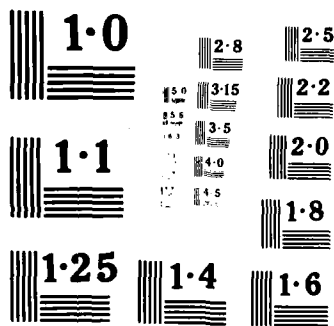   R A SMITH 01 OCT 84 AFOSR-TR-85-0245 AFOSR-80-0045
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SPATIAL AND TEMPORAL VISUAL MASKING AND VISIBILITY

FINAL REPORT
1 October 1984

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Two major studies have been completed this year, and several others are in progress. In visual masking, we have studied the effect of different detection criteria and find that criterion has a much more profound effect than is usually believed. Not only does criterion change alter overall sensitivity, but the qualitative nature of masking may be changed. For example, the same experiment may yield either Weber's Law behavior or power-law behavior, depending on criterion. We conclude that much of

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the literature on spatial frequency masking is essentially unreplicable, since criterion was uncontrolled, and we offer several suggestions for more adequate control. To evaluate the possibility of using motion to enhance the visibility of displayed images, we have been studying hypothetical detectors for moving objects. We began this study with the simplest possible stimulus, a pair of briefly-flashed lines, separated in space and time (a variant of the apparent motion paradigm). Although lateral interactions between line segments have generally been reported to be inhibitory, with this paradigm we find a range of excitatory interactions which suggest a motion detector with a tuned velocity of about 3 deg/sec.

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SPATIAL AND TEMPORAL VISUAL
MASKING AND VISIBILITY

FINAL REPORT

1 October 1984

For: Air Force Office of Scientific Research

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Prepared by

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Summary

Two major studies have been completed this year, and several others are in progress. In visual masking, we have studied the effect of different detection criteria and find that criterion has a much more profound effect than is usually believed. Not only does criterion change alter overall sensitivity, but the qualitative nature of masking may be changed. For example, the same experiment may yield either Weber's Law behavior or power-law behavior, depending on criterion. We conclude that much of the literature on spatial frequency masking is essentially unreplicable, since criterion was uncontrolled, and we offer several suggestions for more adequate control. To evaluate the possibility of using motion to enhance the visibility of displayed images, we have been studying hypothetical detectors for moving objects. We began this study with the simplest possible stimulus, a pair of briefly-flashed lines, separated in space and time (a variant of the apparent motion paradigm). Although lateral interactions between line segments have generally been reported to be inhibitory, with this paradigm we find a range of excitatory interactions which suggest a motion detector with a tuned velocity of about 3 deg/sec.

II.1 The Effect of Criterion on Spatial Masking

INTRODUCTION

In recent years spatial frequency masking has received increasing attention [1-5]. The basic paradigm is quite simple: a subject sets thresholds for a test grating in the presence of a super-imposed mask grating, typically of a different frequency. Despite masking's apparent simplicity, there have been significant qualitative discrepancies between the results of different investigators. In roughly half the literature it is reported that spatial masking obeys Weber's Law; that is, test threshold rises in direct proportion to mask contrast. In other literature, it is reported that test threshold rises as some lesser power (typically between 0.5 and 1.0) of mask contrast. On the basis of a survey of this literature [5], we offered the beginnings of an explanation by hypothesizing that a change in threshold criterion may produce functionally different behavior, and by showing that familarity with a random mask pattern can produce such a criterion change. In this paper we present evidence for the existence of several specific threshold criteria and show that some of these criteria represent detection tasks, while others are more like recognition.

METHODS

Stimuli were generated by a Xitan micro-computer and presented by conventional means on a HP1332A display with P4 phosphor. The experiments were entirely computer-controlled, with the subject signaling responses to the computer via a small hand-held keyboard. The screen was viewed from 75 centimeters, and subtended a visual angle of 10 degrees horizontally by 8 degrees vertically. The screen had a luminance of 55 cd/m^2; its surroundings were at least 10% darker. Subjects viewed binocularly with free fixation; head position was maintained by a headrest.

The test stimulus was always a 4 c/d vertical sinusoid. Band limited random noise stimuli were generated by adding together 8 sinusoids of equal amplitude and randomly chosen phase and with frequencies spaced at equal logarithmic intervals across the range of 2-8 cycles/degree. By changing the phases of the constituent gratings, we could generate a variety of noise patterns with identical power spectra -- apart from edge effects -- but with very different appearance.

Three different psychophysical techniques were used in this study two-alternative forced-choice (2AFC), three-alternative forced-choice (3AFC), and method-of-adjustment (MOA). In the forced-choice experiments the field was always bordered by 1.5 degree mean-luminance edges. The remainder of the field (the central 7 degrees) was divided into two or three equal test bands separated by narrow black lines. In a typical forced-choice trial, the same mask stimulus would appear in all the test bands;

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in addition, the test stimulus was added to a single test band.
The response indicated which band contained the test stimulus.
The observer was given an arbitrary time to respond; in practice
responses were always made within 5 seconds. The forced-choice
staircase alogrithm proceeded as follows. Before the start of
each staircase, the subject set the test modulation close to
threshold. Thereafter, on each correct trial the test contrast
decreased one step (5%). Following an error, the contrast level
at which the error occurred was recorded and test contrast was
increased by 4 steps (2 steps in 3AFC). The subjects received
feedback on error trials. After four errors threshold was taken
to be the average of the four contrasts at which errors occurred.
We initially used a weighted average for this purpose[5], but later
studies showed that this offers no advantage over a simple
average, and this was used thereafter.

In MOA studies, the stimulus filled the entire screen. The
subject could increase or decrease the contrast of the test
stimulus by one step (6%) by pressing one of two buttons. Trials
were continuous, as the change in contrast occurred with no
perceptible break. When the subject achieved a satisfactory
setting, pressing a third button caused the setting to be
recorded and randomly changed the test contrast. The computer
averaged 7 such settings to produce a single threshold estimate,
and then proceeded to the next set of experimental conditions.

The data presented in this paper are typically test
thresholds for a variety of mask contrasts. The various mask
contrasts were always presented in order, starting with the
lowest contrast, to avoid the possibility that prolonged exposure
to the higher mask contrasts might raise thresholds for lower
mask contrasts. We have previsously shown that prolonged
adaptation to a given mask contrast has no effect on masking by
that same contrast[5].

Five subjects were used for different parts of this research,
some of which was done in *New Hampshire* and some in *Michigan*.
The subjects RS, DS, and LA are experienced psychophysists; MJ
and SM are professional subjects who were naive to these
particular experiments.

RATIONALE

Our experiment is conceptualized in Figure 1. Here we see
the outputs of a variety of spatial channels of different center
frequency, viewing a pattern of visual noise which may have a
test grating added to it. On the figure are indicated the mean
output of all the channels (I_{mean}), a measure (σ) of the
variation of these outputs, and the relative output of the
channel most sensitive to the test grating (ΔI). The
detectability of a signal in this pattern of channel responses
reduces to the statistical question of whether ΔI is
sufficiently large that it is unlikely to have occurred by chance
in the random mask. For an ideal observer, ΔI is compared to the
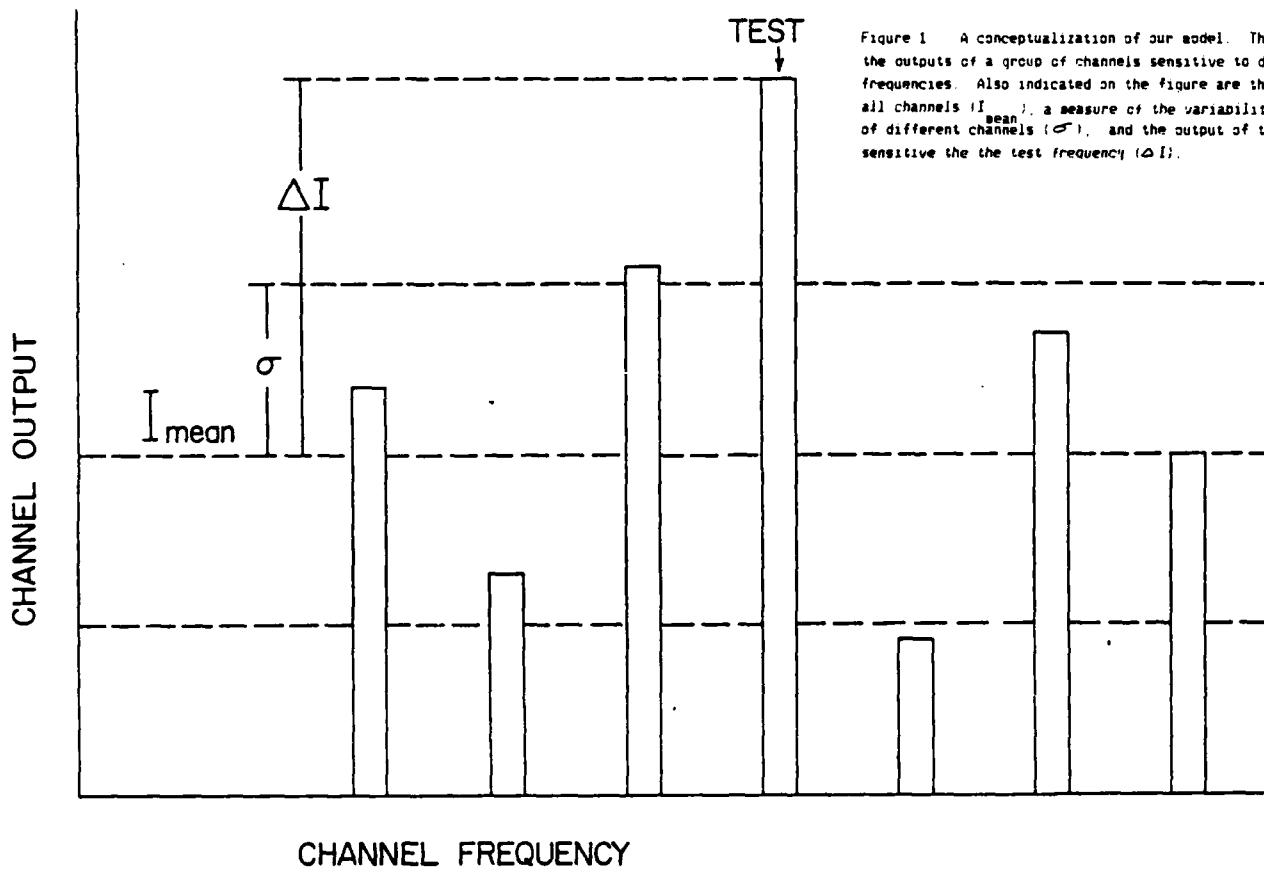width of the distribution of channel outputs (σ) by means of a

Figure 1   A conceptualization of our model.   The bars represent the outputs of a group of channels sensitive to different spatial frequencies.   Also indicated on the figure are the mean output of all channels (I_{mean}), a measure of the variability in the outputs of different channels (σ), and the output of the channel most sensitive the the test frequency (ΔI).

critical ratio ($\Delta I / \sigma$), and if this ratio exceeds some threshold, then detection occurs . This is analogous to the familiar t-test in statistics. Assuming a linear channel response (discussed below), both I_{mean} and σ will be proportional to mask contrast. Substituting for σ , the above critical ratio is seen to be proportional to $\Delta I / I_{mean}$ which is Weber's Law. We conclude that if detection is limited by external noise, then Weber's Law must hold with the Weber fraction being closely related to the signal/noise ratio.

If the output of the channel is a one-to-one, monotonic, non-linear transform of its input, a surprising result occurs. Such a non-linearity is completely transparent and has no effect upon threshold or upon Weber's Law. A proof of this result (known as Birdsall's Theorem) may be found in Lasley and Cohn[6]. It essentially follows from the fact that determining whether a threshold has been exceeded or not is an ordinal operation on the possible output states of a channel, and the proposed nonlinearity preserves the ordering of these states.

In this paper, we shall develop the following hypothesis. If a test pattern is masked by noise, then Birdsall's Theorem applies and detection must obey Weber's Law. If the mask is not noise, then other, more sensitive detection strategies are available. These strategies are typically observed to obey a power law, though we cannot yet explain this particular functional form. It is essential to define precisely the class of mask stimuli which is considered to be noise, and we propose that this class must have a subjective definition. Whatever its configuration, a stimulus is noise if the subject is unable to predict its appearance and detect deviations therefrom. Commonly this predictive ability depends on previous experience. Nachmias and Rogowitz[7] present a similar idea.

RESULTS

Figure 2 (taken from our 1983 paper) shows the effect of learning on spatial frequency detection in the presence of a random mask pattern. Consider the column labeled "Pattern #1". All of these data were taken with the same mask pattern, so that the observer gained familiarity with the mask as the trials progressed. The upper-most curve (done first) shows test threshold for a range of mask contrasts. It is essentially linear and the slope is very nearly 1.0 (i.e. Weber's Law is observed). We now selected a convenient pair of mask contrasts and measured thresholds repeatedly, observing the effect of practice. The data are presented in temporal order, decending. These have not been displaced for clarity; thresholds do indeed decrease monotonically with practice. Of more interest, however, is the fact that not only do thresholds decrease but the slope of the masking function also decreases from 1.0 (Weber's Law) to about 0.65 in the lower curves. This shows quite clearly that the observation of Weber's Law or power law behavior does not depend upon experimental conditions; the same experiment yields either law depending upon practice. It will be seen from the

Figure 2. Subject RS learning to detect the presence of a four cycle/degree test grating with four different random mask patterns. Successive runs with a particular mask pattern are displayed vertically from top to bottom. These data have NOT been displaced for clarity; the change in threshold with practice is real.
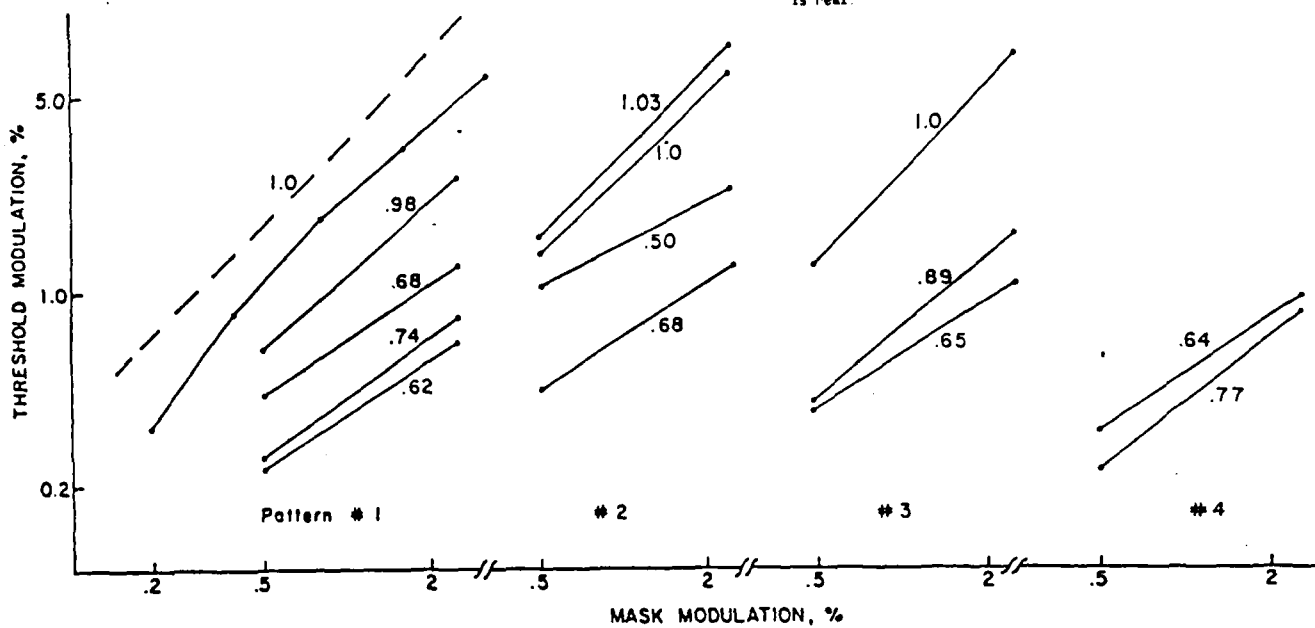
remainder of Fig. 2 that the practice effect is specific to a given noise pattern; when a new noise pattern is introduced (e.g. in the second column of data) the slope of the masking function again rises to 1.0, falling off with further practice.

The remainder of Figure 2 presents a problem. With repeated practice RS' learning becomes faster until in the right-most column he displays power law behavior on the first trial. Is RS actually doing power-law discrimination on new patterns without learning, as these data suggest? If so, it would disprove our hypothesis. In fact, we can show that RS continues to require a period of learning even though that period has become substantially shorter than the duration of a single staircase. Five new noise patterns were presented to RS and thresholds measured in their presence, as in Figure 2. The raw threshold data were now averaged across staircases, specifically we computed the average of the five first errors, the five second errors, etc. These averages are a measure of RS' threshold at different stages of the staircase. It is clear from Fig. 3 that this threshold drops systematically, by more than a factor of 2, as the staircase proceeds. Moreover, there appears to be a decrease in slope with practice as in Fig. 2. Thus RS' learning set does not violate our hypothesis. None of our other subjects has developed such a learning set.

Changing Mask Patterns

If learning the specific configuration of the mask causes the change from Weber's Law to power law behavior, then we might prevent this change by using a different mask pattern on every trial. Learning which involves some other aspect of the task, however, should persist in such an experiment since these other aspects are unchanged. Results from this experiment are seen in Figure 4, showing the slope of the masking function versus number of trials. For comparison, we include data from experiments with an unchanging mask pattern (as in Fig. 2). The results are clear. With an unchanging mask, the slope drops from 1 to about 0.65 in a reasonable number of trials, though this number of trials differs between subjects. For the changing mask condition, however, there is no change in slope. We believe that Weber's Law always holds with changing masks and two-alternative forced-choice. This shows that if the mask is truly noise (i.e. unpredicatable), then Birdsall's Theorem applies and Weber's Law is observed.

Three-Alternative Forced Choice

Whether or not a pattern is noise (in the sense of Birdsall's Theorem) depends not upon the regular or irregular appearance of the pattern, or upon the way it is generated, but upon whether the subject is able to predict its appearance and detect deviations caused by the presence of the test. Consider a simultaneous 3AFC discrimination involving two mask-alone and one mask-plus-test stimuli. If the added test stimulus produces any perceptible change in the pattern, then the subject should be able to select the one field which is different, even if the mask
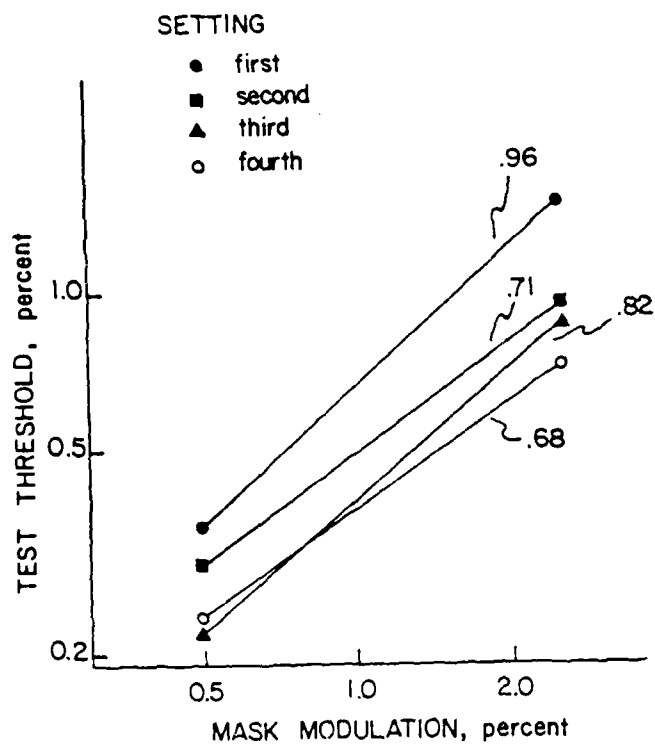
Figure 3   Learning during a single staircase by Subject AS
This figure presents averages of the four settings in a single
staircase averaged over five different staircases   (See text)

We used 6 line spacings (0.05, 0.1, 0.15, 0.2, 0.3, and 0.5 degrees) and 6 temporal delays (0.01, 0.02, 0.04, 0.055, 0.07, and 0.1 seconds). These were conceived as a 6 x 7 array; the additional column contained single-line controls. Catch trials were interspersed randomly, making 35% of the total. A single experimental run consisted of one seen/not-seen judgement for each of the 42 (6 x 7) conditions, plus the associated catch trials, presented in random order. Subjects were typically able to perform 5 runs at a sitting, with a complete experiment requiring 100 runs. Thus each experiment involved about 6000 trials. With 100 trials per point, the standard error of estimate was about 0.05. We halved this error by computing a four element boxcar average, averaging two elements along each dimension. Contour plots were calculated by an automated interpolation algorithm, which placed contours at intervals of 1.3 standard errors of the averaged data. The standard error in the placement of a contour varies, being proportional to, and somewhat less than, the separation between adjacent contours. The subjects were given periodic feedback about hit- and false-alarm-rates, and were able to hold these constant within a few percent.

RESULTS

Results are shown in Figure 1; for convenience we refer to these data as an LIF (line interaction function). Unlike the results of Westheimer or Kulikowski and King-Smith there is no suggestion of a lateral-inhibitory or centre/surround organization. The dominant feature is a bimodal area of facilitation with peaks at the origin (no separation) at a separation of about 50 msec. and 0.15 degrees. The existence of this secondary facilitatory region is the major result of this study. Note that the optimum stimulus for the mechanism shown in figure 1 would appear to be a vertical line whose locus (in space/time coordinates) moves diagonally from the origin through the peak of the secondary facilitatory area; this would be a line moving at about 3.0 deg/sec.

To establish the statistical reliability of this effect, we defined the height of the secondary peak as the mean of the data point at 55 msec and 0.15° and its four nearest neighbors. This was then compared with a baseline, defined as the mean of the six data points at maximum spatial separation. We replicated the experiment of figure 1 once with a different subject, and at least four times with other variations. We never observed an effect (as defined above) of less than four standard errors. The secondary peak was always reasonably compact and centered at 50 to 75 msec and 0.12° to 0.16°. Note, however, that the detailed shape of the contours at low levels is generally not significant, as the standard error of the placement of these contours is large. False alarm rates were 0.20 for PC and 0.33 for EM. The intersession variation of these rates was estimated as $\pm.02$ for PC and $\pm.04$ for EM. Single-line hit rates were 0.38 and 0.51, respectively, with intersession variabilities of $\pm.03$ and $\pm.06$.

II.2 A Detector for Moving Objects

INTRODUCTION

Studies of lateral interactions in vision date back at least to the discovery of Mach bands but quantitative studies have typically used one of several well-established paradigms. In the spatial domain, Westheimer (1965) studied the increment threshold for a small test spot as a function of the size of a superimposed circular field. Kulikowski and King-Smith (1973) used a comparable technique in which detection of a test line is influenced by subthreshold flank lines of varied spacings. Both of these studies found facilitation for small separations, and inhibition for somewhat larger ones. Interactions over time have been studied with theoretically parallel experiments on the detection of pairs of homogenous light flashes, separated in time rather than space. Recent studies (Rashbass, 1970; Ueno, 1973) measure an impulse response in which closely-spaced flashes summate, while flashes separated by somewhat longer times inhibit. Both spatial and temporal interactions are in qualitative agreement with the dynamics of retinal receptive fields; these display summation between stimuli which are close in space and time, while lateral inhibition occurs at only larger distances and after a brief delay (Kuffler, 1953). The only psychophysical study to systematically study both spatial and temporal interactions used the Westheimer paradigm. Teller et al (1971) varied both the size of the surrounding disk and the ISI between the test flash and the onset of the disk. This more general study confirmed the pattern of Kuffler-like dynamics, in that lateral inhibition occurred only after a delay of about 40 msec. Our experiment is comparable to Teller et al's, except that we used rectilinear stimuli. We measured the detectability of two briefly-flashed lines as a joint function of their separation in space and time.

METHODS

Stimuli were displayed on an HP 1332A CRT, in a 30 cd/m^2 luminous patch 4° wide and 5° high, viewed from 70 cm. Line stimuli 0.8' wide and 1.5° high were flashed for 10 msec in the middle of the field. Fixation was aided by two vertical vernier lines; the test lines being parallel to, and equidistant from, the midpoint of the verniers. The total energy of each test line was equal to that of a 50 cd/m^2 line, 10 msec in duration and 0.8' wide. In a typical trial, the background luminance appeared and awaited a ready-signal from the subject. The test line appeared 700 msec. after the subject's signal, preceeded by an audible beep. The screen remained luminous for another 700 msec., and then turned off briefly to process the subject's response. The average duty-cycle was 6 seconds on, one-half second off. The subject was given feedback for incorrect answers.

he is motivated, this may occur slowly, or not at all.

An unfortunate conclusion from this is that many masking studies (especially those using MOA) are effectively unreplicable. We can reproduce the external conditions of an experiment, but only in a few cases (e.g. highly practiced subjects using forced-choice) can we be sure of the detection strategy used. Thus, while the factors we have elucidated seem to us sufficient to account for the diversity of results in the literature, there is no apparent way to show (i.e. by replication) which factors were critical in a particular study, or to show that other factors -- perhaps unknown to us -- were not operative.

Finally, we offer a practical conclusion. We regard 3AFC as a major advance in the study of spatial masking, especially when the issues of detection versus identification are involved. It is the only technique we know (excepting over-learned 2AFC) which largely eliminates variation in detection strategy, by removing the identification-like aspects of the task. This is useful for studying the relationship between detection and identification, and is essential if we desire to isolate the pure detection mechanisms in masking experiments. Another advantage is that a three-alternative staircase converges more reliably than a two-alternative staircase, since the probability of a correct guess is reduced. A final advantage is surprising. The data shown in Figure 5 were taken from naive subjects who had _never_ done masking discriminations before. These discriminations are notoriously difficult; to our knowledge no one has previously obtained reliable masking data from naive subjects without an extensive period of practice. The net result of all of these considerations is that 3AFC yields reliable masking data in much less time than any other psychophysical technique we have used.
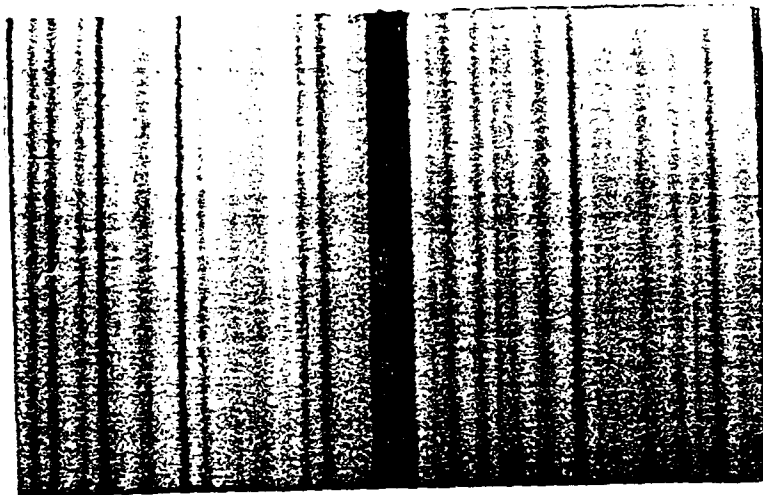
Figure 10   A typical forced-choice random-mask stimulus pair.
It is easy to see that the two stimuli are different, but very
difficult to decide which is mask-plus-test   and which is mask-
alone

masking noise, and not at all by the inherent sensitivity of the visual system. Note that Birdsall's Theorem is formulated entirely in terms of the statistical properties of the signal; threshold behavior is largely transparent to the properties of the visual system. Thus such experiments may tell us little about visual physiology.

When the subject is presented with a non-random, sinusoidal mask, Weber's Law may nonetheless be observed. This might occur because the subject still needs to learn the appearance of the mask. From a different point of view, this is equivalent to saying that faced with an unfamiliar discrimination, the subject chooses a very conservative criterion. Another reason for Weber's Law with sinusoidal masks is that there exist configurational criteria which produce Weber's Law even in the absence of visual noise. Of these criteria, we feel that the bar-width criterion deserves attention. This yields thresholds similar to those set by subjects without special instructions. In addition, some of our naive subjects have spontaneously described this as their criterion.

In the literature, MOA psychophysics are almost always associated with Weber's Law[5]. This may be because configurational criteria are easier to use. The fact that we were able to achieve power-law behavior with MOA seems entirely attributable to motivation. Unlike forced-choice, MOA provides no inherant motivation for increased sensitivity. In general, the more we motivated our subjects to set low thresholds, the lower the exponent in their power laws.

The distinction between the two types of criterion is made clear in figure 10, which shows a pair of mask-alone and mask-plus-test patterns from our first experiment. If a subject is asked to detect "any difference", he will do so easily; the added 4 c/deg test grating is readily detected. But if he is asked to which noise pattern the test has been added, his replies will be near chance; he cannot yet identify that particular pattern of channel activation which characterizes a 4 c/deg grating, given the level of masking noise. If, however, he is told which pattern is mask-alone, and asked to determine whether a test has been added to the other, he can easily do so. These changes are not because of any changed performance in his visual system, but because different tasks and/or additional information may convert an apparent identification-type task into a detection-type task. Evaluating the effect of available information (or uncertainty) is not always easy. Our stimuli were relatively well-defined: the masks were spectrally-flat, band-limited noise and the tests were always 4 c/deg at a specified phase. We find that simply randomizing the test phase between trials greatly extends the learning period necessary in our first experiment (Figure 1); undoubtedly relaxing other constraints would have a similar effect. The problem has yet another dimension. Whatever information may be available to the subject provides only a limit on detectability; we have seen that the subject must often learn to use the information. Unless

fraction of 1.25. The results of this experiment are shown in Figure 9. The data for the two subjects are similiar except that SM's slopes are slightly greater than those of RS. Our major expectations are confirmed. The dark bar and bar width criteria display Weber's law. Furthermore the dark bar data show approximately the predicted value of the Weber fraction. The data for the absolute criterion, however, display power law behavior. Thus we see that the adoption of different criteria in method-of-adjustment experiments not only influences threshold but actually changes the power law observed.
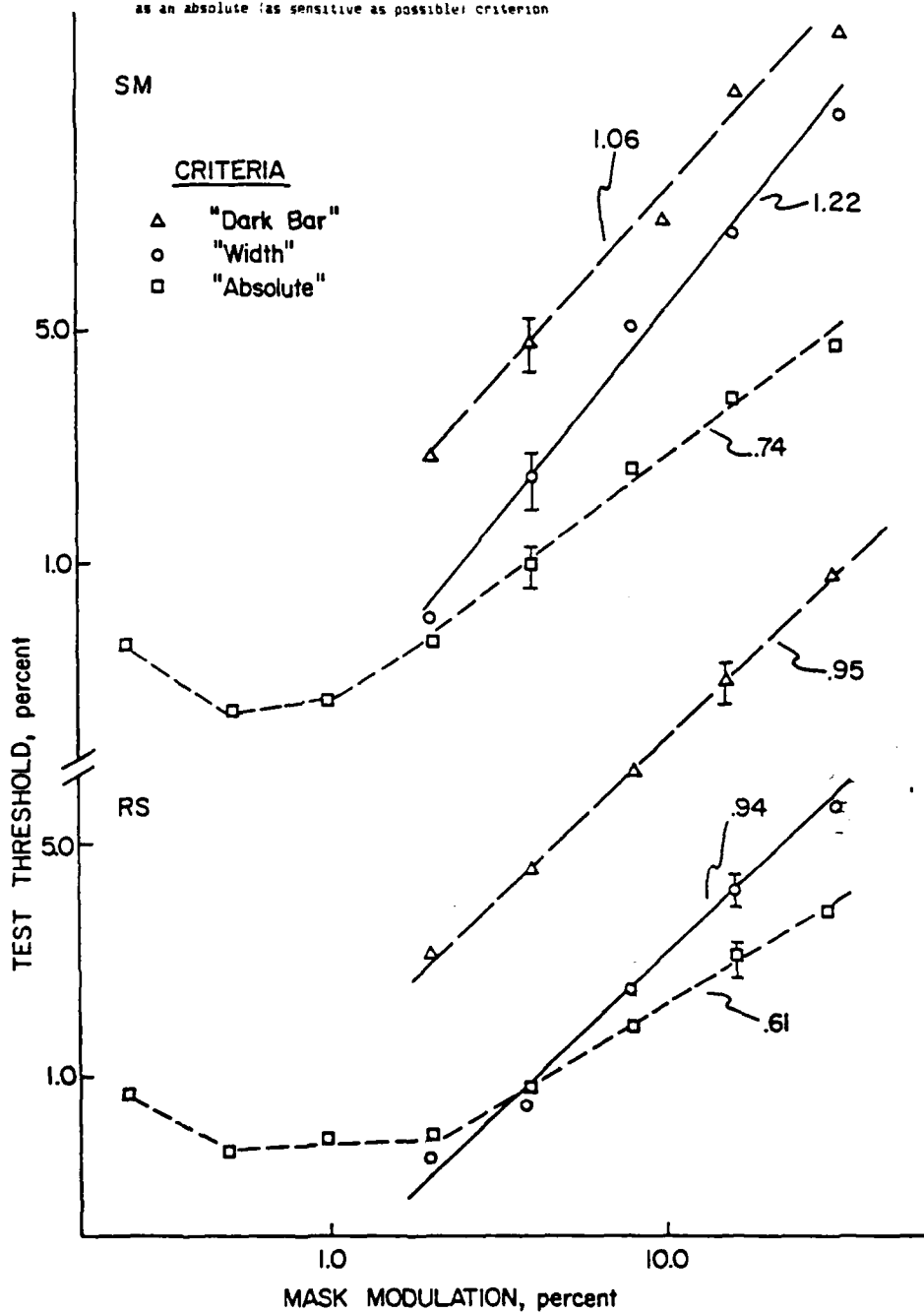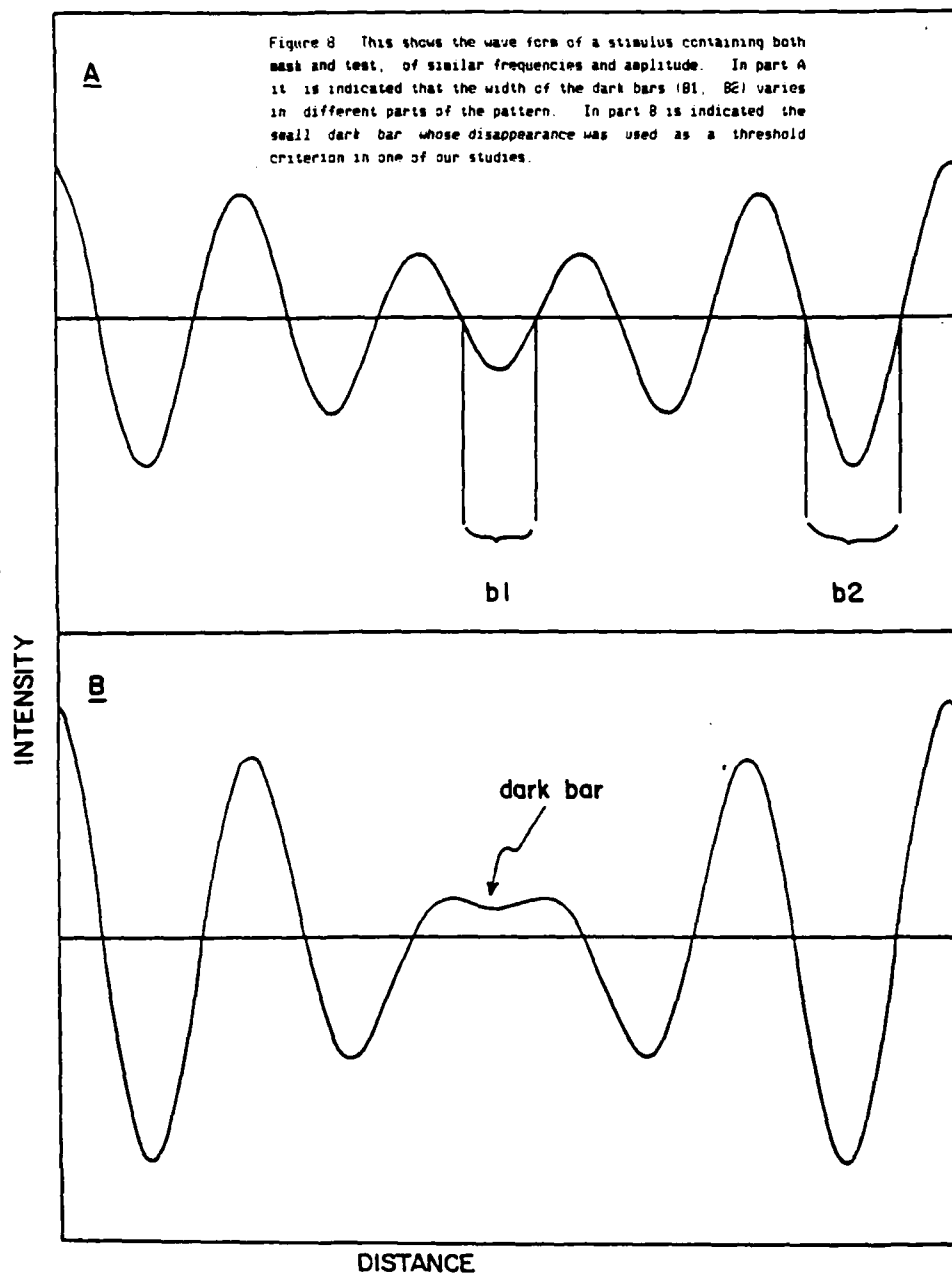
DISCUSSION

We have referred to similarities between spatial masking and the processes of detection and identification. In particular, our theoretical explanation (especially Birdsall's Theorem) is in many ways equivalent to that presented by Lasley and Cohn[6] to distinguish luminance detection and discrimination. We can now make these similarities explicit. Classically detection and identification have been quite distinct paradigms: the former is discriminating a test stimulus from no stimulus, while the latter is discriminating between two different test stimuli. Recent theories based on visual detectors have blurred the distinction somewhat, since "identification" may now be defined as detection by a particular detector. In such a model, "detection" might be the presence of a criterial response from any detector. Under these definitions, our analysis suggests that masking by noise stimuli (involving only one detector -- or a small related set) is an example of identification, while masking by a familiar stimulus (detecting a change from any detector) is detection. Other definitions are possible; in particular it may be objected that masking is not a true identification paradigm, since two test stimuli are not involved. Provided the considerable similarities are recognised, we have no objection to a narrower definition of identification. For this reason, we have referred to noise masking as "identification-like". The essential point is that in noise masking, the observer must know something about the test stimulus, and detect the known feature in the noise. In masking by a familiar pattern, no particular feature need be known; any detectable change is sufficient.

We believe that we are now in a position to explain much of the diversity in the literature on Weber's Law in spatial-frequency masking. Subjects can use at least two quite different threshold criteria in masking experiments. These yield not only different thresholds, but different functional behavior with changes in mask contrast. In some paradigms, we can be sure what criterion was used and understand the results accordingly, but in many paradigms the criterion is uncertain and the results are correspondingly difficult to interpret. Let us therefore survey some common masking experiments from this point of view.

When the mask is noise (or equivalently, when the observer is uncertain of mask configuration) then the observer's ability to discriminate is limited entirely by the amplitude of the

Figure 9 Effect of Criterion Thresholds for 4 c/deg test and 5 c/deg mask, for the two criteria described in Figure 7, as well as an absolute (as sensitive as possible) criterion

Figure 8 This shows the wave form of a stimulus containing both mask and test, of similar frequencies and amplitude. In part A it is indicated that the width of the dark bars (B1, B2) varies in different parts of the pattern. In part B is indicated the small dark bar whose disappearance was used as a threshold criterion in one of our studies.

A

b1   b2

B

dark bar

INTENSITY

DISTANCE

with practice. Thus even the appearance of sinusoidal masks has
to be learned. It follows that such masks are, to some extent,
noise in the functional sense that the subject cannot detect the
test with full sensitivity until he is fully familiar with the
mask. Thus Birdsall's Theorem may well apply to non-random
masks, particularly with inexperienced subjects and
psychophysical procedures (e.g. MOA) which do not encourage
maximal sensitivity.

Configurational Criteria

Even if Birdsall's Theorem does not apply, there is a second
way in which the subject's choice of criterion may lead to
Weber's Law with harmonically pure stimuli. The subject may
attempt to identify a particular feature which occurs in the
complex test-plus-mask pattern. Since the overall configuration
of a complex grating depends solely on the ratio of its
components, such a criterion -- rigidly followed -- will lead
to Weber's Law. Many such configurational criteria may be
devised; in the next experiment we investigate two of these.

For these experiments, we must use a more subjective
psychophysical procedure (MOA), instructing the subject to use
different criteria under otherwise identical conditions. An
advantage of MOA psychophysics is that a significant part of the
masking literature has used this method. It has the obvious, but
unavoidable, disadvantage that we have no real control -- beyond
subjective report -- over what criterion is actually used.

Consider three different threshold criteria. The first we
term the absolute criterion; the subject sets thresholds as
sensitively as possible, by whatever cues he may find. This is
probably not the usual criterion in MOA; even experienced
subjects often choose a criterion which is relatively high. The
second criterion is the bar-width criterion, shown schematically
in Figure 8A. This figure shows the sum of two sinewaves (i e
mask and test) of similar but unequal frequency and amplitude.
The width of the bars in the resulting complex grating is less in
the region of destructive interference than in the region of
constructive interference. Subjects were asked to set threshold
by looking for a just-perceptible change in bar width. Since the
subject's JND for bar width will be relatively constant for
different contrasts[8], this is a geometrical property occurring
at a fixed ratio of mask to test contrast. In short, Weber's Law
will apply. The final criterion is exemplified in Figure 8B,
where the contrast of the hypothetical test grating has been
increased somewhat over Figure 8A, producing a readily detectible
feature. This is the small dark bar (indicated by the arrow)
which occurs in the middle of an extended bright field. If the
contrast of the test grating in Figure 8B were increased
slightly, the dark bar would disappear altogether. The
disappearance of this dark bar was the final criterion used by
our subject. The objective disappearance of the bar is
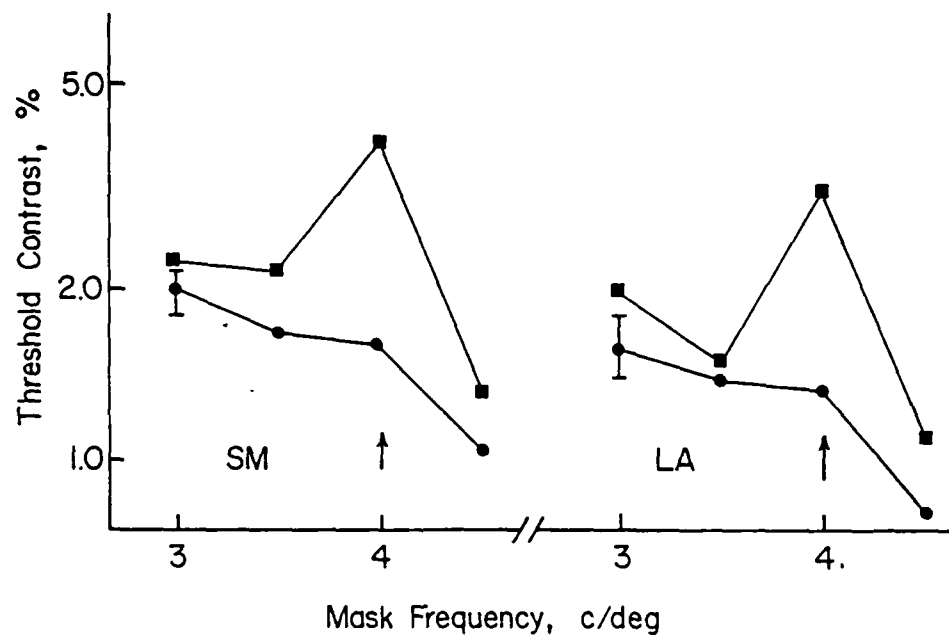calculable; for sinusoids of 4 and 5 c/deg, it occurs at a Weber

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Figure 7. Learning to detect a 2nd-harmonic test. Mask is 2 c/deg, 0.08 contrast, test is 4 c/deg in cosine phase. The upper curves are averages of trials 1-3, the lower are averages of trials 7-9.
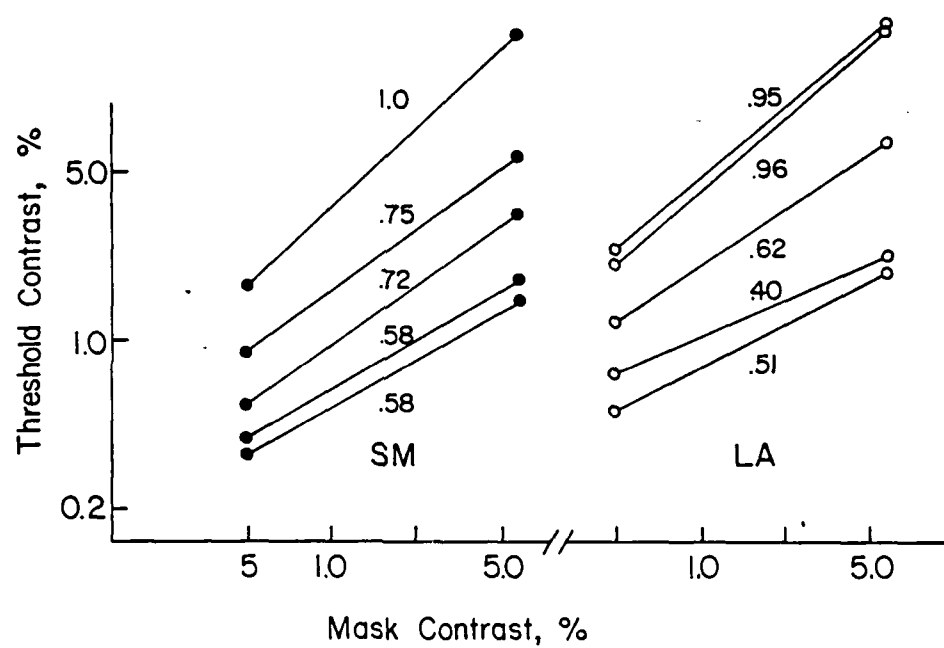
Figure 6. Learning by naive subjects with a sinusoidal mask. This is similar to Figure 2, except that the mask is 5 c/deg, rather than noise.

is totally unfamiliar. To test this, we repeated the experiment of Fig. 4 with simultaneous 3AFC (rather than 2AFC). As before, a different mask pattern was used on every trial. The results for two subjects are shown in Fig. 5, along with some limited data using 2AFC for comparison. Our prediction is confirmed; the 3AFC results are not only more sensitive, but they clearly obey a power law rather than Weber's Law. There is a decrease in threshold with practice, which suggests some generalized learning effects. Given the difficulty of the task this is not surprising, but it only strengthens our conclusions; neither a power law nor any significant learning are ever observed with changing masks and 2AFC. We attribute the fact that SM's 2AFC data are considerably noisier than the 3AFC data to the greater difficulty of the task, and to the inherently better convergence of a 3AFC staircase. Unfortunately, MJ (like most unpracticed subjects) was totally unable to do the 2AFC task.

Harmonically Pure Stimuli and the Method of Adjustment

The evidence presented so far supports our two-criterion hypothesis for masking by visual noise. Is it possible to apply a similar analysis to the commonly-used sinusoidal mask? Although a sinusoidal mask is mathematically predictable (as indeed were our pseudo-random noise masks) the subject may nonetheless require experience before he can detect small changes in its expected appearance. Fiorentini and Berardi[9] found that subjects required 100-200 presentations to fully learn to discriminate subtle differences in 2-component complex sinusoids. Thus we might observe (perhaps to a reduced degree) the learning phenomenon of Fig. 2 with sinusoidal masks. Data from such an experiment are shown in Figure 6, which shows SM and LA (both naive to sinusoidal masks) learning to detect a 4 c/deg test in the presence of a 5 c/deg mask using 2AFC. The results are consistent with our hypothesis; discrimination improves with practice, and the slope decreases. Unfortunately this was a one-time observation; after taking these data, both subjects gave slopes of about 0.65 with any harmonically pure mask. We have not found another naive subject whose data are clean enough to interpret.

We can demonstrate the "learning" of a sinusoidal stimulus in another way. It seems probable that certain pairs of mask and test will provide a harder task than others. Specifically if mask and test are in the ratio of 1:2 then detection involves a subtle, second-harmonic distortion in the shape of each sinusoid, while for other ratios (e.g. 3:5) the various bars in the sinusoid will be of different shapes with the same shapes recurring at the period of the beat frequency. Even without knowing the detailed appearance of a single cycle, the subject can still recognize this repetitive beat pattern. Figure 7 shows 2AFC thresholds in the presence of a 2 c/deg mask for several tests which are close to the mask's second harmonic. As expected, the second-harmonic mask is considerably more effective than the anharmonic ones, but loses much of this effectiveness
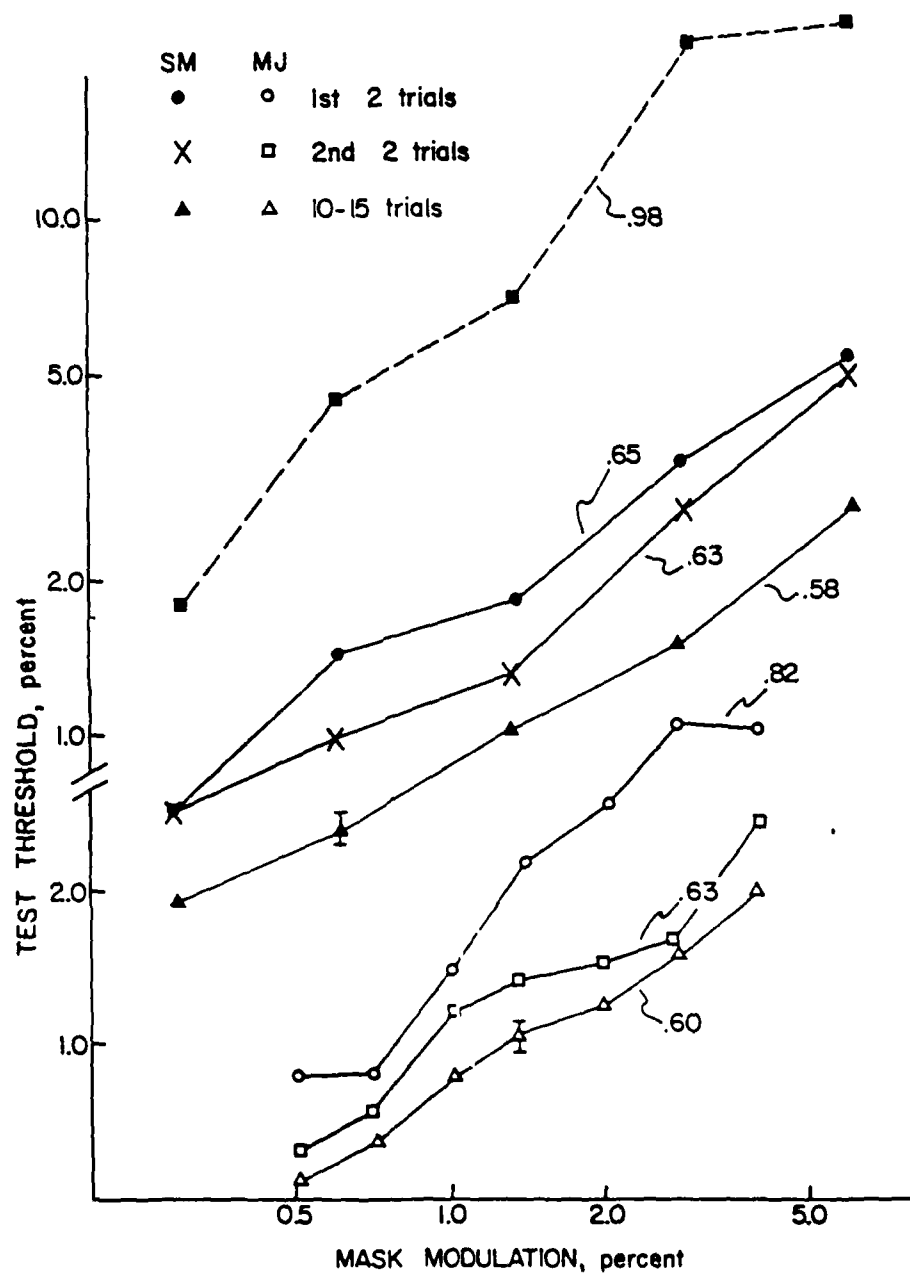
Figure 5 Masking functions for three-alternative forced-choice
with continually changing masks. For comparison, the dotted line
shows the results of a similar experiment using two-alternative
forced-choice for Subject SM. Like most naive subjects MJ was
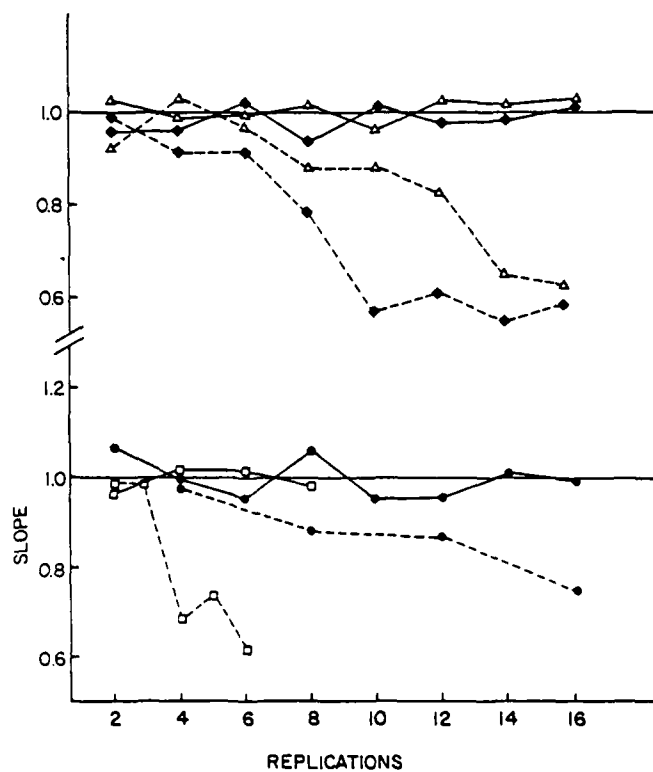unable to do this task at all.

Figure 4. Slope of the 2AFC masking function with a continually
changing mask (solid lines). The slope is seen to remain at 1.0
(Weber's Law) over many trials, while the slope with the same
mask presented repeatedly (dotted lines) decreases to about 0.65.
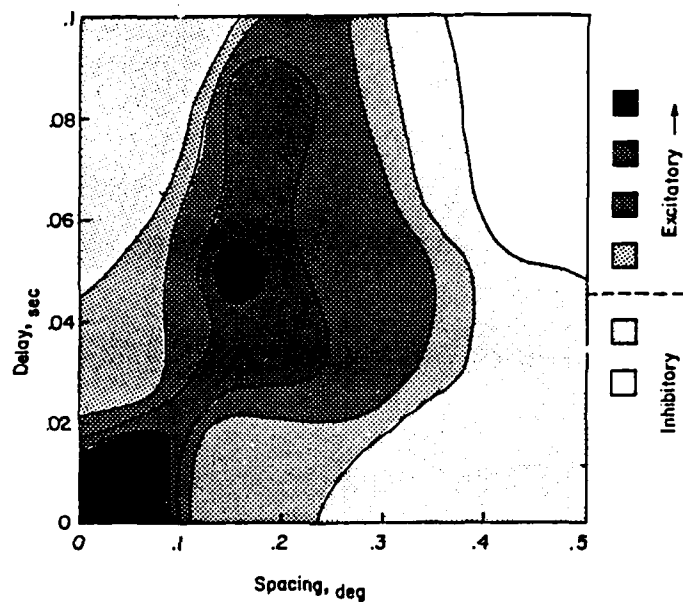Subjects: RS (□); DS (●); LA (■); SM (△)

Fig 1 Contour plot of the probability of detection versus spatial and temporal separation of the two test lines "Excitatory" and "inhibitory" are relative to the calculated probability of detecting either line independently The lowest contour line is p = 0 42. higher contours are spaced at 0 03 intervals

Figure 2 is a replication of Kulikowski and King-Smith's static three-line paradigm. The test and two one-third-luminance flanks were presented simultaneously using a Gaussian temporal presentation with a half-width of 0.5 seconds (as used by Wilson and Bergen, 1979). The results are quite similar to those in the literature: facilitation at small spacings is replaced by inhibition at larger spacings. Similarly, figure 3 is a replication of the two-flash experiment. The subject detected the presence of a pair of 10 msec, whole-field flashes as a function of their temporal separation. These data show a typical pattern of facilitation, followed at longer ISIs by inhibition, followed by disinhibition at still longer ISIs. The temporal parameters of this function (e.g. ISI to peak inhibition) are a strong function of luminance (Ueno, 1977). Our data agree well with Ueno's data for a similar luminance.

DISCUSSION

Attempting to assign a functional interpretation to the LIF raises a number of questions which we cannot yet answer. We will, nonetheless, address the following issues: 1) does the LIF measure the behavior of a single visual detector, or is it a composite; 2) is the underlying mechanism functionally motion sensitive; and 3) why is the LIF so different from the results of other experiments of which it was intended to be a generalization?

Single and Multiple Mechanisms

There do not appear to be any theories of multiple spatio-temporal mechanisms, but an extensive literature on essentially spatial mechanisms is readily generalized. Kulikowski and King-Smith's original measurement of a spatial-only LIF was strongly criticised by Graham and Rogowitz (1976), who showed that probability summation between spatial channels could so distort subthreshold additivity experiments that the results bore little resemblance to the bandwidth or spatial sensitivity of the underlying channels. These concerns seem fully applicable to this experiment. On the basis of present evidence, then, the LIF is only a psychophysical entity; we make no claims about underlying neurophysiology. Note, however, that the actual extent of Graham and Rogowitz' proposed distortion is largely unknown, and may be small. In particular, Hines(1975) and Wilson and Bergen(1979) have used Kulikowski and King-Smith's paradigm to measure a linespread function which was then used in their linear models of spatial detectability. While the physiological reality of their proposed mechanisms is debatable, the considerable predictive success of these models justifies an attempt to generalize this approach to spatio-temporal stimuli.

Motion Detection

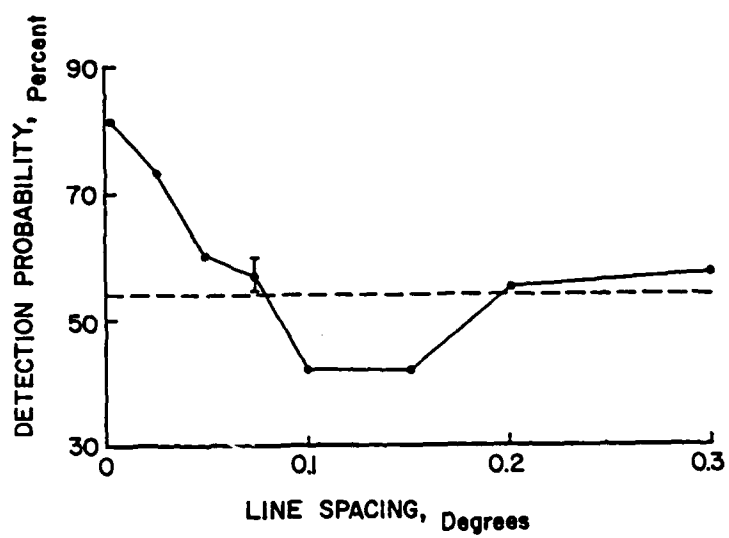It is tempting to equate the mechanism underlying the LIF

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Fig 2. Visibility of a test line as a function of the separation of two sub-threshold flank lines. Presentation was a 0 5 second half-width Gaussian ramp. The dashed line is the probability of seeing the test line alone.
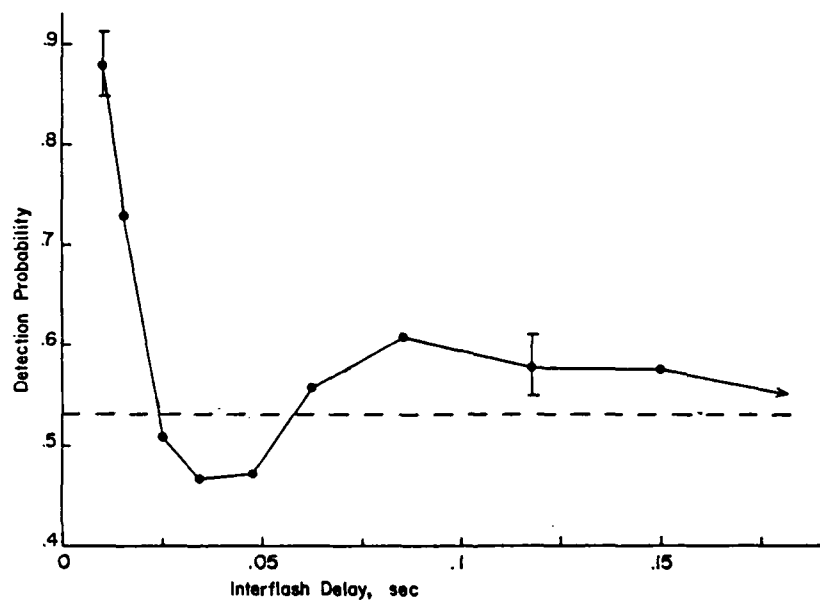
Fig 3 Visibility of a pair of 10 msec whole-field flashes. as
a function of their separation in time The dashed line is the
calculated probability of seing either flash independently

with a motion detector; the stimulus to which it should be most
sensitive is a line moving with a velocity of about 3 deg./sec.
Theoretical discussions of motion detectors (Reichardt, 1961;
Barlow and Levick, 1965) describe entities with properties
similar to the LIF. We must exercise caution however. since this
conclusion involves extrapolating from briefly-flashed lines to
quite different stimuli. Such an extrapolation is valid only if
the underlying mechanism is linear. Moreover to establish that
the LIF mechanism functions as a motion detector will require
extensive studies relating it's properties to the actual
perception of motion. At present, the association of the LIF with
motion detection is a tempting but quite unproven hypothesis.

If the LIF taps motion detection mechanisms, why do we find
only a single detector. tuned to a single velocity? Given our
range of spatio-temporal separations. it would not have been
possible to find detectors with a velocity very much different
from what we found. It is also possible that detectors tuned for
different velocities and spatial patterns exist, but that they
are not very sensitive to thin lines and so were unobserved. We
are actively searching for such mechanisms.

Related Studies

We have already briefly summarized the better-known
literature, and have seen that this generally supports a
Kufflerian model of the spatio-temporal dynamics of lateral
interactions. A few studies suggest a compatible, but more
detailed picture. Smith and Richards (1969) found that lateral
interactions appeared to propagate across visual space at about
1.0 degrees/second. Van der Wildt and Vrolijk (1981) also
measured propagating inhibition with a velocity of 4 deg/sec in
an experiment which is identical to our present experiment with
the following exceptions: 1) their data were taken off the
fovea, typically at 3° nasal, 2) they used points of light,
rather than lines. While the difference in velocity might be
explained by retinal locus, we suggest below that the the
difference between excitation and inhibition is a result of the
different stimulus configuration.

It was our original expectation that these experiments would
also measure the spatial and temporal dynamics of Kuffler-type
lateral inhibition. In fact, the LIF primarily shows delayed
lateral facilitation, rather than inhibition. We have replicated
some of the experiments showing lateral inhibition (figures 2,3)
and our results are in good agreement with those in the
literature. Thus the apparent contradiction does not seem to be
the result of an artifact or idiosyncrasy in our procedure;
rather there appears to be a genuine qualitative difference
between our paradigm and these related experiments.

We find only one experiment in the literature which directly
tests our result. McGarvey and Cohn (1983) studied the
visibility of two flashed, rectilinear LEDs at four space/time
separations. Only one of their separations (40 msec and 0.1

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degrees) fell within our secondary facilitatory region, but that point showed clear facilitation.

It is possible to plausibly organize these various results in terms of systems already described in psychophysics and neurophysiology. Results consistent with the lateral inhibitory behavior of retinal neurons are obtained with 1) concentric stimuli, 2) point stimuli, 3) line stimuli in prolonged presentation, and 4) unpatterned light flashes. To obtain secondary facilitation, as in the LIF, it is apparently necessary to use both linear stimuli and rapid temporal presentation. This agrees with the psychophysical concept of the transient visual system. This system is commonly described as being most responsive to motion or rapid temporal varation, and to relatively coarse, rectilinear stimulus contours. We tentatively suggest, therefore, that when a transient, rectilinear stimulus is present, then a set of visual mechanisms is invoked which is wholly inoperative with static stimuli, and that these mechanisms primarily show a facilitation which is offset in both space and time.

II.3 Ongoing Studies

The following studies are still in progress and final write-ups are not yet available.

1. The Pedestal Effect: an inherent nonlinearity?

We proposed that it might be possible to enhance the detection of spatial targets on CRT displays by adding a sub-threshold facilitating signal to the display. This was based on the observation (Nachmias and Kocher, 1978) that the detection of faint stimuli may be facilitated (as much as 3x) by the addition of a subthreshold pedestal, which is typically identical to the target stimulus. At first sight this may appear trivial, but the effect works even in two alternative forced-choice, where the pedestal is added to both the target and blank stimuli. Two hypotheses have been suggested to account for this effect. 1) The pedestal is occasionally detected, and shows the observer when and where to look, reducing his uncertainty. 2) There may be an accelerating nonlinearity in the transduction of near-threshold signals. The uncertainty effect has been tested repeatedly (see, e.g. Lasley and Cohn, 1981) and is certainly operative under at least some circumstances. However, the second hypothesis has never been directly tested. In a first effort to separate the two hypotheses (Swift and Smith, 1984), we studied the pedestal effect with continuously-presented, slowly-moving pedestal gratings. Such a pedestal provides no information about the location of the target in either space or time. Nonetheless, we found a substantial pedestal effect, suggesting that something other than a reduction of uncertainty was operative. There was one weakness in this conclusion; the pedestal effect was tuned for the frequency of the target. Perhaps the pedestal reduced uncertainty about the size (but not the location) of the target, and this was the cause of the observed facilitation.

We are engaged in a series of experiments to clarify this issue, by more fully eliminating uncertainty. In one experiment, we used vertical bars for target and pedestal stimuli in a 2AFC paradigm. Uncertainty was eliminated by the presence of "delimiters", which were thin bright lines of constant luminance at the edges of the target. The delimiters appeared coincidentally with the target presentation so they delimited the target in both space and time. We found that faint delimiters acted as effective pedestals, in themselves, supporting the idea that the pedestal effect results from uncertainty. Furthermore, when we used relatively bright delimiters, the addition of a pedestal produced little or no facilitation. All of this argues against a nonlinearity in low contrast vision, but an objection to this conclusion is that placing delimiters right at the edge of the target bars makes the detection task very difficult, probably because this task is usually done by comparison across the edge. To remedy this we have programmed these experiments on

the Grinnell 2-dimensional image processor. In two dimensions, it is possible to delimit our target stimuli without obliterating all edges (e.g. by using dotted lines, marking only the corners of a rectangle, etc.) These data are not yet complete, but any non-linearity appears to be small.

On the other hand, we have also measured the subjective contrast of faint stimuli with a subjective rating technique. In this case, the accelerating non-linearity is very clear. At present we have no explanation for this apparent discrepancy.

2. Velocity mechanisms studied through velocity discrimination

We are also attempting to find velocity channels using a velocity discrimination paradigm. This is analagous to the use of wavelength discrimination to isolate the three cone systems. If velocity channels exist, the ratio of activation of the differently tuned channels would be likely to encode velocity. Discrimination sensitivity would be highest where the sensitivities of the channels were changing most rapidly with respect to one another. This would typically occur where the velocity sensitivity functions cross. Each crossing would be represented by a minimum in the discrimination function. This technique has recently been used by Mandler(1984) with flickering fields to chart temporal frequency channels. In view of the close relationship between movement and flicker, comparison of our results and those of Mandler should prove interesting.

Our procedure has undergone considerable refinement. We are attempting to remove temporal transients from the presentation, having found that they produce flatter discrimination functions. Our current procedure sequentially presents two moving stimuli, the subjects task is to pick which interval contained the fastest movement. The contrast of each presentation is modulated in time by a gaussian, and the screen contains a mean luminance field when not in a presentation. The screen is masked by a diffusing screen such that only the central two degrees is used for the discrimination. Many types of stimuli can be used, as yet we have worked primarily with lines, gaussian bars, and gratings. We are able to use velocities from 0.5 to 32 d/s. Using stimuli of constant superthreshold contrast, we find:
1. Velocity discrimination is a assymetrical u-shaped function, with the poorest discrimination at the lowest velocities (.5 to 1 d/s). The best discrimination is achieved at 4 d/s, and degradation occurs at velocities higher than 8 d/s.
2. Gratings produce the smoothest u-shape, and the best discriminability. Aperiodic stimuli produce flatter functions. Both classes of stimulus produce a secondary minimum at around 22 d/s, but the effect is small and we do not yet trust its validity. The level of discriminability is remarkable at the highest velocities, because the stimuli are so blurred (by the visual system) that their forms are unrecognizable.

These results imply the existence of two channels, with peak sensitivities at about 1.4 and 10 d/s, and possibly a third at 32

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d/s (or higher). This roughly corresponds to findings of Thompson, using a different procedure. He suggests the existence of two channels, centered on either side of 4 d/s. Our data look much like Mandlers temporal frequency discrimination functions, although comparison is difficult because his conditions did not use temporal frequencies low enough to show our low velocity falloff. His data appear to have a bit more resolution, showing separate minima at 2,5 and 30 hz, with a very pronounced dip in discriminability at 12 hz. (This corresponds to the weaker decline in our own data). His data appear to show channels at about 3, 12 and some higher temporal frequency. Basicly, the correspondence is good. We may be dealing with the same population of channels.

We intend to replicate our experiments at constant perceived contrasts, perhaps 0.5, 1 and 1.5 log units above contrast threshold at each velocity tested. This should reveal channels having similar sensitivity functions. We need to systematically investigate the individual differences between subjects as well, the absolute levels of discriminability appear to differ widely between observers, in a manner not correlated with psychophysical experience.

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V. Professional Personnel

Robert A. Smith, PhD -- Principal Investigator
Steven C. Panish, PhD -- Research Scientist
Dan J. Swift,, PhD -- part-time investigator (summer)

VI. Interactions

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