AFAMRL-TR-80-117

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Aerospace Medical Research Laboratory

ANALYSIS OF DYNAMIC VISUAL PROCESSING

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DECEMBER 1980

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FOR THE COMMANDER

Charles Bates, Jr.

CHARLES BATES, JR.
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AIR FORCE/56780/26 January 1981 — 150

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: (18) AFAMRL-TR-80-117 ✓	2. GOVT ACCESSION NO.: AD-A094 077
3. RECIPIENT'S CATALOG NUMBER:	
4. TITLE (and Subtitle): (6) ANALYSIS OF DYNAMIC VISUAL PROCESSING	5. TYPE OF REPORT & PERIOD COVERED: (7) Technical Report
	6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): (10) Allan J. Pantle	8. CONTRACT OR GRANT NUMBER(s): (15) F33615-77-C-0523
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Miami University, Department of Psychology, Oxford, OH 45056	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62202F; (16) 7184 (17) 11 31
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, OH 45433	12. REPORT DATE: (11) December 1980
	13. NUMBER OF PAGES: 128 (12) 128
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Vision	Texture Perception	Fourier analysis model
Human Visual System	Spatial Filtering	Masking
Spatial Frequency	Perceptual Constancy	Sustained and Transient Channels
Motion Perception	Signal Detection	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The empirical studies ~~described in this report~~ were designed to elucidate the visual mechanisms or channels responsible for the spatiotemporal processing of dynamic imagery. The studies are conveniently placed into four different categories according to the type of display employed. A sustained-transient channels model of visual function was used as the framework for the conduct and interpretation of the experiments.

(1) In the first series of (continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE studies it was shown that the pattern of masking effects produced by a background of particular spatial frequency content upon a set of test targets cannot be predicted without knowing the temporal characteristics of both the background and target. An experiment on light-dark adaptation demonstrated that a spatial contrast sensitivity function defined by either a pattern or flicker criterion changes in shape when the level of light-dark adaptation is changed. In an experiment designed to be optimal for observing the spatial spread of an inhibitory effect of transient channels on sustained channels, none was obtained.

(2) Studies of the effects of sine-wave adaptation on perceptual organization. Selective adaptation to sine-wave gratings was found to bias the perceptual organization of a bistable spatiotemporal display. Evidence was most conclusive that the perceptual grouping of elements into a unit was the result of passive low-pass filtering of spatial frequency components by transient channels.

(3) Studies with alternating, Julesz-type random-element patterns. In experiments in which the perception of a global subjective figure depended upon local correlations of individual elements in successive time frames, it was found that the clarity of the subjective figure decreased gradually as the orientation difference between elements in the successive frames increased. This result suggests that the first stage of the figure formation process involved signal processing in high spatial frequency channels.

(4) Studies of dynamic texture processing. The perception of a subjective figure based upon texture cues in a dynamic display was found to depend upon a process which consisted of at least two adaptable components: one component involving a representation or coding of the spatial details of the individual texture elements themselves, and another component involving a representation or coding of the figure as a whole. The perception of global figures discussed under (3) and (4) is most easily understood in terms of a two-stage process in which a low-pass spatial filter operation is performed on a topographic pattern of activity in arrays of high spatial frequency sustained channels.

The four types of phenomena described in this report can be used independently (a) to evaluate the quality of different types of dynamic displays and (b) to identify potential sources of success and failure in visual performance tasks involving human operators. Taken together they reveal much about the manner in which the visual system detects and identifies forms, targets, and objects in cluttered and uncluttered backgrounds, how the visual system responds to their movement, and how forms or objects retain their identity despite changes in their internal make-up or local structure over time. With more research it should be possible to specify more exactly how the different organizational tendencies described in this report interact and to spell out in more detail their relationship to various aspects of the sustained-transient channels model of visual function.

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GENERAL INTRODUCTION

Visual phenomena and displays

The empirical studies described in this report were designed to elucidate the visual mechanisms or channels responsible for the spatio-temporal processing of dynamic displays. We used four different types of displays to approach the problem of visual spatiotemporal information processing in four unique ways. In the first series of studies we employed temporally modulated sine-wave gratings; in the second series of experiments we used sine-wave adapting displays which were shown to interact with line-element displays; in the third series of experiments we used dynamic, random-element displays in which global subjective figures were not visible in individual frames but depended upon a temporal cross-correlation process for their emergence; and in the fourth series of adaptation-test studies, we used random, dynamic, line-element displays in which global subjective figures were visible in individual frames of the display. The unique characteristics of each type of display and the advantages associated with the use of each display are described in the separate sections of the report. On the whole, the studies taken together reveal much about the manner in which the visual system detects and identifies forms, targets, and objects in cluttered and uncluttered backgrounds, how the visual system responds to their movement, how movement can degrade the quality of the images of targets or objects, and how forms or objects retain their overall identity (perceptual or object constancy) despite changes in their internal make-up or local structure. Each of the four types of displays and the unique approach with which they are associated can easily be exploited in further experiments designed to understand visual processing of dynamic displays.

Sustained-transient model of visual information processing

There is considerable neurophysiological and psychophysical evidence which demonstrates the existence of separate sustained and transient neurons or channels in mammalian visual systems. In humans sustained channels have been shown psychophysically to behave like intermediate-bandpass spatial filters and low-pass temporal filters. One characterization of sustained channels that has proved successful in describing the results of experiments with static imagery is the Fourier-analyzer model (Pantle, 1974). Transient channels have been shown psychophysically to behave more like low-pass spatial filters and intermediate-bandpass temporal filters. The temporal frequency response characteristics of the transient channels were explored in depth by Pantle (1975, 1978).

The sustained-transient model of visual information processing (Kulikowski and Tolhurst, 1973; Breitmeyer and Ganz, 1976) is used as the framework for the conduct and interpretation of the experiments described in this report. In the first part of the report which deals with sine-wave grating experiments, we have attempted (1) to determine whether the sustained-transient model can predict and provide an account of the simultaneous masking of targets by both steady and flickering backgrounds, (2) to determine whether the spatiotemporal properties of both sustained and transient channels change during dark adaptation, and (3) to determine whether there is spatial interaction at a distance between sustained and transient channels. In the second part of the report which deals with experiments in which dynamic line-element and point displays are used, we have attempted (1) to determine whether competition between sustained and transient channels can account for the alternate perceptual organizations of a bistable motion display (Pantle and Picciano, 1976), (2) to determine whether temporally extended processing of high spatial frequency information by sustained channels can serve as the first stage in the emergence of global characteristics of objects, and (3) to determine the adequacy of the sustained-transient model for explaining dynamic texture processing.

SIMULTANEOUS SINE-WAVE MASKING

In an earlier report Pantle (1974) summarized the results of experiments in which he measured contrast detection thresholds for sine-wave grating targets superimposed on sine-wave backgrounds. The backgrounds were steadily presented and the targets were superimposed on the background for 1.7 sec. Because the background and target were steady, the masking effects reported by Pantle were probably due to visual interactions in sustained channels. In order to have a broader framework for understanding sine-wave masking effects in transient as well as sustained channels, we repeated and extended the original masking experiments using flickering and steady backgrounds. A discussion of the purpose of each experiment accompanies the description of its specific method and results. A consideration of the specific experiments follows the presentation of the general method and procedures used in all the masking experiments.

General methods

The stimulus gratings were generated on the face of Tektronix 5103 oscilloscope with a P31 (green phosphor). The general technique described by Pantle (1973) was used to produce the patterns. In each condition of each experiment the stimulus patterns were two sinusoidal gratings. One of the gratings served as the background upon which the second target grating was superimposed (added algebraically) at predetermined intervals by a timing circuit. The contrast (modulation amplitude) and spatial frequency of the background grating could be varied without affecting the characteristics of the test grating or the space-average luminance of the display. Similarly, the contrast and spatial frequency of the target grating could be varied independently. In order to minimize the local retinal adaptation produced by the background grating, it was made to drift continuously across the retina at a very slow rate (.005°/sec). When the target grating was presented, it drifted at the same speed as the background and remained phase-locked to it. The relative phase of the target and background gratings was set so as to maximize the peak-to-trough difference of the complex waveform formed by the superimposed gratings. The space-average luminance of the pattern was 2.5 mL. The patterns were viewed through a rectangular hole in a cardboard screen. They subtended a visual angle of 3°40' horizontally and 3°08' vertically. The hue of the cardboard screen approximately matched that of the patterns; its luminance was 1.5 mL; and it subtended a visual angle of 9°00' horizontally and 7°25' vertically. Subjects viewed the display binocularly from a distance of 137 cm. They fixated a small black spot in the center of the display. No artificial pupils were used.

General procedure

In each experimental session a temporal, force-choice staircase procedure was used to determine a subject's contrast threshold for the target grating superimposed upon the sinusoidal background. The contrast threshold provided a quantitative measure of the target's visibility. Each session began with the subject inspecting a background grating of a given spatial frequency and contrast. The initial inspection period lasted for 3 min. Thereafter the background remained on, and on the average an experimenter initiated a test trial every 12 sec. Each test trial consisted of two intervals separated by a period of 3 sec. Each interval was accompanied by an auditory tone, and the target grating was superimposed on the background grating during one of the test intervals according to a random schedule. The remaining interval contained only the background grating. The subject attempted to identify the interval which contained the test target.

A staircase (threshold tracking series) was started with the target contrast set well above the subject's threshold. Then it was increased or decreased depending upon the correctness of the subject's response on each forced-choice trial. If the subject's response was correct on three successive trials, the contrast of the target was reduced by a step for the next trial. If the subject's response was incorrect, the contrast was increased by a step. For thresholds below 1 percent we used a step size of 0.13 percent contrast up until the first reversal in the direction of contrast change over a series of trials. After the first reversal, the step size was 0.06 percent; after the third reversal, 0.03 percent. For thresholds above 1 percent, all the step sizes were doubled. In all conditions the staircase was terminated at the fourth reversal, and the contrast value at that time defined the subject's threshold.

Generally, three thresholds were obtained per session. If more than one background contrast was used per session, backgrounds of higher contrast were always used after those of lower contrast. Each new background contrast was inspected for 3 min before threshold measurements were begun. Only one target and background spatial frequency were used in a single session.

<u>Experiment A: Effects of a steady background on intermediate spatial frequency targets</u>

In Pantle's (1974) original sine-wave masking experiments, a target grating was steadily presented for 1.7 sec on a steady background, and the masking effects obtained were attributed to visual interactions in sustained channels. However, because the target had a rapid temporal onset and offset, it is possible that transient channels made some contribution to the detection of the target, especially when the target had a low spatial frequency. If so, the masking effect of the background may have been less than maximal, and the magnitude of the interactions in sustained channels may have been underestimated. For this reason, we repeated and extended the original masking experiments by using targets with gradual onsets and offsets as well as abrupt onsets and offsets. If transient channels had contributed to the detection of the target in the original experiments, then the function which relates target contrast threshold to background contrast would be expected to be steeper using gradual onset-offset targets, i.e., with the possibility of a contribution from transient channels essentially eliminated. We also extended the original experiments by using a flickering target grating in order to maximize the contribution of transient channels. Under these circumstances we expected the masking effect of a steady background to be minimal, and the function which relates target contrast threshold to background contrast to be very shallow.

Method and results. In Experiment A we measured the contrast detection threshold for a 2-c/deg grating (target) superimposed upon a 6-c/deg background. Three trained psychophysical observers served as subjects in the experiment, and the data obtained with each of the subjects (AJP, KIH, and SIK) are given in Figures 1-3, respectively. In each figure, each curve represents the forced-choice contrast threshold

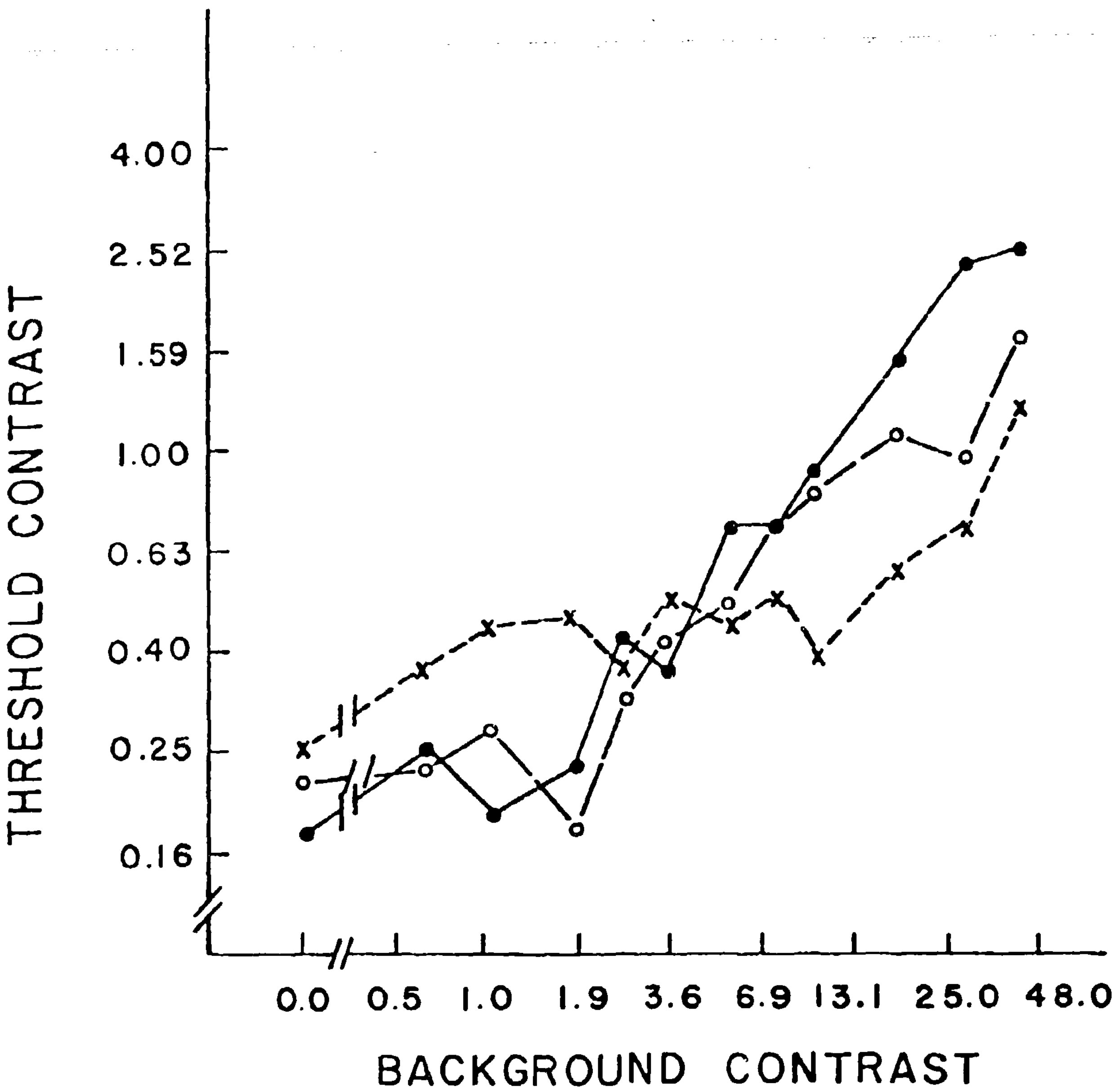


Fig. 1. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject AJP.

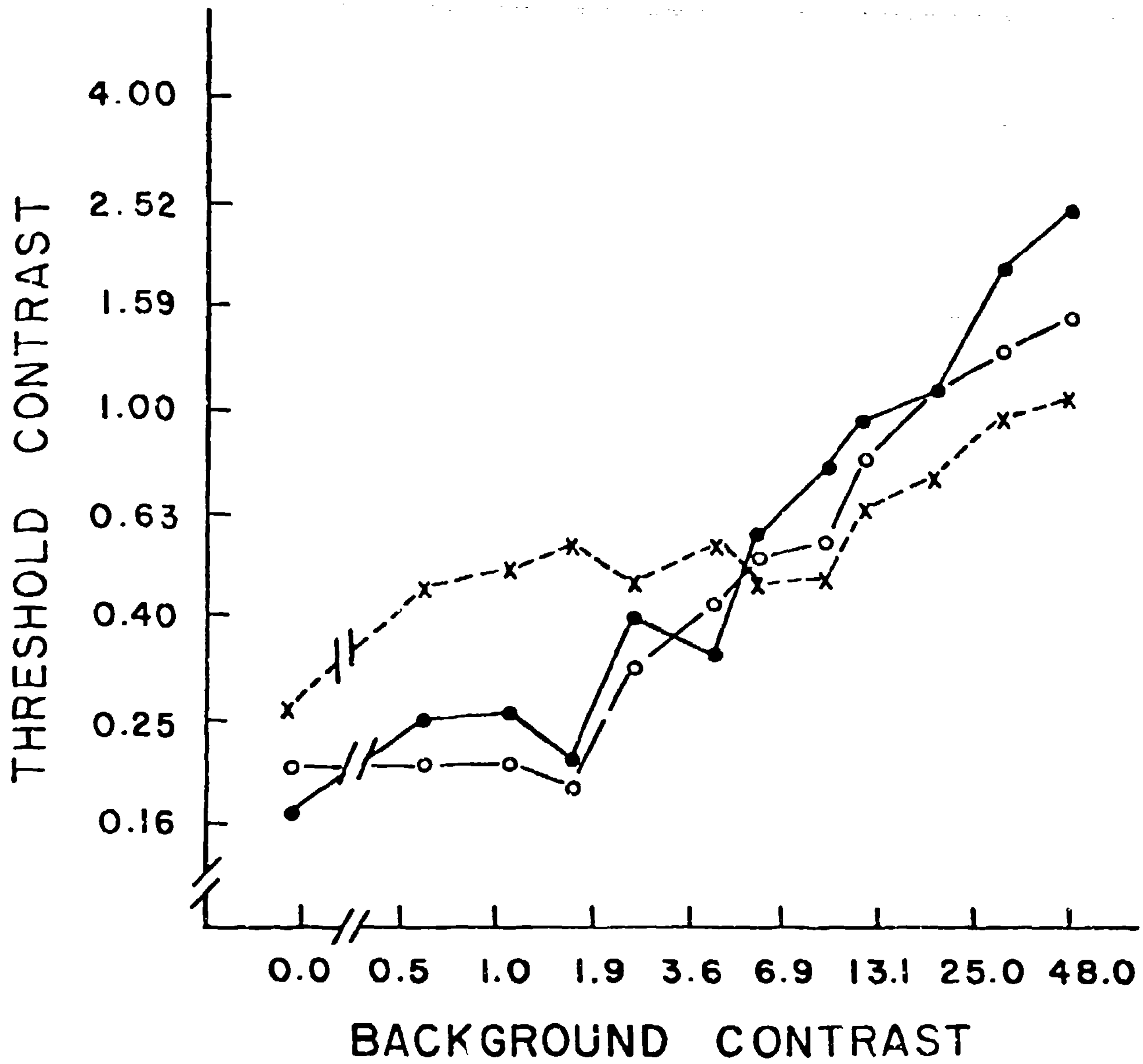


Fig. 2. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject KIH.

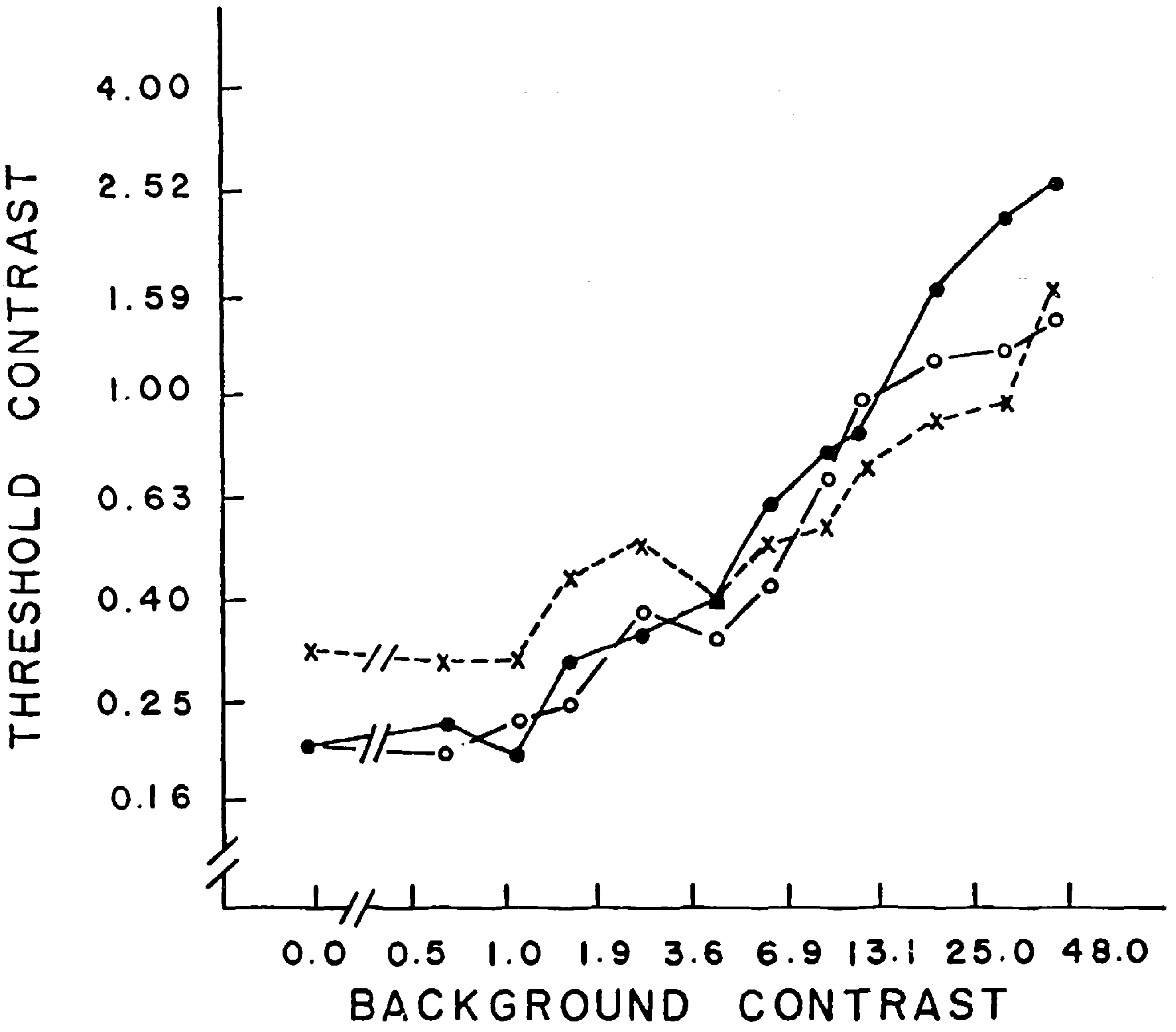


Fig. 3. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject SIK.

(ordinate) for one of three types of test targets as a function of the contrast of the background grating (abscissa). The three types of test targets were defined by their temporal characteristics. (1) In one case, when the target grating was presented in one of the intervals of a test trial, it was steadily presented and had a gradual onset and offset. That is, its contrast increased linearly over 0.25 sec from zero to the value chosen for the trial, remained at the chosen level for 1.75 sec, and then decreased linearly to zero over the next 0.25 sec. Hereafter, thresholds obtained with these temporal parameters are called GS thresholds (G for gradual onset-offset, and S for steady presentation). (2) In another case, the target grating was steadily presented, but had an abrupt onset and offset. The contrast remained at the value chosen for the trial for 2 sec, but unlike the first case, the contrast reached the chosen level virtually instantaneously and decayed back to zero virtually instantaneously. Hereafter, these thresholds are called AS thresholds (A for abrupt onset-offset, and S for steady presentation). (3) In the remaining case, the target grating was temporally modulated at 0.5 Hz. Square-wave modulation was used. The modulated signal was ramped on and off as in the first case above. Hereafter, these thresholds are called GF thresholds (G for gradual onset-offset, and F for flicker presentation). Each data point is based on one staircase, with the exception of a few data points which are geometric means of two staircases. The leftmost data point in each figure is the contrast threshold for the test target on a zero-contrast background, i.e., on a uniform background. Hereafter, this value will be called the unmasked threshold.

An inspection of Figures 1-3 reveals that the data for all three subjects are similar in all important respects. For this reason further discussion of the results of Experiment A is based on the average threshold data shown in Figure 4. Each data point in Figure 4 is the geometric mean of the contrast thresholds of the individual subjects.

As can be seen in Figure 4, the contrast threshold for an AS target (open circles) remained unchanged over a small range of low background contrasts, i.e., over background contrasts ranging from zero to 1.6 percent. With increases of background contrast beyond 1.6 percent, the AS threshold rose steadily. The increase of the AS threshold in the region of high background contrasts is approximately linear in the log-log plot of Figure 4, and this means that the AS threshold is a power function of background masking contrast. The exponent of the power function, estimated from a best-fitting straight line (method of least squares), is 0.62. The behavior of the AS thresholds is essentially identical to that observed by Pantle in an earlier report (1974).

A number of different comparisons among the three threshold functions are important theoretically:

(1) The GS threshold function (solid circles) has almost the same shape as the AS threshold function, and it is only slightly higher (0.1 log unit) on the average at high background contrasts. It can be concluded that the rapid temporal transients associated with the abrupt onset and offset of the AS target were not large enough to permit the AS target to escape to any significant extent the masking produced by the steady background. The contribution of transient channels to the detection of AS targets was presumably minimal or nonexistent. Therefore, it would appear that at threshold the visual interactions between target and

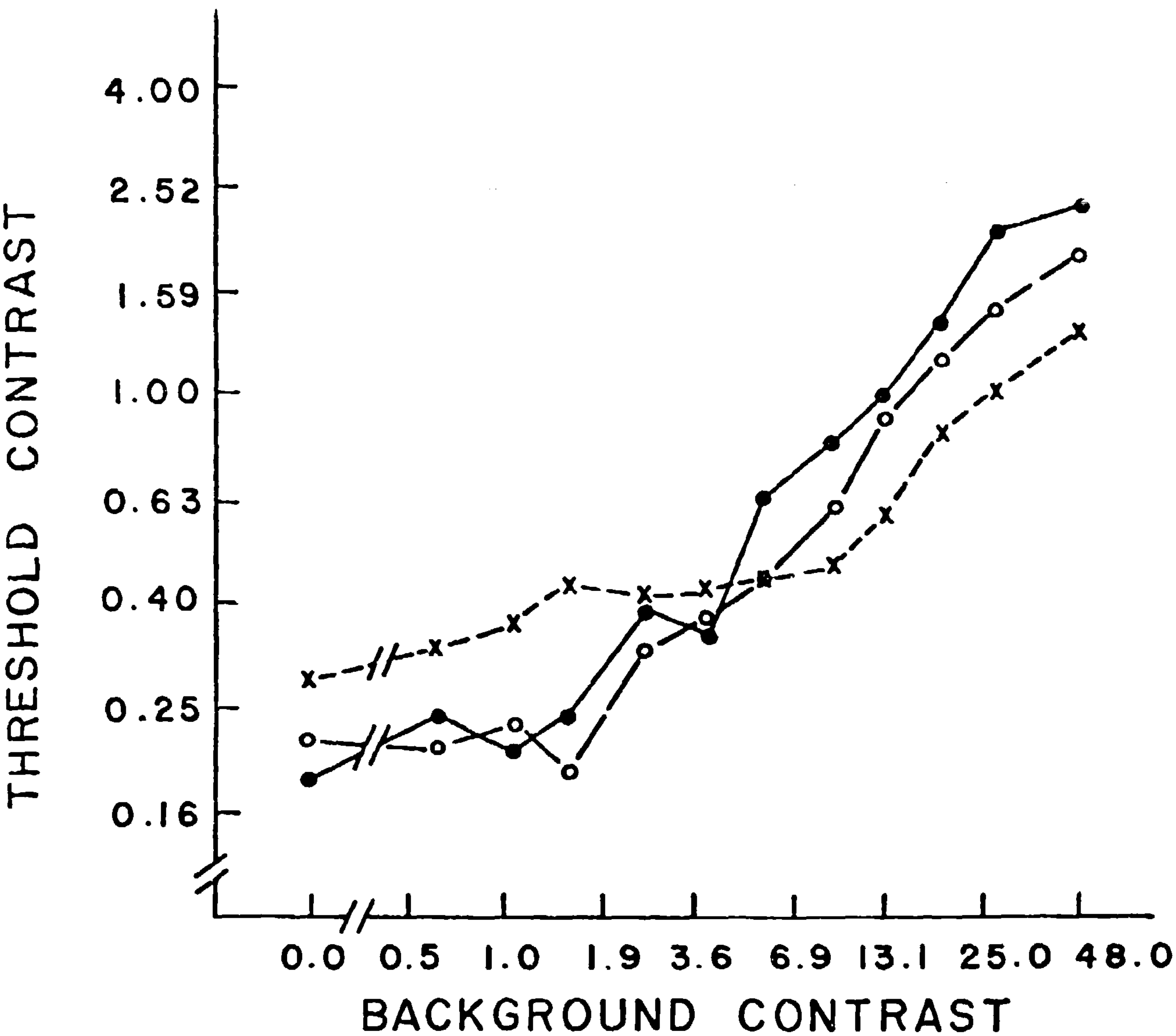


Fig. 4. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Average data.

background can be attributed entirely to sustained channels when GS or AS targets are employed. Consistent with this interpretation is the fact that all the subjects perceived the GS grating and the AS grating as a gradual change in the spatial structure of whatever steady background was present.

(2) The masking effect of the steady background on the flickering target grating was smaller than its effect on the steady gratings. This is easily seen in Figure 4 where the GF threshold function (X's) rises at a slower rate than the other threshold functions. Moreover, the GF threshold was higher than the GF and AS thresholds at low background contrasts, but it was lower than the other thresholds at high background contrasts. The GF function crosses over the other two threshold functions at a background contrast of approximately 5 percent. The behavior of the GF threshold in relation to the GS and AS thresholds is consistent with the idea that the GF threshold switched from a dependence on sustained channels at low background contrasts ($<$ 5 percent) to a dependence on transient channels at high background contrasts ($>$ 5 percent).

Because sustained channels have a low-pass temporal frequency response, time-average contrast is a critical determinant of their response. The time-average contrast of the GS and AS gratings which remained on during an entire test interval would have been twice as great as that of the GF grating which was present during half of a test interval and absent the other half (5-Hz square-wave modulation). If sustained channels mediated the detection of the GF and the steady targets at low background contrasts, then the GF thresholds would have been expected to be higher than the steady target thresholds. Consistent with this interpretation is the fact that GF gratings appeared subjectively steady at threshold. Their flicker was not visible, and it was not possible for a subject to know whether he was seeing a GF or a steady grating.

If the GF grating were mediated by sustained channels at high background contrasts as well as at low background contrasts, then the masking effect of the steady background on the GF target should have been as great as it was on the steady targets. It wasn't. Presumably, the increasing amounts of noise produced in sustained channels by higher background contrasts had less of an effect on the GF grating than on the steady gratings because the detection of the GF grating was taken over by transient channels as the sustained channels were rendered insensitive by noise. That such a changeover took place is supported by the fact that the GF grating at threshold was perceived as a flicker or "twinkling" either of or through the high contrast background. Very little or no change of spatial structure due to the GF grating was apparent during a test trial. No corresponding changeover in the channels responsible for the detection of the steady gratings took place, presumably because their temporal characteristics were not appropriate for stimulating transient channels. In the next sine-wave masking experiment we employed a flickering background grating to further test hypotheses about the role of sustained and transient channels in the detection of grating targets.

Experiment B: Effects of a flickering background on intermediate spatial frequency targets

Experiment B was of exactly the same type as Experiment A with the exception that the background masking grating was flickered on and off instead of being steadily presented. Compared with the steady background, the flickering background would be expected to produce relatively more noise in transient channels and relatively less noise in sustained channels. Because sustained and transient channels make differential contributions to the grating targets we employed, the pattern of masking effects obtained with a flickering background ought to be qualitatively and quantitatively different from that obtained with the steady background in Experiment A.

Method and results. The specific methods and procedures used in Experiment B were identical to those of Experiment A with one exception. The background masking grating was flickered on and off at a rate of 0.5 Hz as it drifted across the display screen at the very slow rate of 0.005^{o}/sec. Square-wave modulation was used. When the GF target was superimposed on the background grating, it flickered in phase with the background.

The results obtained with the three trained subjects (AJP, KIH, and SIK) are presented in Figures 5-7, respectively. The format of the figures is the same as that used for the results of Experiment A. Because the data for the individual subjects were similar in all important respects, their data were averaged. Each data point in Figure 8 is the geometric mean of the contrast thresholds of the individual subjects.

As can be seen in Figure 8, the GS and AS threshold functions are very similar. Both functions are essentially flat over the range of background contrasts ranging from zero to 5 percent. For background contrasts in excess of 5 percent, the GS and AS thresholds were directly related to background contrast. Although the shapes of the GS and AS threshold functions of Experiment B are qualitatively the same as the

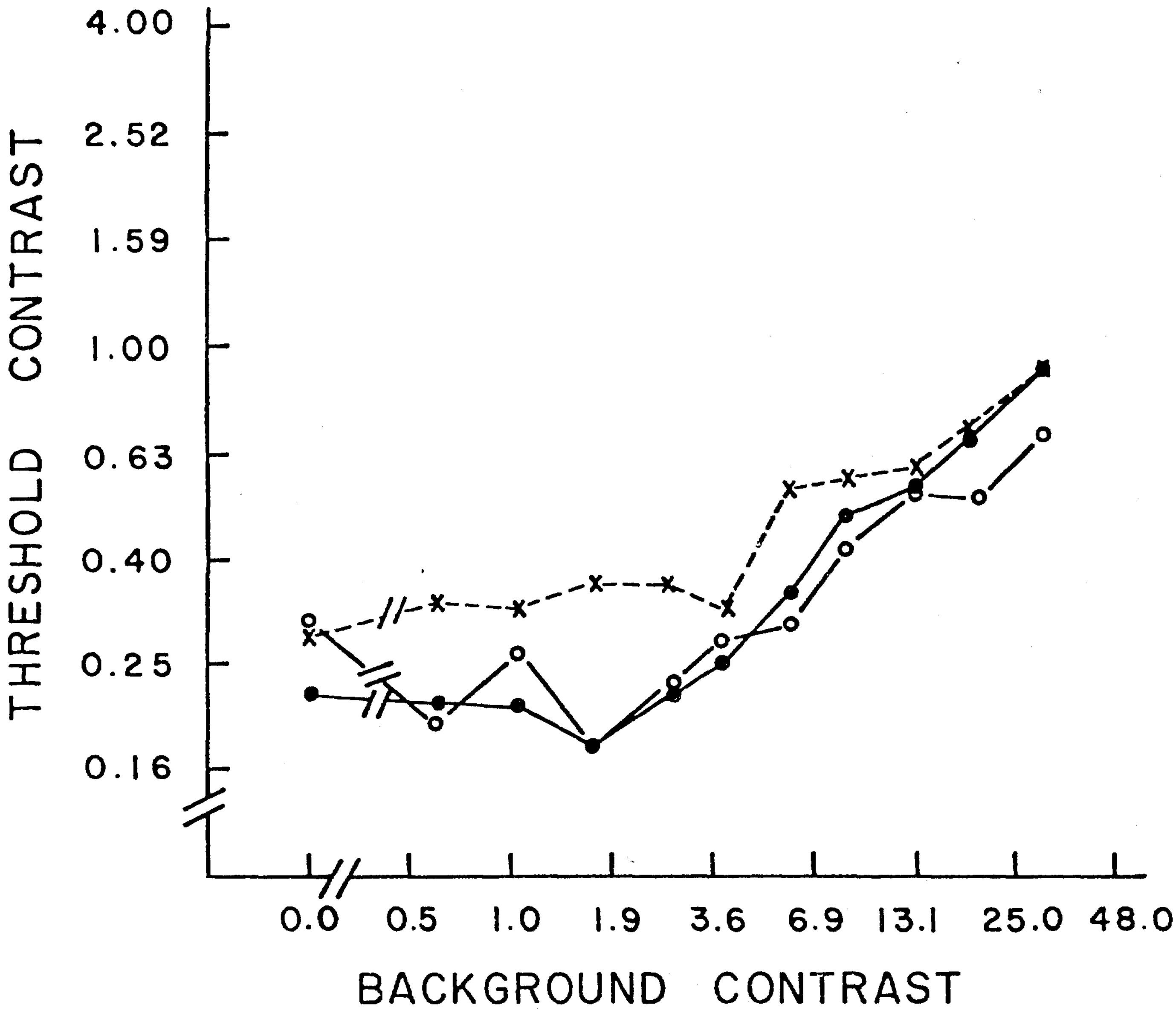


Fig. 5. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, flickering sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject AJP.

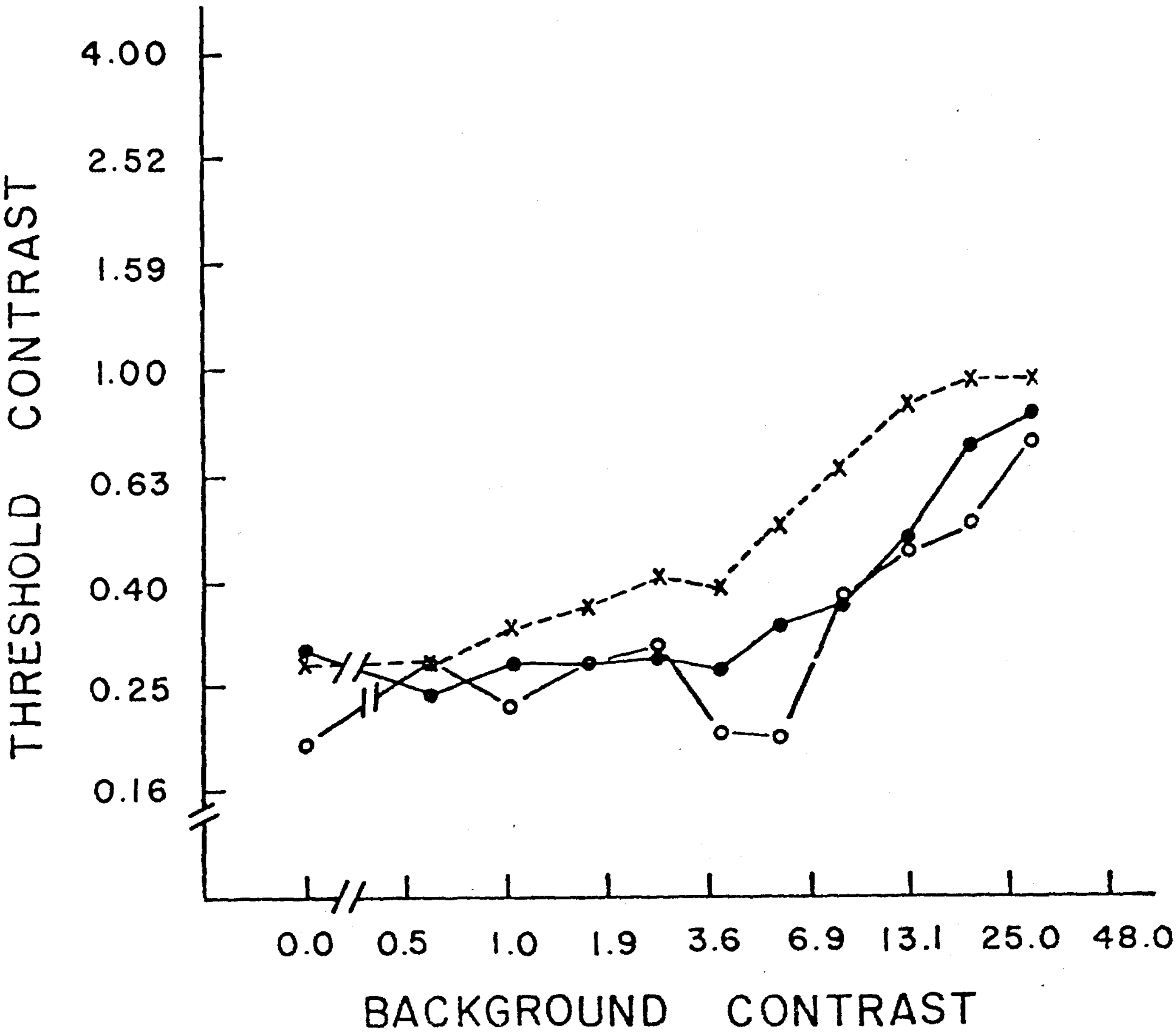


Fig. 6. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, flickering sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject KIH.

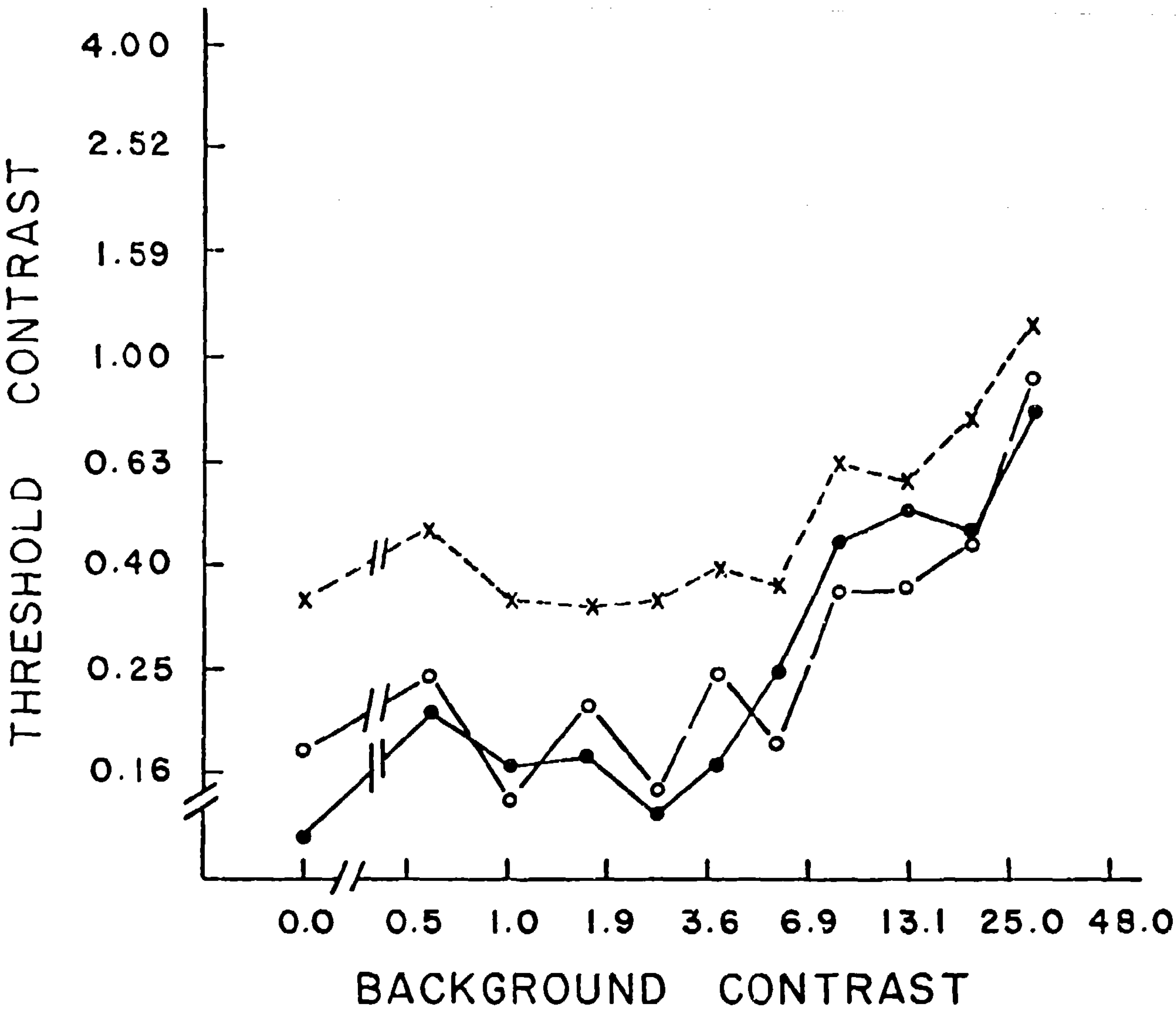


Fig. 7. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, flickering sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Subject SIK.

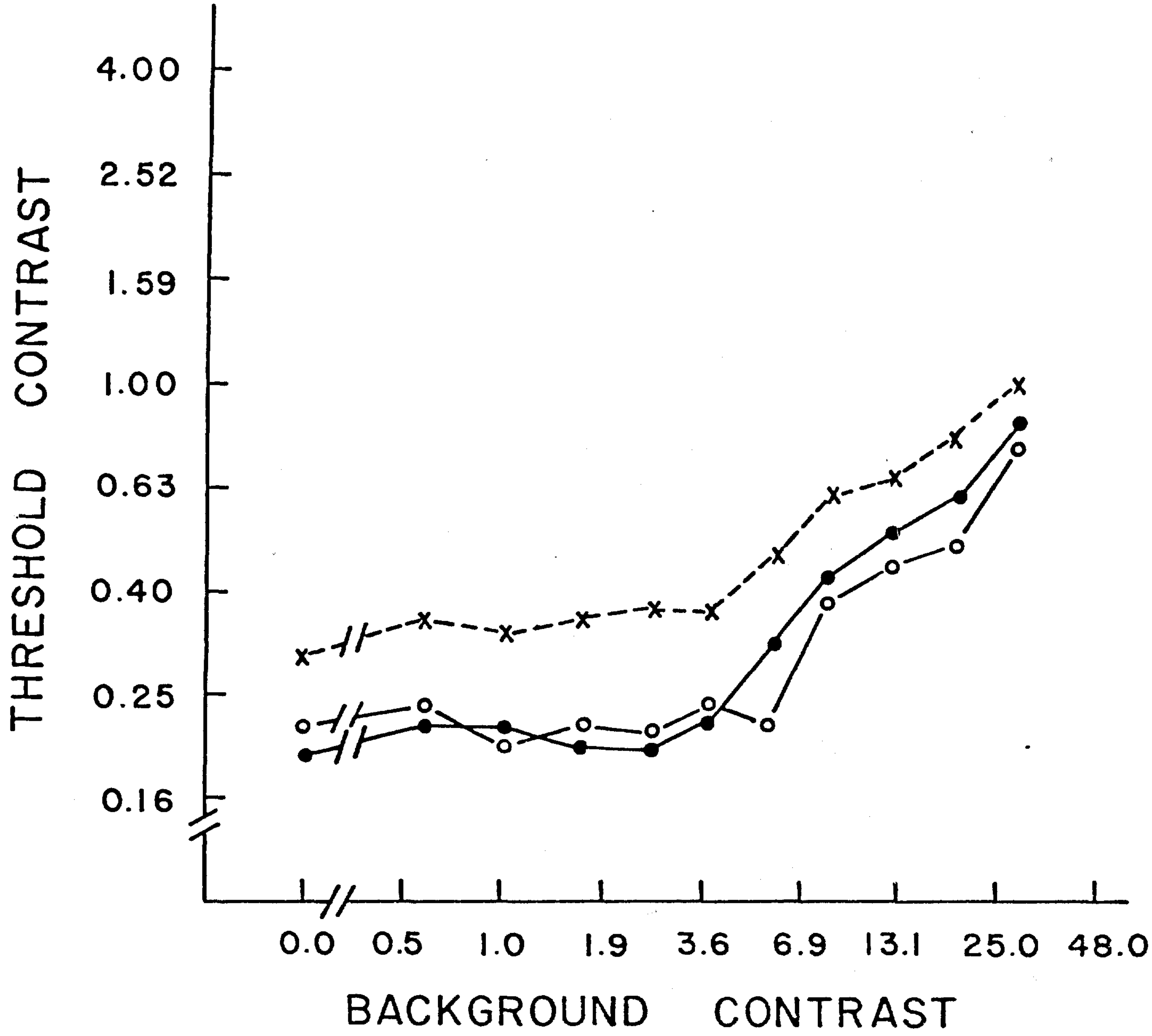


Fig. 8. Contrast threshold for a 2-c/deg sine-wave target superimposed upon a 6-c/deg, flickering sine-wave background. Solid circles: gradual onset-offset, steadily presented target; open circles: abrupt onset-offset, steadily presented target; and X's: gradual onset-offset, flickering target. Average data.

corresponding functions in Experiment A, they are quantitatively different. With the steady background of Experiment A, the GS and AS thresholds began to rise above the unmasked threshold sooner (at a background contrast of 1.6 percent), and at a background contrast of 25 percent the GS and AS thresholds of Experiment A were approximately double the corresponding thresholds of Experiment B. In both respects the masking effect of the flickering background of Experiment B on the steady targets was significantly smaller than the effects of the steady background of Experiment A. One explanation of the reduced masking effectiveness of the flickering background is that sustained channels were simply less sensitive to the flickering background than to the steady background by virtue of their low-pass temporal frequency response. As a consequence, the steady background would have produced less noise in the sustained channels responsible for the detection of the steady targets.

Unlike the GF thresholds in Experiment A, the GF thresholds in Experiment B were higher than the thresholds for the steady targets even at high background contrasts. Moreover, the flicker of the GF grating was not visible at any background contrast. The findings are consistent with the idea that sustained channels mediated the GF threshold at all background contrasts. Unlike the steady background of Experiment A, the flickering background apparently produced enough noise in transient channels to prevent them from taking over the detection of the GF target at high background contrasts.

If, indeed, the detection of the GF grating in Experiment B were mediated by sustained channels at all levels of background contrast, then it should not matter whether the GF target was temporally in phase or out of phase with the background. Detection performance by means of sustained channels would be based upon a more or less time-averaged response to the target added to a time-averaged response to the flickering background. Because sustained channels do not preserve information about the temporal modulation of the target or background, it would not matter whether the stimuli which signalled their presence were in or out of phase. A different outcome might be expected if the GF target were mediated by transient channels. In this case the temporal modulation of the target and background would not be an aspect of the stimulus which was flitered out, but rather an aspect which was critical for the occurrence of a response. As a consequence, it would matter whether the target and background were temporally in or out of phase.

The thresholds for the in-phase GF grating in Figure 8 (X's) have been replotted in Figure 9 (X's) along with the thresholds for an out-of-phase GF grating (squares). The in-phase and out-of-phase thresholds are identical for the entire range of background contrasts studied. The finding corroborates the earlier conclusion that the detection of the GF target was mediated by sustained channels when it was superimposed upon a flickering background.

The results of the first two sine-wave masking experiments are consistent with a sustained-transient channels model. Two more experiments, with a target and a background of lower spatial frequency, were conducted to test the generalizability of the sustained-transient hypothesis in accounting for sine-wave masking results.

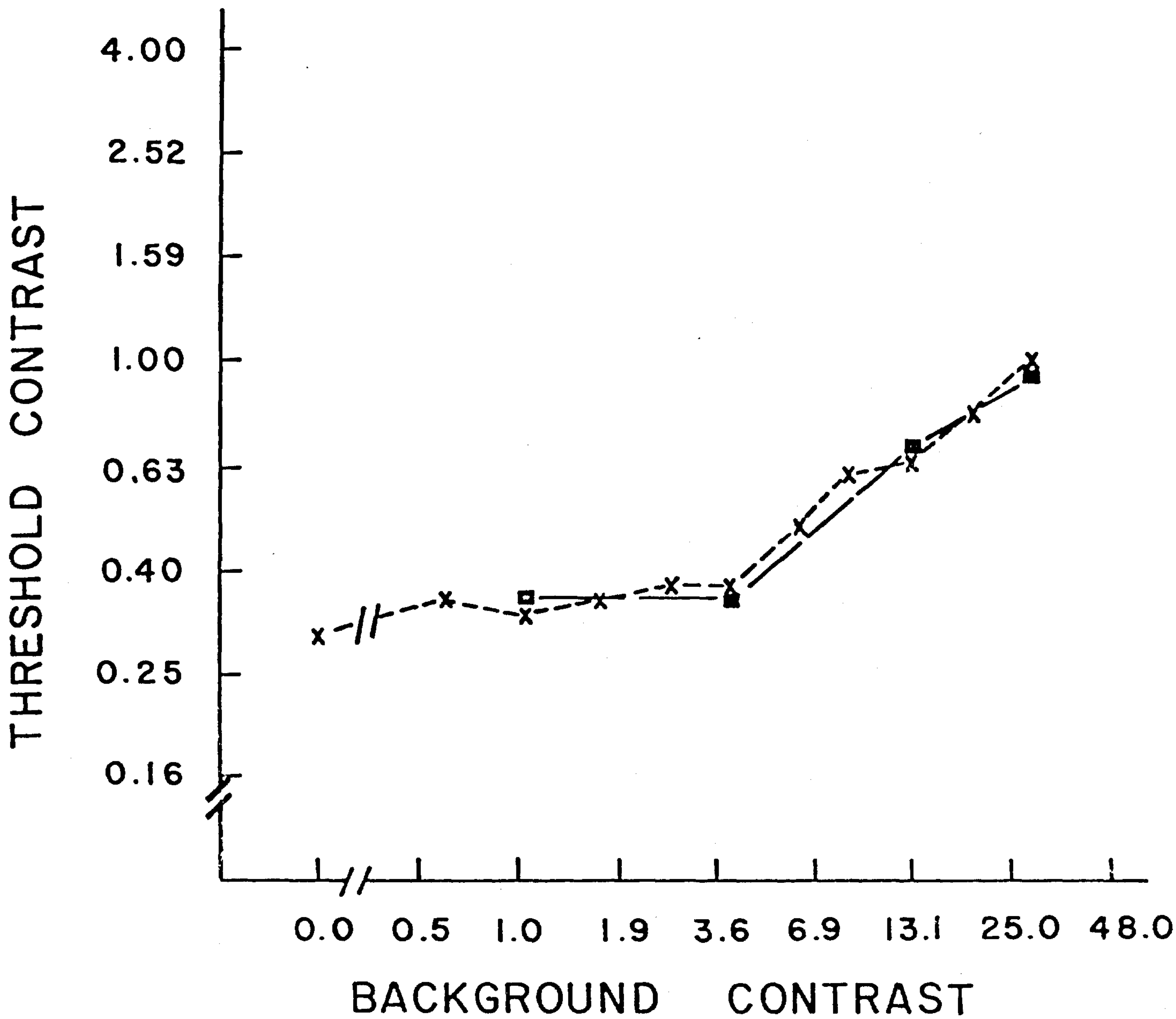


Fig. 9. Contrast threshold for a 2-c/deg, flickering target superimposed upon a 6-c/deg, flickering background. X's: in-phase condition; squares: out-of-phase condition. Average data.

Experiment C: Effects of a steady background on low spatial frequency targets

In the first two sine-wave masking experiments we measured the effects of a steady and a flickering background on the visibility of a 2-c/deg sine-wave target. With a zero-contrast background, the 2-c/deg target was more visible when it was steady than when it was flickering. Presumably, the spatial frequency of 2 c/deg favored sustained channels over transient channels, and sustained channels are more sensitive to steady than to flickering stimuli. In the next two experiments we investigated the effects of a steady and a flickering background on the visibility of a 0.6-c/deg sine-wave target. With no background present, the 0.6-c/deg target was more visible when it is flickering than when it was steady. The low spatial frequency presumably favors transient channels which are more sensitive to flickering than to steady stimuli.

Method and results. The specific methods and procedures used in Experiment C were identical to those of Experiment A with the following exceptions. The spatial frequency of the target grating was 0.6 c/deg, and the spatial frequency of the background masking grating was 1.8 c/deg. Even though the absolute spatial frequencies of the target and background were changed, their ratio remained the same--1:3. The viewing distance was 68 cm, half that in Experiment A. As a consequence, all the display dimensions were approximately twice as large as in Experiment A. Because the AS and GS thresholds in the first two experiments were always almost identical, and any small difference between them was not of any significant theoretical interest, only GS and GF thresholds were measured in Experiment C.

The results of two experienced psychophysical observers (AJP and KIH) were essentially identical, and they are shown in Figures 10 and 11, respectively. The format for presenting the data is the same as in previous figures. In each figure the upper curve (circles) is the data obtained with the GS grating; the lower curve (X's), the data obtained with the GF grating. There are two important aspects of the results. First, unlike the results with the 2-c/deg target, the GF threshold is lower than the GS threshold at low background contrasts (< 1.9 percent). This finding is consistent with past research and has been taken as evidence that transient channels are more sensitive than sustained channels at 0.6 c/deg. Second, the threshold for the 0.5-Hz target grating remained below that for GS grating, and climbed at a slower rate as the background masking contrast was raised. At a background contrast of 25 percent, the GF threshold was only 1.5-2 times its unmasked threshold, while the GS threshold was 4-5 times its unmasked threshold. Presumably, the 1.8-c/deg steady masking grating affected the transient channels responsible for the detection of the GF grating much less than it affected the sustained channels reponsible for the detection of the GS grating. In agreement with these conclusions is the fact that the flicker, but not the spatial structure, of the GF grating was visible at all levels of background contrast whereas the rev: .e was true for the steady test grating. In the last sine-wave masking experiment we repeated Experiment C except that the background was temporally modulated.

Experiment D: Effects o' a flickering background on low spatial frequency targets

Experiment D was the same as Experiment C with the exception that the background masking grating was flickered on and off instead of being

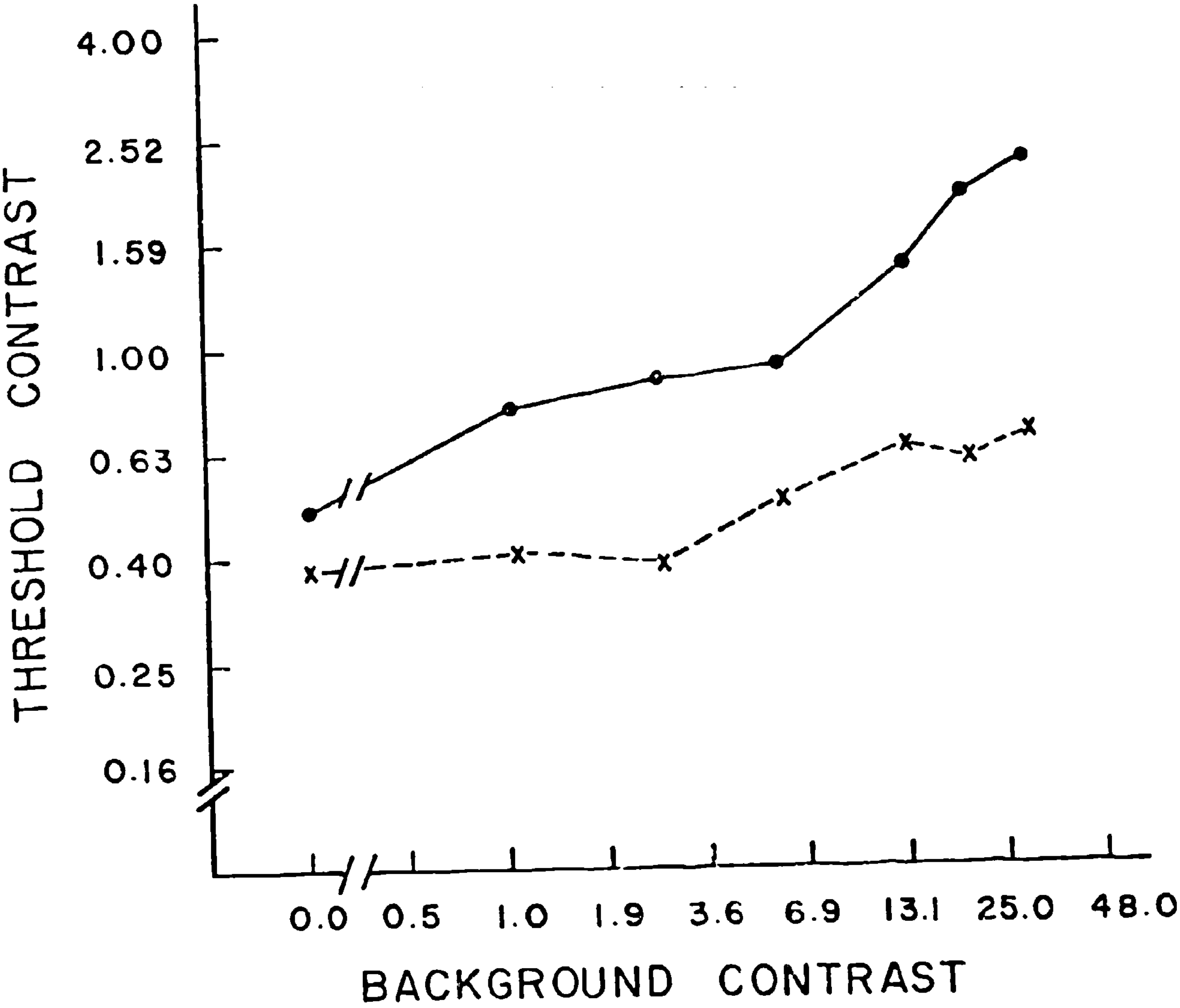


Fig. 10. Contrast threshold for a 0.6-c/deg sine-wave target superimposed upon a 1.8-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; X's: gradual onset-offset, flickering target. Subject AJP.

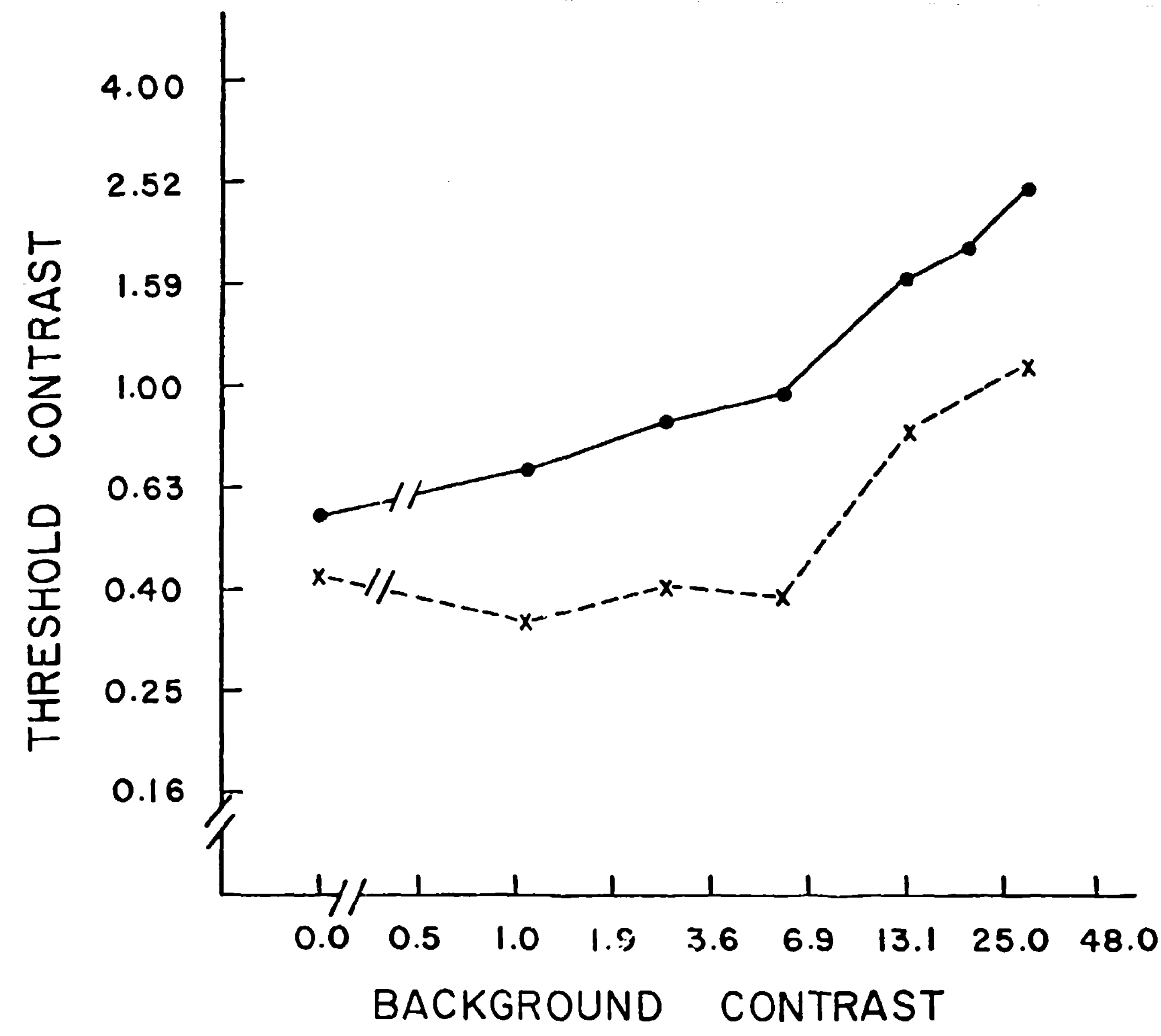


Fig. 11. Contrast threshold for a 0.6-c/deg sine-wave target superimposed upon a 1.8-c/deg, static sine-wave background. Solid circles: gradual onset-offset, steadily presented target; X's: gradual onset-offset, flickering target. Subject KIH.

steadily presented. Compared with the steady background, the flickering background would be expected to produce relatively more noise in transient channels and relatively less noise in sustained channels. As a consequence, the GF threshold, rather than remaining below the GS threshold at all background contrasts as it did in Experiment C, ought to approach or perhaps even exceed the GS threshold at high background contrasts.

Method and results. The specific methods and procedures used in Experiment D were identical to those of Experiment C with one exception. The background masking grating was flickered on and off at a rate of 0.5 Hz as it drifted across the display screen at the rate of 0.017°/sec. Square-wave modulation was used. When the GF target was superimposed on the background grating, it was flickered in phase with the background in some conditions and out of phase (180° phase shift) in other conditions.

The results for two subjects (AJP and KIH) were identical in all important aspects, and they are shown in Figures 12 and 13, respectively. Again, the format for presenting the data is the same as in previous figures.

In each figure the GS thresholds are represented by solid circles. The GS threshold increased as the contrast of the flickering background was increased, gradually at first and then more quickly as the background contrast exceeded about 3.6 percent. The GS threshold ranged from an unmasked value of about 0.4-0.5 percent to a high of about 2.5 percent for a background contrast of 17-25 percent. The five-fold change, and even the absolute values of the GS threshold, are not much different from those obtained with a steady background in Experiment C. At all background contrasts, the spatial structure of the grating target was visible at

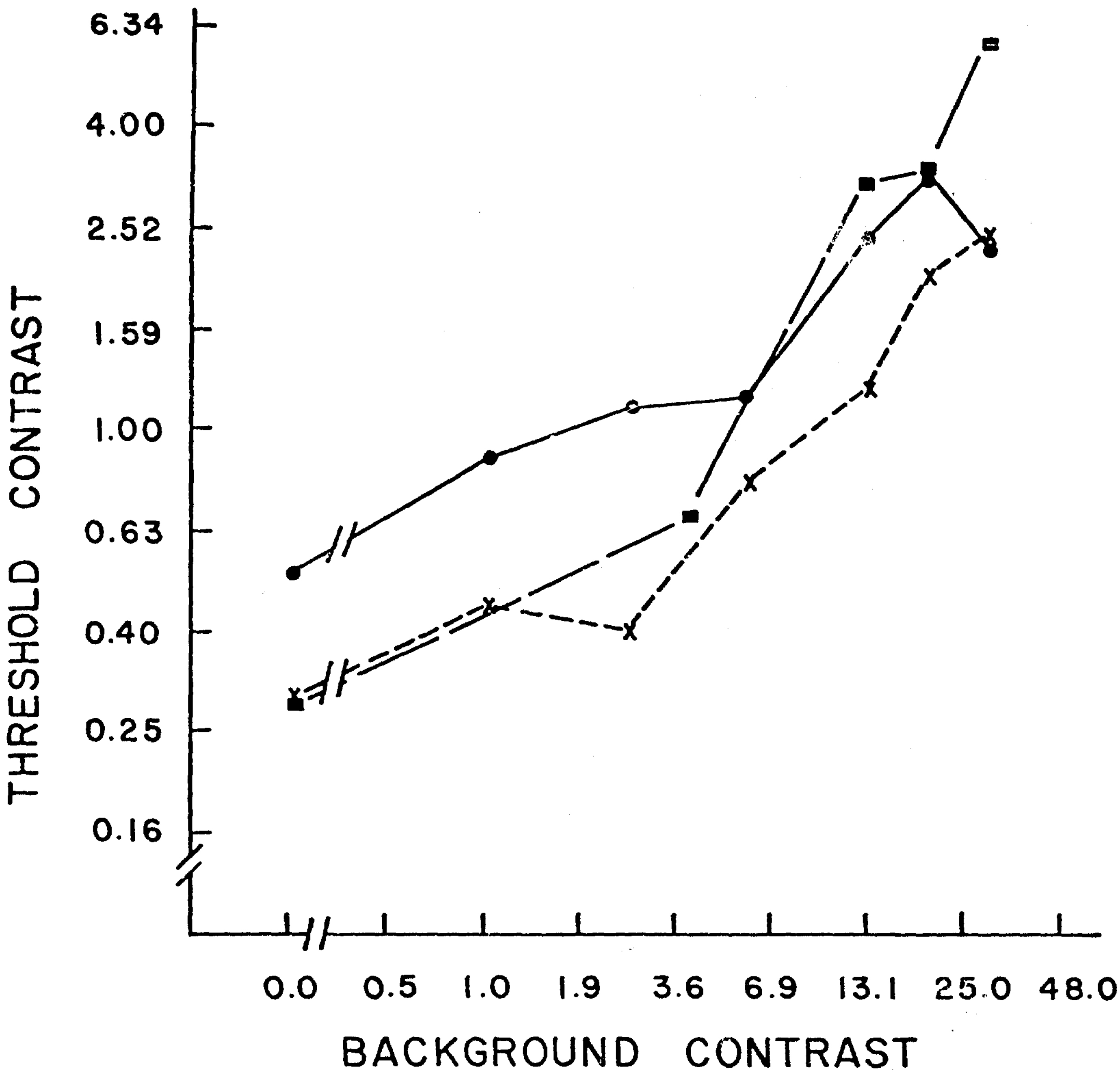


Fig. 12. Contrast threshold for a 0.6-c/deg sine-wave target superimposed upon a 1.8-c/deg, flickering background. Solid circles: gradual onset-offset, steadily presented target; X's: gradual onset-offset target flickering in phase with the background; and squares: gradual onset-offset target flickering out of phase (180°) with the background. Subject AJP.

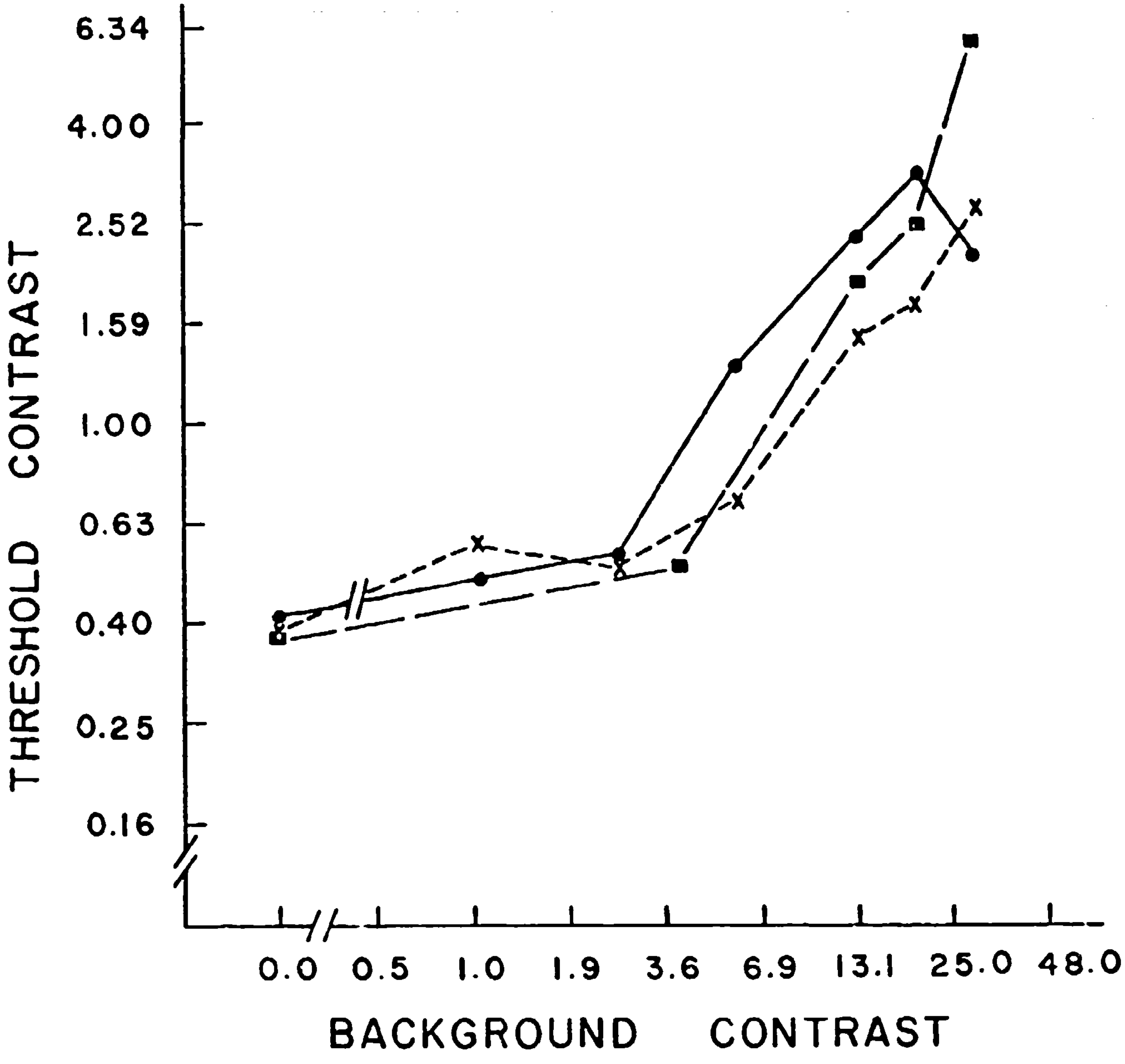


Fig. 13. Contrast threshold for a 0.6-c/deg sine-wave target superimposed upon a 1.8-c/deg, flickering background. Solid circles: gradual onset-offset, steadily presented target; X's: gradual onset-offset target flickering in phase with the background; and squares: gradual onset-offset target flickering out of phase (180°) with the background. Subject KIH.

threshold. The quantitative results and the threshold appearance of the target make it likely that sustained channels mediated the detection of the GS target, and that the observed changes in the GS threshold were due to noise produced in sustained channels by the flickering background.

The X's in each figure represent GF thresholds obtained with the target which was temporally in phase with the flickering background. The behavior of the in-phase GF threshold differs in two important respects from its behavior in Experiment C. First, it increased by a factor of 6-7 over the range of flickering background contrasts. With the steady background of Experiment C, it increased only by a factor of 2 over the same contrast range. Second, with a high contrast flickering background (25 percent), the GF threshold was equal to or greater than the GS threshold. With a steady background of the same contrast (25 percent in Experiment C), the GF threshold was a factor of 2-3 below the GS threshold. The relatively large effect of a flickering background, compared with a steady background, on the GF threshold is even more pronounced for the flickering target which was out of phase with the background (squares in Figures 12 and 13). For the out-of-phase target, the increase of the GF threshold was fourteen-fold over the range of background contrasts studied. At threshold, the GF target appeared as a cyclic pulsation of light intensity over a large part of the display. The depth of the pulsation or flicker produced by the out-of-phase target at threshold in the presence of a high contrast background appeared to be as great as that produced by other stimuli with a temporal modulation many times threshold. The changes of the GF threshold and the appearance of the GF target at threshold strongly suggest that transient channels mediated the detection of the GF target, and that the observed changes in the GF threshold were the result of noise produced in transient channels by the flickering background.

Our series of four sine-wave masking experiments fit remarkably well within the framework of a sustained-transient channels model of visual function. In the next section we attempted to examine differences in the spatiotemporal properties of sustained and transient channels at different levels of light-dark adaptation.

PATTERN AND MOTION THRESHOLDS: EFFECTS OF TEMPORAL FREQUENCY AND LIGHT-DARK ADAPTATION (EXPERIMENT E)

It has been known for some time that the spatial contrast sensitivity function shifts toward a greater sensitivity at lower spatial frequencies as stimulus duration is decreased (Nachmias, 1967), as temporal frequency is increased (Watanabe, 1968), or as the space-average luminance of the stimulus is decreased (Van Nes and Bouman, 1967). One possible interpretation of the shift is that it results from a changeover in the channels which mediate the detection of the stimulus, i.e. from mediation by sustained channels to mediation by transient channels which are relatively more sensitive at lower spatial frequencies. With this interpretation one need not postulate any changes in the functional characteristics of the sustained or transient channels themselves to account for the shift in spatial frequency sensitivity. A second interpretation of the shift is that it is due to a change in the functional properties of one or both of the two types of channels.

One way to decide between the two interpretations is to obtain spatial contrast sensitivity functions based upon two different threshold criteria: (1) one at which the movement or flicker of the stimulus is just visible (flicker threshold), and (2) another at which the spatial structure of the grating becomes distinct (pattern-recognition threshold). If the flicker thresholds represent activity in transient channels and the pattern-recognition thresholds represent activity in sustained channels as a number of researchers believe (e.g., Kulikowski and Tolhurst, 1973), then any change in the contrast sensitivity function based upon one of the criteria can be taken to mean that the functional properties of the respective underlying mechanism had changed. Therefore we examined the spatial contrast sensitivity function based upon each criterion for any changes which accompanied variations in the temporal frequency and space-average luminance of stimulus gratings.

Method

The subject's task was to adjust the contrast of a moving sinusoidal grating until either: (a) its bars were just detectable (pattern threshold), or (b) its temporal modulation or flicker was just detectable (flicker threshold).

The gratings were generated on the face of an oscilloscope (Tektronix 5103 with a P-31 phosphor) using analog equipment and signals. Three characteristics of the gratings were varied during the course of the experiment: temporal frequency, spatial frequency, and space-average luminance. The gratings were moved at one of three temporal frequencies--0.6, 5.0, or 10.0 Hz. In order to generate a sufficiently wide range of spatial frequencies, two different viewing distances had to be used--43.2 and 195.6 cm. At the short viewing distance the gratings subtended 10° vertically and $11^{\circ}45'$ horizontally, and they had a spatial frequency of 0.33, 0.67, 1.33 or 2.67 c/deg. The gratings subtended $2^{\circ}14'$ vertically and $2^{\circ}36'$ horizontally at the long viewing distance. At this distance gratings of 2.67, 5.33, and 10.67 c/deg were employed. The gratings were viewed through a rectangular hole in a cardboard surround, whose color approximately matched the scope face and whose luminance was one-half the space-average luminance of the grating.

The gratings had one of three different space-average luminances--5, 0.05, or 0.005 mL. The light levels were controlled with neutral density filters placed in a rigidly mounted viewing hood. Except for the grating and its surround, the room was dark. Essentially then, the luminance of the grating and surround determined the state of light-dark adaptation of the observer.

The two types of threshold (pattern and flicker) were obtained for every combination of spatial frequency, temporal frequency, and dark-adaptation state, i.e. for 63 different conditions.

For each of the 63 conditions, the two types of threshold were obtained using a tracking procedure (Method of Adjustment). Initially, the contrast of the grating was set at a random point well above or below that of the observer's threshold. The observer (using a servo-device) increased or decreased the contrast of the grating to "bracket" his threshold. A tracking series terminated when the observer was confident of his threshold judgment. Approximately 10 reversals in the direction in which the observer adjusted the contrast of the grating were ordinarily required to obtain a threshold estimate.

Three estimates of the pattern threshold contrast and the flicker threshold contrast were obtained in each of the 63 conditions for each of the three observers. During each experimental session, one pattern and one flicker threshold were obtained for two of the 21 different combinations of spatial frequency and space-average luminance at each of the three temporal frequencies. A minimum of 2 min elapsed between runs in the different conditions. Before each experimental session the subject dark-adapted for 15-20 min. If more than one space-average luminance was used in a session, additional adequate dark adaptation time was allowed between conditions. If more than one spatial frequency was presented in a session, a minimum of 5 min elapsed between different spatial frequency conditions.

The order in which the different conditions of spatial frequency and luminance were presented was counterbalanced across subjects. Three experienced psychophysical observers participated in the experiment. Two observers wore corrective lenses, and one had normal vision without optical correction.

Results

Consider first the results for the close viewing distance (spatial frequencies between 0.33 and 2.67 d/deg). They are summarized in Figures 14 and 15. In Figure 14 there are three spatial contrast sensitivity functions based upon pattern thresholds (solid circles), and three, based upon flicker thresholds (open circles). Each function is collapsed across the repeated measurements obtained for each observer, across observers, and across different temporal frequencies. Each of the three curves for each type of threshold represents the results for a different space-average luminance (level of light-dark adaptation). There are three important trends in the data. (1) Both the pattern and flicker functions shift upward as space-average luminance decreases, indicating an overall loss of both pattern and flicker sensitivity for greater degrees of dark adaptation. (2) Both the pattern and flicker functions rotate toward a more positive slope as space-average luminance decreases, indicating that sensitivity to low spatial frequencies (0.33 and 0.67 c/deg) gains relatively on sensitivity to high spatial frequencies for greater degrees of dark adaptation. The relative gain is greater for pattern than for flicker sensitivity. The results are consistent with the second hypothesis

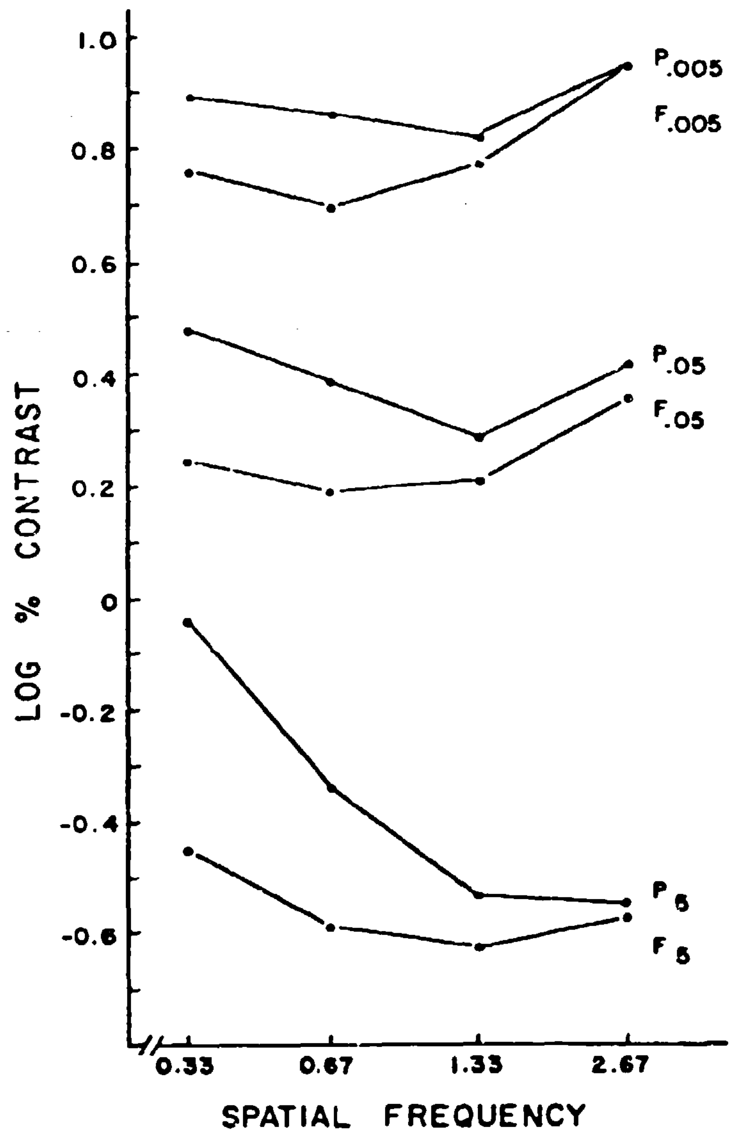


Fig. 14. Log pattern threshold (P--solid circles) and log flicker threshold (F--open circles) as a function of the spatial frequency of a sine-wave grating. Measurements made at three space-average luminances: 5, 0.05, and 0.005 mL.

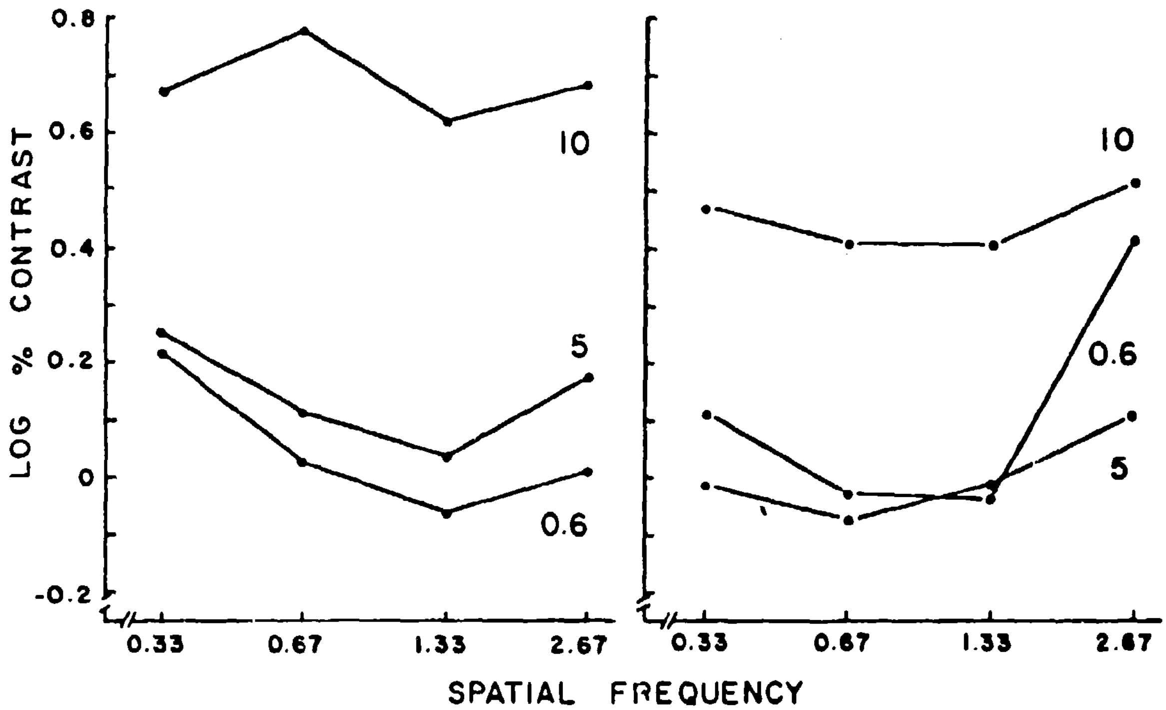


Fig. 15. Log pattern threshold (left panel) and log flicker threshold (right panel) as a function of the spatial frequency of a sine-wave grating. Measurements made for three different temporal frequencies: 0.6, 5, and 10 Hz.

discussed in the introduction to this study, namely that the functional properties of sustained and transient channels change with level of dark adaptation. (3) The difference between the pattern and flicker functions decreases as space-average luminance decreases. As noted before, both pattern and flicker sensitivity decrease as the light level is decreased, but pattern sensitivity changes less and therefore gains relatively on flicker sensitivity for greater degrees of dark adaptation. This result appears contrary to the first hypothesis discussed in the introduction to this study, namely that there is a changeover from sustained to transient channels as dark adaptation increases. There appears to be a tendency in the opposite direction.

In Figure 15 there are six spatial contrast sensitivity functions, three in the left panel (solid circles) based upon pattern thresholds and three in the right panel (open circles) based upon flicker thresholds. Each function is collapsed across repeated measurements obtained for each observer, across observers, and across different space-average luminances. Each of the three curves in each panel represents the results for a different temporal frequency. There are three important aspects of the data in Figure 15. (1) The pattern thresholds increased monotonically with temporal frequency (left panel of figure), whereas the flicker thresholds were at their lowest overall at 5 Hz and they were higher at 0.6 and 10 Hz (right panel of figure). The pattern thresholds have a low-pass temporal frequency characteristic, while the flicker thresholds have an intermediate band-pass, temporal frequency characteristic. (2) Overall, the flicker thresholds were lower than the pattern thresholds for temporal frequencies of 5 to 10 Hz, but at 0.6 Hz the pattern thresholds were close to the flicker thresholds, and even lower at the highest spatial frequency (2.67 c/deg). The properties of pattern and flicker thresholds discussed under (1) and (2) are consistent with those found by other researchers, and in general indicate that the putative sustained channels are most sensitive to high spatial frequencies and relatively insensitive to flicker, and that the transient channels are more sensitive to low spatial frequencies and to flicker. (3) Besides the relative changes between pattern and flicker thresholds which result from variations in temporal frequency, there were also changes <u>within</u> the sets of pattern and flicker thresholds <u>themselves</u> resulting from manipulation of temporal frequency. The low spatial frequency cutoff for the pattern threshold tends to disappear as temporal frequency is increased for 0.6 to 10 Hz, an effect similar to that produced by decreases in space-average luminance. The results are consistent with the second hypothesis discussed in the introduction, namely that the measured functional properties of sustained channels change with temporal frequency. Also, the flicker threshold functions do not remain constant in shape at the different temporal frequencies. The change in shape is most pronounced <u>across</u> the two highest spatial frequencies (1.33 and 2.67 c/deg) where the rate of increase of flicker thresholds was greatest for the lowest temporal frequency (0.6 Hz). The difference in the rate of change can be taken to mean that the relative insensitivity of the transient channel to high spatial frequencies is enhanced at the lowest temporal frequency, a fact which again testifies to the importance of considering changes in the description of the properties of transient and sustained channels <u>themselves</u> with spatiotemporal variations of stimulus parameters.

The results for the far viewing distance are summarized in Figures 16 and 17. The format for presenting the results is the same as that used in the figures for the close viewing distance. With the equipment available, it was impossible to measure thresholds for the 10.67 c/deg grating at the lowest space-average luminance (0.005 mL) because the thresholds often exceeded 25 percent. Therefore, the summary data given in Figures 16 and 17 include only threshold measurements made at space-average luminances of 5 and 0.05 mL. In terms of the goals set forth for the light-dark adaptation experiment, an examination of thresholds for high spatial frequency gratings would appear to be of less theoretical import than those for low spatial frequency gratings. Changes in the shape of the overall spatial contrast sensitivity function occur primarily in the low spatial frequency region, and it is in that region where relative changes in the pattern and flicker thresholds were most likely to be observed.

In Figure 16 there are two spatial contrast sensitivity functions based upon pattern thresholds (solid circles); and two based upon flicker thresholds (open circles). Each function is collapsed across the repeated measurements obtained for each observer, across observers, and across different temporal frequencies. There are two significant aspects of the data. (1) Sensitivity decreased by a log unit or more (the threshold functions shift upward) when the DC level of the display was reduced from 5 to 0.05 mL. (2) The decrease of both pattern and flicker sensitivity with spatial frequency was greater for a space-average luminance of 0.05 mL than it was for a space-average luminance of 5 mL. At 0.05 mL the dropoff in sensitivity was 0.4-0.5 log unit in the spatial

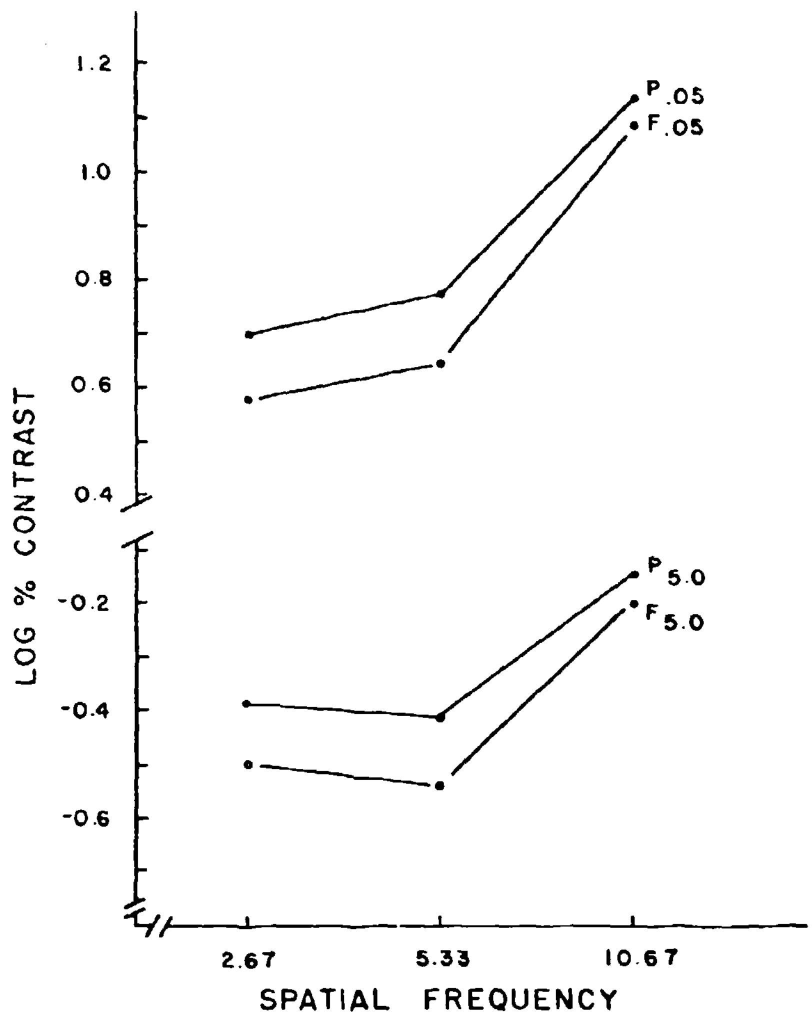


Fig. 16. Log pattern threshold (P--solid circles) and log flicker threshold (F--open circles) as a function of the spatial frequency of a sine-wave grating. Measurements made at two space-average luminances: 5 and 0.05 mL.

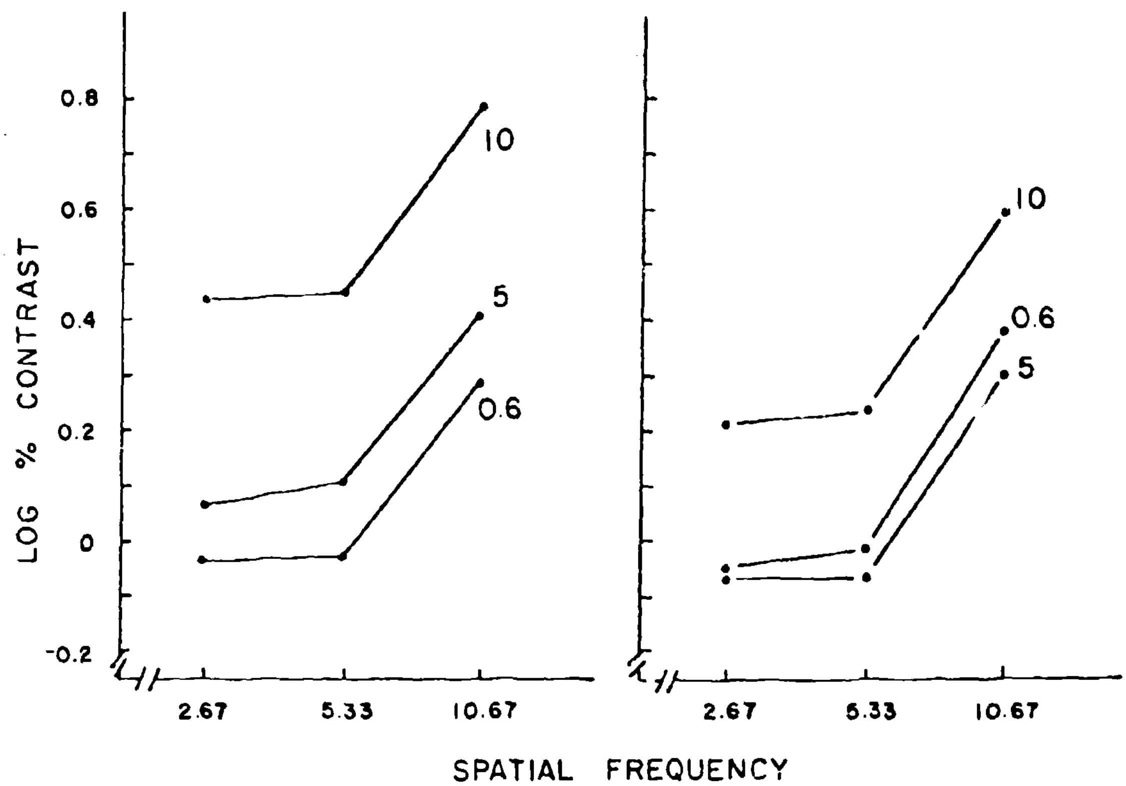


Fig. 17. Log pattern threshold threshold (left panel) and log flicker threshold (right panel) as a function of the spatial frequency of a sine-wave grating. Measurements made for three different temporal frequencies: 0.6, 5, and 10 Hz.

frequency range of 2.67 to 19.67 c/deg, while at 5 mL it was only 0.2-0.3 log unit. Again, the change in the high spatial frequency rolloff of both pattern and flicker sensitivity from one level of light-dark adaptation to the next supports the hypothesis that the functional properties of both sustained and transient channels change with changes in light-dark adaptation.

In Figure 17 there are six spatial contrast sensitivity functions, three in the left panel (solid circles) based upon pattern thresholds and three in the right panel (open circles) based upon flicker thresholds. Each function is collapsed across the repeated measurements obtained for each observer, across observers, and across the two space-average luminances. There are two salient aspects of the data. (1) The pattern thresholds increased monotonically with temporal frequency (a low-pass characteristic), while the flicker thresholds were lowest at an intermediate temporal frequency (a resonant characteristic). (2) All six functions in Figure 17 have nearly identical shapes. This can be taken as evidence that a change of temporal frequency produces little or no change in the spatial frequency response of sustained and transient channels in the 2.67-10.67 c/deg region of the spectrum. Whatever change there is in the spatial frequency response of sustained and transient channels due to temporal frequency appears to be restricted to low spatial frequencies (see Figure 15).

SPATIAL SPREAD OF MASKING (EXPERIMENT F)

Armstrong and Sekuler (1972) and Tolhurst and Thompson (1975) have reported that the threshold for a test grating is not affected by a steady, non-overlapping surround grating with similar spatial frequency content. This result suggests that, if the visual system performs some type of crude Fourier analysis of visual stimuli, the analysis is piecemeal and carried out on local areas of an extended scene. By contrast, Weisstein *et al*. (1977), using a forward masking procedure, found that a single bar could *uniformly* mask a test grating of the same orientation even though the grating extended spatially in either direction to retinal areas not covered by the bar. Weisstein *et al*.'s results constitute evidence that stimulus-analyzing mechanisms produce some sort of widely distributed representation (code) of visual inputs. One possible resolution of the apparently discrepant findings and conclusions of Armstrong and Sekuler and of Weisstein *et al*. is as follows. In Weisstein *et al*.'s experiment it might not be the common spatial frequency components of the masking bar and the test grating that interacted. It could be that the low spatial frequency components of the bar which had a rapid onset and offset stimulated transient mechanisms which in turn inhibited the response of sustained channels to the test grating (e.g., see Breitmeyer and Ganz, 1976). In the Armstrong and Sekuler (1972) and Tolhurst and Thompson (1975) experiments the annular surround grating was not flashed on and off but remained on steadily. Consequently, the spatiotemporal properties of the surround grating probably were not appropriate for stimulating transient channels.

In order to test the hypothesis that there is a spatial spread of the inhibitory effect of transient channels on sustained channels, we repeated the kind of experiment conducted by Sekuler and Armstrong and by Tolhurst and Thompson with temporally modulated surround gratings. We measured the forced-choice contrast threshold for a 4^{o}-wide target grating flanked on either side by 4^{o}-wide gratings. Both the target and flanking gratings were vertical sinusoidal gratings. The target grating had a spatial frequency of 6 c/deg, and it drifted at the very slow rate of 0.3 Hz. These target parameters should have maximized the contribution of sustained channels to the detection of the target grating. The flanking gratings had a spatial frequency of 1 c/deg, and they drifted at 5 Hz. These parameters are optimal for stimulating transient channels. Contrast thresholds for the target grating were identical when flanked by zero-contrast gratings (uniform fields) or gratings of 20 percent contrast. Under conditions designed to be optimal for observing the spatial spread of an inhibitory effect of transient channels on sustained channels we saw none. The negative finding raises questions about the nature of the mechanisms responsible for the masking in Weisstein _et al_.'s experiment, and more generally about proposed sustained-transient models of metacontrast (e.g., Breitmeyer and Ganz, 1976).

BIASING A BISTABLE MOTION DISPLAY BY SINE-WAVE ADAPTATION

In this section an experiment using the bistable spatiotemporal display described by Pantle and Picciano (1976) was employed. Briefly, competing sensations of stroboscopic movement are produced by a cyclic alternation of two stimulus frames. Frame 1 contains three stimulus elements (A, B, C) arranged in a horizontal row on an otherwise uniform background. Frame 2 contains three identical elements (D, E, F), also arranged horizontally but shifted to the right such that the positions of elements E and F of Frame 2 overlap those of B and C, respectively, of Frame 1 (see Figure 18). When stimulus conditions are appropriately selected, the spatiotemporal display gives rise to a bistable percept: either the observer perceives a group of three elements moving back and forth as a whole ("group movement") or he perceives the overlapping elements as stationary and a third element moving back and forth from one end of the display to the other ("element movement"). The display differs from those used in the correlational movement and cluster movement studies described later in other sections of this report chiefly in that the elements which are of interest and which are perceived to move in the display are presented against a blank (noise-free) background. In past studies many of the factors which favor each of the sensations evoked by the display, and many of the properties of the mechanisms which give rise to the two sensations, have been determined (Pantle and Picciano, 1976; Petersik and Pantle, 1979; Pantle and Petersik, in press).

With few exceptions, little effort has been made to study interactions between periodic (sine-wave patterns) and non-periodic stimuli. Two

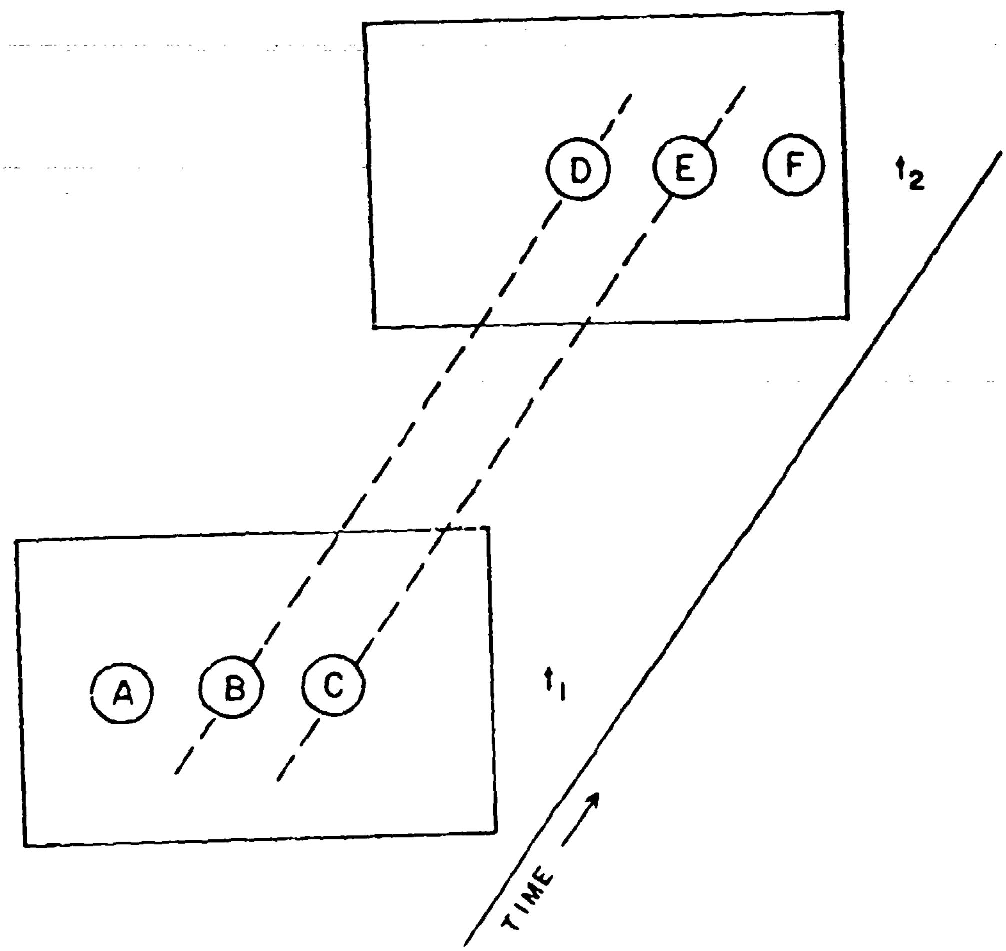


Fig. 18. A schematic representation of the spatiotemporal display used to create two competitive perceptual organizations.

notable exceptions are as follows: (1) Experiments have been conducted to determine the manner in which two stimuli, one periodic and the other not, sum at threshold, and to determine the manner in which a suprathreshold adapting stimulus affects the threshold visibility of a second stimulus when one stimulus is periodic and the other not (e.g., Kulikowski and King-Smith, 1973; Weisstein and Bisaha, 1972). (2) The perceptual effects which result from the spatial filtering (in the sine-wave frequency domain) of visual patterns have been studied (e.g., Ginsburg, 1971.)

The present experiments are an attempt to understand better how the various sine-wave components of the stimulus frames of the bistable spatiotemporal display described by Pantle and his colleagues contribute to the alternative suprathreshold percepts that the display elicits. To this end an adaptation-test paradigm was used in a series of experiments in which observers first adapted to a flickering on-off sine-wave grating or to a phase-shifting sinusoidal grating and then viewed the element-group test display and reported the sensations they experienced. By examining the effects of the adapting gratings, it was expected that something might be said about the contribution of sustained and transient mechanisms to the percepts evoked by the bistable display.

Experiment G: Spatiotemporal factors

In the first experiment the adapting gratings were of a low and an intermediate spatial frequency, each temporally modulated in two different ways.

Stimuli. Both adaptation and test stimuli were generated on a CRT screen coated with a rapid decay phosphor (P31) by a Xitan Alpha III microcomputer system. The beam of the CRT display was swept horizontally by a ramp signal at the rate of 0.75 msec/cm and vertically with a slightly off-screen triangular wave of 160 MHz. The sweep was triggered in synchrony with a pulse (every 9.5 msec) to the microcomputer which modulated the intensity of the beam according to a set of 768 previously stored values. The net result was that 768 vertical lines were painted in succession on the CRT screen with a refresh rate of 105 Hz. Any arbitrary pattern of vertical lines of varying intensity (whether it be a grating, a single line, a uniform field, etc.) could be displayed on the CRT screen simply by programming the computer to read out an appropriate set of 768 values to control the CRT beam intensity as each successive line was painted on the screen.

The test display contained two alternating frames, each of which contained vertical line elements. The three lines of each frame extended the entire distance from the bottom to the top of the CRT screen. The lines were $4^{o}46'$ long, 4.5' wide, and had a luminance of 9.0 mL. The center-to-center distance between the lines was 30'. The uniform areas around the lines of each frame had a luminance of 6.0 mL. During a test trial, the two frames of the test display were presented in a continuous, alternating sequence. Each frame of the sequence had a duration of 240 msec, and the interval between frames was variable from trial to trial--either 10, 20, 30, or 40 msec. The overall height and width of the frames of the test display were $4^{o}46'$ and $6^{o}15'$ respectively.

There were seven different adapting displays, each of which contained two alternating frames whose height and width matched those of the test display. The duration of each frame of the adapting displays was 240 msec. The interval between frames was a spatially uniform field whose luminance was the same (6.0 mL) as the background of the frames of the test display.

The two frames of one of the adapting displays were sine-wave gratings (3 complete cycles of 0.5 c/deg) whose half period corresponded to the distance between the end lines of a frame of the test display. The only difference between the frames was their spatial phase so that when the two frames were alternated with an interval of 40 msec (ISI) between them, a single grating appeared to shift abruptly back and forth. The spatial phases of the two frames were such that the position of the peak of a bright bar of the grating of one frame corresponded to the middle line of one of the frames of the test display, and the position of the peak of a bright bar of the grating of the second frame corresponded to the middle line of the second frame of the test display. A second adapting display was identical to the first one except that its two frames were alternated with an ISI of 10 msec.

The two frames of the third and fourth adapting displays were sine-wave gratings (12 complete cycles of 2.0 c/deg) whose period matched that of the lines of the frames in the test display. The spatial phase of both frames was the same so that when the two frames were alternated, a single grating appeared to turn on and off or flicker abruptly in place. The spatial phase of the frames was such that the peaks of the bright bars of the gratings corresponded to the positions of the lines in the frames of the test display. The ISI for one of the 2.0-c/deg adapting displays was 40 msec; and for the second 2.0-c/deg display, 10 msec. All four sine-wave adapting displays had a space-average luminance (6.0 mL) equal to the background of the frames of the test display, and their contrast was 0.5.

The three remaining adapting displays were controls. One was simply a spatially uniform field which remained on for all periods between the presentations of the test display. Its luminance was 6.0 mL. It provided baseline measurements of the percentage of element and group movement responses reported with the test display in the absence of any type of pattern or movement adaptation. The other two adapting displays were identical to the test display (i.e. contained frames with identical lines), with one having an ISI of 10 msec and the other, 40 msec. The 10-msec adapting display with lines provided measurements of the percentage of element and group movement responses reported with the test display after adaptation to element movement. The 40-msec adapting display with lines provided measurements of the percentage of element and group movement responses reported with the test display after adaptation to group movement.

Procedure. At the beginning of any session an observer viewed one of the seven adapting displays for 2 min. Thereafter, the adapting display was interrupted once every 10.5 sec for a test trial. During the test trial the test display was presented for 5 cycles (where one cycle = Frame 1 + ISI + Frame 2 + ISI), and it was immediately preceded and followed by a spatially uniform field. The uniform field both before and after the test display lasted 0.5 sec, and it served to separate the adapting from the test display. The uniform field had a luminance of 6.0 mL. During any session only one adapting display was used, and each test display (10-, 20-, 30-, or 40-msec ISI) was presented four times. The different test displays were presented in a random order, and after each trial the observer indicated whether he had seen element or group movement. There were six subjects in the experiment, three trained psychophysical observers and three naive observers. Enough sessions were run to obtain 24 judgments for the trained subjects and 16 judgments for the naive subjects for each test display (ISI)-adapting display combination.

Results. The percentage of group movement responses at each ISI was determined for each subject in each adapting condition. The pattern of results was the same in all important respects for the different subjects, and therefore the data points in subsequent figures are the means of the percentages for the six subjects. The results of the experiment are summarized in Figures 19-21. In each panel of each figure, the solid curve represents the data obtained with the spatially uniform adapting field. In the absence of any pattern or movement adaptation, the percentage of group movement responses increased from 0 to 100 as the ISI of the test display increased from 10 to 40 msec.

The two dashed curves in Figure 19 show the percentage of group movement sensations elicited by the test display for the four ISIs after (1) inspection of the line adapting display with a 40-msec ISI, i.e. adaptation to group movement, or after (2) inspection of the line adapting display with a 10-msec ISI, i.e. adaptation to element movement. The curve in the left panel of Figure 19 gives the results for the condition in which the observer adapted to element movement. The curve is elevated relative to the solid curve and indicates that the percentage of group movement sensations increased (element movement sensations decreased) after adaptation to element movement. The dashed curve in the right panel of Figure 19 gives the results for the condition in which the observer adapted to group movement. The curve is depressed relative to the solid curve, indicating that the percentage of group movement responses decreased after adaptation to group movement. The results with the line-adapting

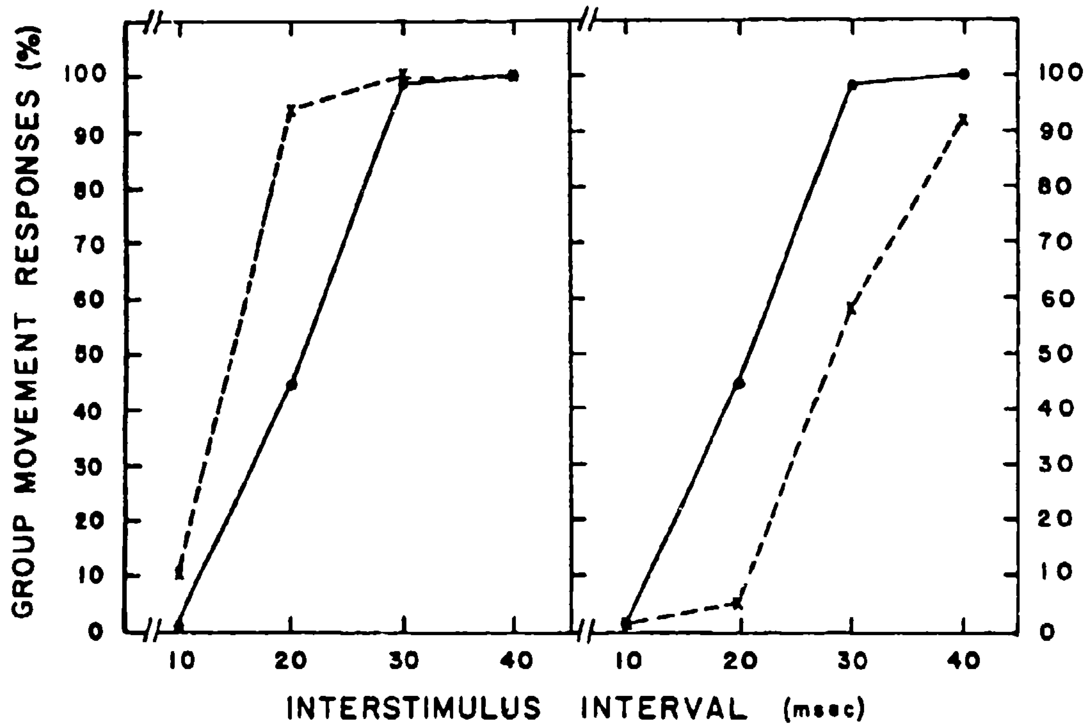


Fig. 19. Percentage of group movement responses as a function of interstimulus interval. Solid curve: control data; dashed curve in left panel: element movement adaptation; dashed curve in right panel: group movement adaptation.

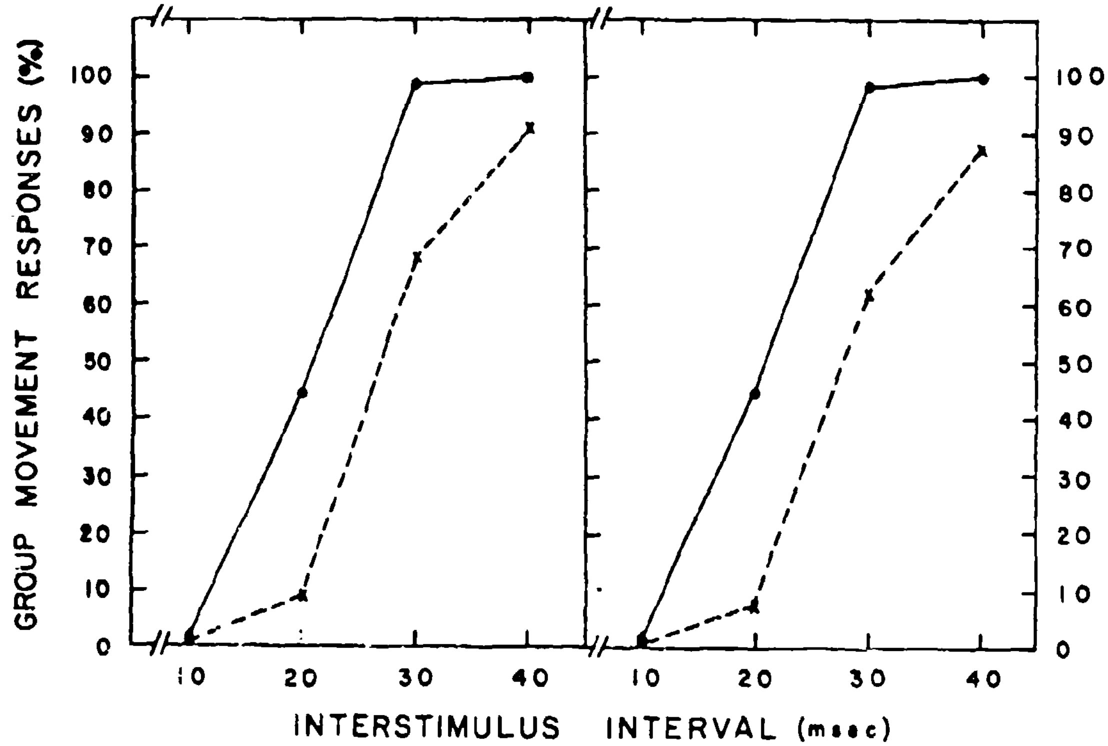


Fig. 20. Percentage of group movement responses as a function of interstimulus interval. Solid curve: control data; dashed curve in left panel: 0.5-c/deg sine-wave adaptation with off-time of 10 msec; dashed curve in right panel: 0.5-c/deg sine-wave adaptation with off-time of 40 msec.

displays demonstrate that the two movement sensations can be selectively adapted. The ability to selectively adapt the sensations implies in turn that the two sensations were mediated by separate mechanisms. The remaining conditions in the first experiment are an attempt to delimit the spatial and temporal frequency characteristics of the separate mechanisms by sine-wave adaptation.

Each of the dashed curves in Figure 20 represents the percentage of group movement sensations obtained after inspection of one of the 0.5-c/deg adapting gratings. The dashed function on the left represents the results obtained when the adapting grating was shifted back and forth (phase-shifted) with an ISI of 10 msec; the dashed function on the right, when the adapting grating was phase-shifted with an ISI of 40 msec. Both dashed curves are depressed relative to the solid control curve and show that the percentage of group movement responses decreased after adaptation to the 0.5-c/deg grating. The decrease in both cases was as large as the decrease obtained after adaptation to group movement itself (compare dashed functions in Figure 20 with the dashed function on the right in Figure 19). The 0.5-c/deg gratings appear to produce maximal adaptation of the mechanism or channels responsible for the group movement sensation. This being so, the temporal modulation rate of the 0.5-c/deg grating was not critical.

Each of the dashed curves in Figure 21 represents the percentage of group movement sensations obtained after adaptation to one of the 2.0-c/deg gratings. The dashed function on the left represents the results obtained when the adapting grating flickered with an off-time of 10 msec; the function on the right, when the adapting grating flickered with an

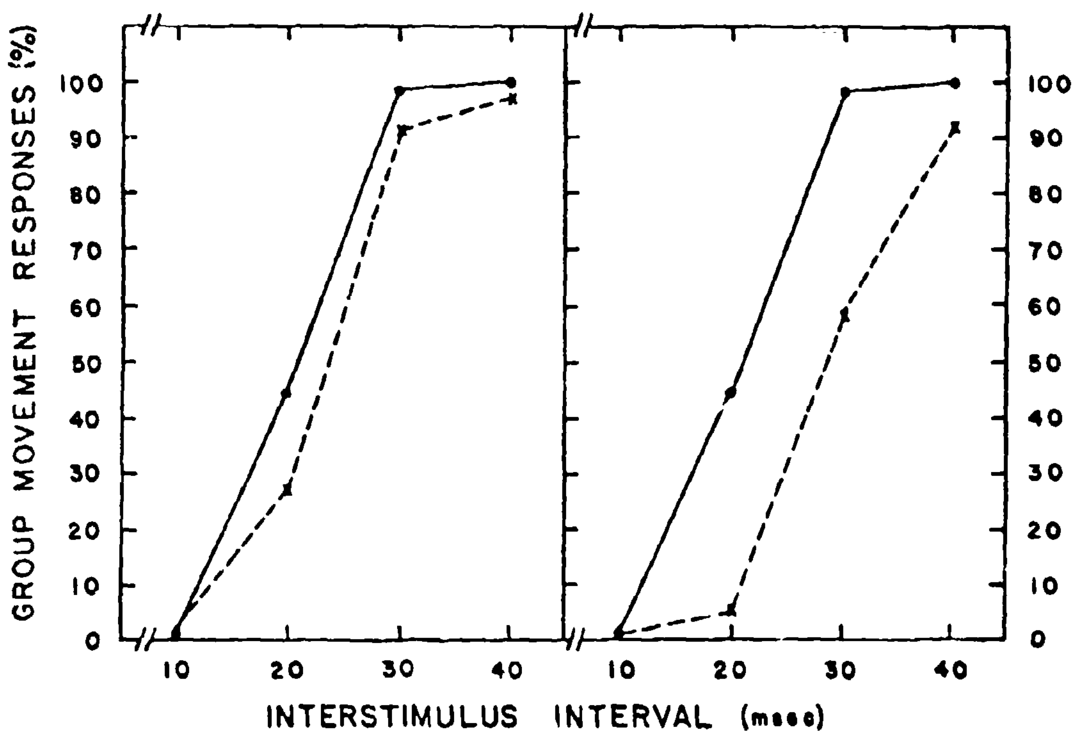


Fig. 21. Percentage of group movement responses as a function of interstimulus interval. Solid curve: control data; dashed curve in left panel: 2.0-c/deg sine-wave adaptation with off-time of 10 msec; dashed curve in right panel: 2.0-c/deg sine-wave adaptation with off-time of 40 msec.

off-time of 40 msec. The function on the left is only slightly depressed relative to the solid control curve, indicating that the percentage of group movement responses was not much changed by adaptation to the 2.0-c/deg grating with the 10-msec off-time. By contrast, the function on the right is depressed considerably relative to the control curve, indicating that the percentage of group movement sensations decreased after adaptation to the 2.0-c/deg grating with the 40-msec off-time.

A simple space domain analysis of the present experiment might lead one to expect that prolonged inspection of the 2.0-c/deg adapting grating would decrease the percentage of element movement sensations relative to the uniform-field control. The 2.0-c/deg grating had the same periodicity as the lines in the element-group display, and it would not be unreasonable to expect that the grating would weaken the response of the visual system to the lines as individual lines. This did not happen. Moreover, it is not clear how a simple space domain analysis could explain the fact that the 2.0-c/deg grating with an off-time of 40 msec weakened the group movement sensation more than one with an off-time of 10 msec.

The results of the present experiment, however, are consistent with a sustained-transient model of visual function. Transient channels would be expected to act like low-pass, spatial frequency filters. Such filters would preserve the low spatial frequency components which define the group of lines as a whole or unit and remove the high-frequency components which define the individual elements. By adapting the transient channels then, it should be possible to reduce the percentage of group movement sensations elicited by the element-group display. Within this framework, the data indicate that transient channels were more readily adapted by a 0.5-c/deg grating than by a 2.0-c/deg grating, and more readily by an on-off, 2-c/deg grating whose off-time is 40 msec versus 10 msec. Both of these inferred spatiotemporal response properties are consistent with what is known about transient channels from other research. Additional tests of the sustained-transient model's ability to account for sensations elicited by the element-group display were made in a second experiment.

Experiment H: Spatial and phase factors

In Experiment G adapting gratings were either flickered on and off in place with a 0° phase shift (the 2.0-c/deg ratings) or else were phase-shifted by 90° (the 0.5-c/deg gratings). In the present experiment comparisons among the adapting effects of counterphase gratings (180° phase shift between successive frames of an adapting sequence) of different spatial frequency were made. Also, we used some adapting gratings with a spatial frequency that was higher than those employed in Experiment G.

Stimuli and procedure. The apparatus and procedure were the same as those of the first element-group experiment with the following exceptions. There were four new sine-wave adapting displays. One of the adapting displays was a 0.5-c/deg, counterphase grating with an off-time of 40 msec. One frame of this display was in sine-phase with the left edge of the CRT display, and the second frame was phase-shifted by 180°. Two of the adapting displays were 6-c/deg, counterphase gratings, one with an off-time of 10 msec and the other with an off-time of 40 msec. One frame of each of the displays was in cosine phase with the lines of the test display, and the second frame was displaced from the first by 180°. The fourth adapting display was a 6-c/deg on-off grating with both frames in cosine phase with the lines of the test display. Its off-time was 10 msec. The fifth adapting display was a control display, a uniform field whose space-average luminance was the same as that of the sine-wave adapting gratings. There were four subjects in the experiment, two of them trained and two naive. Enough sessions were run to obtain 16 judgments for each subject for each test display (ISI)-adapting display combination.

Results. The percentage of group movement responses at each ISI was determined for each subject in each adapting condition. The pattern of results was the same for all subjects, and therefore only group data are provided in the summary figures. The results of the experiment are given in Figures 22 and 23. In each part of each figure, the solid function represents the data obtained with the spatially uniform adapting field.

The dashed function on the left in Figure 22 gives the results obtained with the 0.5-c/deg, counterphase adapting grating; the dashed function on the right in Figure 22, results obtained with the 6-c/deg, counterphase adapting grating. It is clear from the figure that adaptation to the 0.5-c/deg grating weakened the group movement sensation more than adaptation to the 6-c/deg grating. These results are consistent with those of Experiment G in showing that the mechanism responsible for the group movement sensation has a low-pass, spatial filter response.

Figure 23 provides a comparison of the relative adapting effects of the 6-c/deg counterphase and the 6-c/deg on-off gratings, each with a 10-msec ISI. Data for the counterphase grating are on the left in the figure (dashed function); and data for the on-off grating, on the right. The curve for the on-off grating is slightly elevated relative to the control curve, while the curve for the counterphase grating is slightly depressed.

The on-off grating, therefore, appears to weaken the element movement sensation slightly, while the counterphase grating appears to weaken the group movement sensation. Of all the adapting gratings employed in the two element-group experiments, the 6-c/deg, on-off grating had spatio-temporal characteristics most suited for stimulating and adapting sustained channels. The slight elevation of the 6-c/deg on-off curve, then, is consistent with other evidence (Pantle and Petersik, in press) which suggests that sustained channels are at least in part responsible for the element movement sensation. If the sustained-transient hypothesis is correct, then the decrease in the percentage of group movement sensations produced by the 6-c/deg counterphase adapting grating means that the counterphase grating adapted transient channels slightly more than sustained channels. The smaller adapting effect (or possibly complete absence of an effect) of the counterphase grating on sustained channels compared to the on-off grating was probably a direct consequence of the temporal integration of the contrast of successive frames of the adapting display by sustained channels. The contrasts of the 180° phase-shifted frames of the counterphase display would sum to zero (sum destructively), while the non-zero contrasts of the frames of the on-off grating would be preserved (summed constructively).

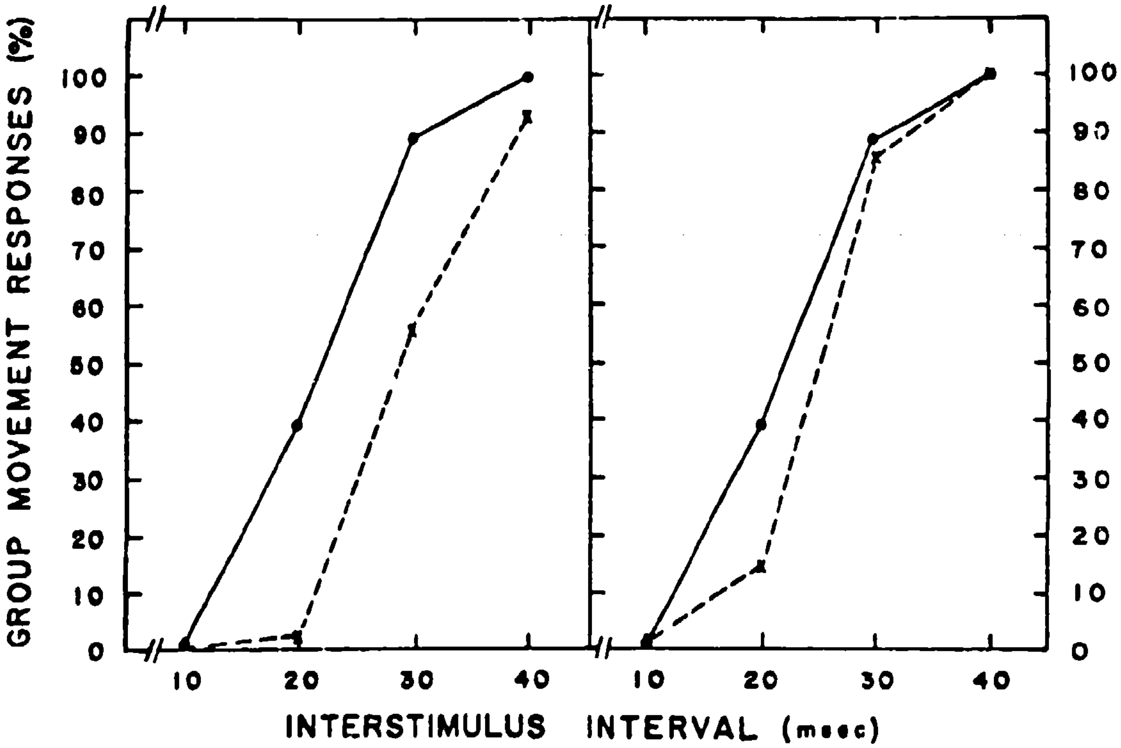


Fig. 22. Percentage of group movement responses as a function of interstimulus interval. Solid curve: control data; dashed curve in left panel: 0.5-c/deg, counterphase adaptation; dashed curve in right panel: 6-c/deg, counterphase adaptation. Off-time of 40 msec for sine-wave adaptation at both spatial frequencies.

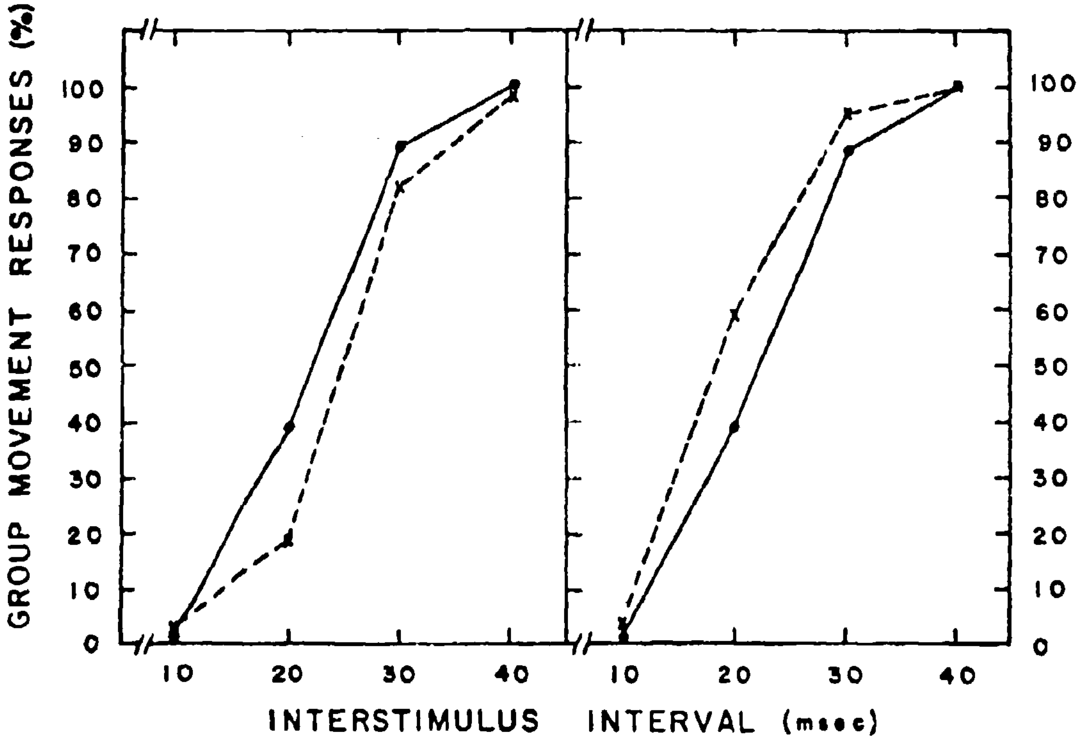


Fig. 23. Percentage of group movement responses as a function of interstimulus interval. Solid curve: control data; dashed curve in left panel: 6-c/deg, counterphase adaptation; dashed curve in right panel: 6-c/deg on-off adaptation. Off-time of 40 msec for both types of adaptation.

TEMPORAL DEFINITION OF FORM

In the series of experiments reported here, stroboscopic movement was studied by alternating two random-element patterns like those used by Julesz (1971), Braddick (1973, 1974), Bell and Lappin (1973) and others. A typical pair of random-element patterns is shown in Figure 24. The two frames are identical except for an area which is displaced horizontally in one matrix with respect to its position in the other. If the two frames in Figure 24 are presented alternately, the displaced area can be seen as a subjective figure segregated from the background. The display differs from that used in the studies of the movement of texture clusters (Section VII) chiefly in that there are no physical cues present for perceptual grouping of elements <u>within</u> any single frame of the displays. Because there is no basis for the segregation of the global subjective figure in either frame alone, the spatiotemporal relationship between the light and the dark portions of the two frames of the display must give rise to the subjective figure. The subjective figure emerges only if the interstimulus interval (ISI) is not too long and the displacement is not too great (Braddick, 1973; Bell and Lappin, 1973).

In principle, it should not matter whether dots, squares, or lines are used as elements in the patterns as long as they are homogeneous within and across patterns. In our first experiment we used lines as elements in an attempt to replicate results from previous experiments which used dots or squares as elements. In the second experiment we tried to determine some of the prerequisites for the local match-ups of elements across the display frames.

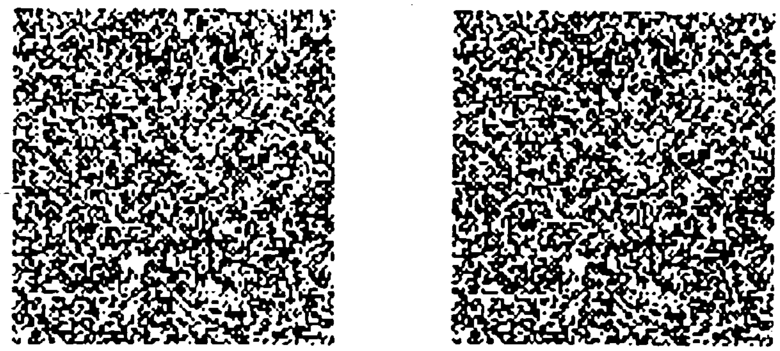


Fig. 24. Examples of random-element, Julesz-type patterns which give rise to a subjective figure when alternated in time.

Experiment I: Spatiotemporal variables

Braddick (1973) alternated random-element patterns with squares as elements to produce stroboscopic movement of a subjective figure. He looked at the effects of ISI and the degree of displacement (across frames) of the figure area. As ISI and displacement increased, the clarity of the figure and the ability of an observer to discriminate the orientation of the figure decreased. Bell and Lappin (1973), using dots as elements, essentially replicated Braddick's results, but they used a different dependent measure--discrimination of the direction of movement of the figure. The direction discrimination measure also decreased as ISI and displacement increased.

Using lines of two different lengths as elements, we wanted to determine whether the detectability and clarity of the subjective figure which corresponds to the displaced area in alternating random-line patterns decrease as ISI and the degree of displacement increase. We expected to replicate the results of the past similar experiments, and after doing so, to extend our knowledge of the mechanisms underlying the stroboscopic movement phenomenon which is produced by alternating random-line patterns.

Stimuli. Figure 25 shows a typical stimulus frame used in the first experiment. Figure 26 illustrates position constraints placed upon the line-elements within a 31 by 25 cell imaginary matrix used to generate a stimulus frame. All frames were generated such that half the cells within the imaginary matrix in Figure 26 contained lines and half were blank. When a cell contained a line, the line was placed randomly at 1 of 30 different positions across the horizontal dimension of a cell (with the

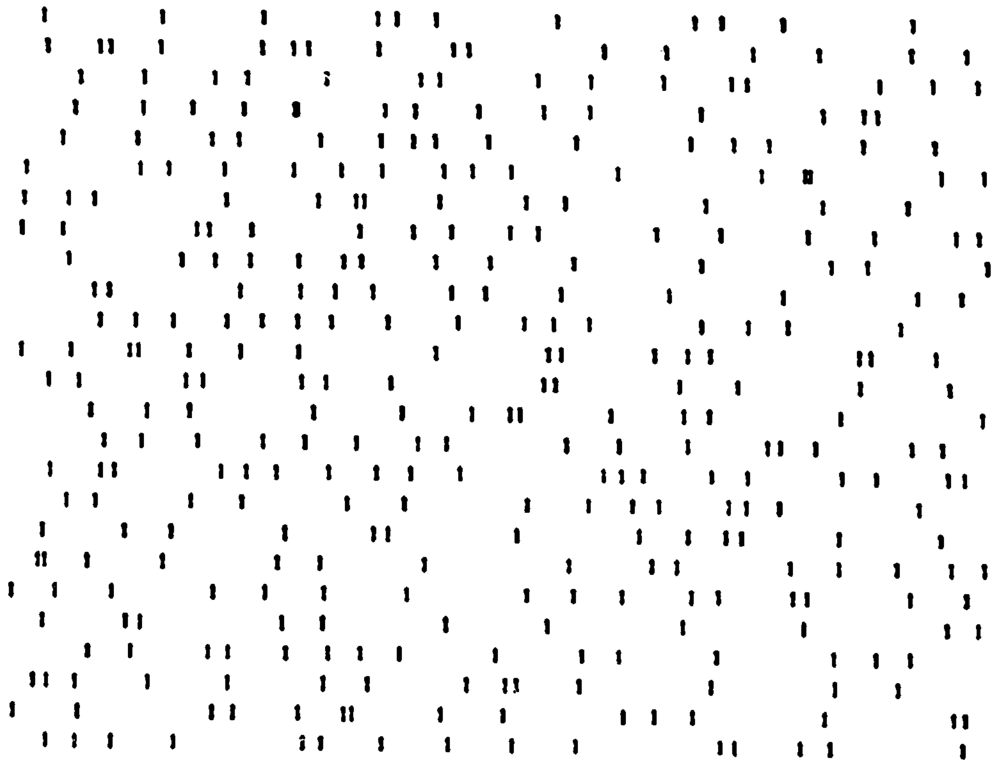


Fig. 25. A typical stimulus frame used in Experiment I to generate a subjective figure.

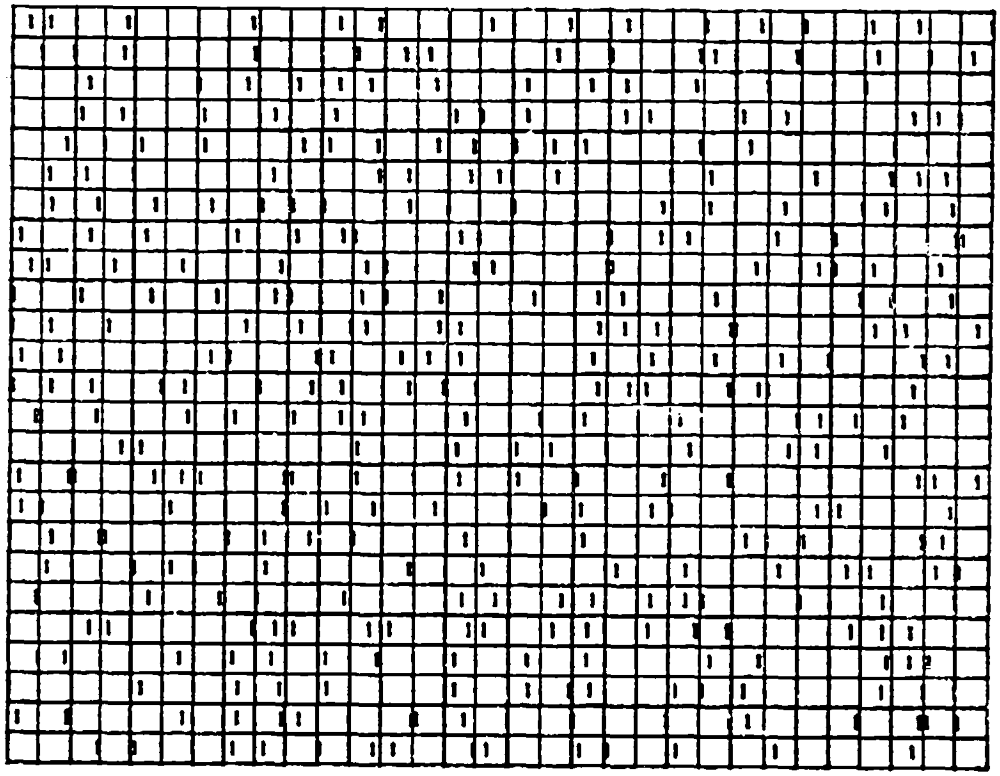


Fig. 26. A schematic illustration of the manner in which an imaginary matrix was used to generate the stimulus frames of Experiment I.

constraint that no two lines were closer than 1/5 of a cell width). In order to minimize the occurrence of large groups of dark or light elements, which are easily detectable and could interfere with the clarity of the global figure, no more than three consecutive cells in a row had identical contents (either all lines or all blanks).

Our dynamic displays consisted of the alternate presentation of a pair of frames. For the first frame, the position of blanks and lines in the cells of the imaginary matrix were randomly chosen. The second frame was generated under the constraint that (1) the positions of a subset of lines (figure area) were identical (+1 correlation) to those of a subset in the first frame and (2) the remainder of the background lines in the second frame were positioned within cells that were blank in the first frame and vice versa (-1 correlation between line positions). When the two frames were alternated to produce a dynamic repetitive display, the overall position of the second frame was shifted either ½-cell width or one-cell width to the right of the first frame. As a result, the figure lines were all shifted in the same direction and by the same amount (either ½-cell width or one-cell width) whenever the first frame was replaced by the second, whereas there was no systematic displacement of the background elements in the two frames. Under appropriate conditions, the observer would perceive the group of +1 correlated elements as a global subjective figure moving back and forth across a background.

The overall size of each frame was 13.4^{0} wide and 10.8^{0} high. Each cell in the imaginary matrix of each frame was 26' on a side. The figure area measured 5.2^{0} by 2.6^{0}, was centered within the 25 row by 31 column imaginary matrix and was oriented either vertically (12 rows by 6 columns) or horizontally (6 rows by 12 columns) for any one pair of frames. In half the trials a horizontal figure area was presented, and in the other half, a vertical figure area. The shift in the position of the figure area which occurred when the frames were interchanged was 13' for the displacement of ½-cell width or 26' for the displacement of one-cell width. Two different line lengths were used for the elements of the frame, either 9' or 18'. The luminances of the short and long line elements were 0.13 and 0.075 mL, respectively. (In previous experiments of the same kind, the luminance of elements has been shown to have no effect on the percepts produced by the display.) The display was viewed from a distance of one meter in a completely dark room. The dark spaces between the line elements of the frames of the display had a luminance of less than 0.001 mL. Each frame in a display sequence (trial) lasted for 170 msec. The interval between frames (hereafter ISI) was varied. It was either 10, 30, 50, 80 or 120 msec. The total time for which each sequence of frames was presented was 2 sec. In all, there were forty different types of displays or conditions which resulted from the factorial combination of the two orientations of the figure area, two displacements of the second frame with respect to the first, two line-element lengths, and five ISIs. The pair of frames which was alternated to produce the dynamic display for each condition was generated with a different random seed for each trial for each subject to ensure that differences among the conditions were not due to the particular random patterns used for any condition. Stimulus frames were generated by a PDP 11/10 computer and stored in display files on a floppy diskette. To present a pair of alternating frames to a subject, the contents of the appropriate display files were transferred to the computer's memory. Under program control a VT-11 Graphics Display Processor (Digital Equipment Corporation) utilized the information in the computer's memory to produce the pattern on a VR 14 CRT display with a P-31 phosphor.

Subjects. Six graduate students served as volunteer observers for the experiment. Three of the students were experienced psychophysical observers and three were not. Visual acuity of all students was either 20/20 or corrected to 20/20.

Procedure. Each observer participated in one experimental session which lasted less than one hour. During the session there were seven blocks of forty trials, one trial in each block with one of the forty different displays. The order of presentation of the displays within a block was random, and the first block of forty trials was used as practice and was not analyzed as part of the results. There were approximately 5 seconds between each 2-second trial. After each trial the observer's task was to report whether the figure area (seen as a global subjective figure) was vertical or horizontal and how clear the subjective figure appeared on a scale from 1 (unclear) to 7 (clear). The clarity judgment was based on how distinct the subjective figure appeared against the background and how sharp its subjective contours appeared.

Results and discussion. Both the discrimination (of orientation) and clarity data were essentially identical for all six observers, and therefore only group data are reported. The observers were always able to identify correctly the orientation of the figure area for both line lengths, for both degrees of frame displacement, and for all ISIs; i.e., their responses were 100% correct in all conditions. The results are somewhat in contrast to those of Braddick (1974) who found that observers were unable to discriminate the orientation of correlated groups of elements in dynamic random-element displays with ISIs as long as 80 or 120 msec. One possible reason for the difference in results is that our experiment was conducted in the dark. While our second experiment was run chiefly for other reasons, it was conducted in a lighted room to determine whether the amount of room illumination would affect the error rate.

The phenomenal appearance of the figure area (global subjective figure) changed for the different displays. Qualitatively speaking, the subjective figure varied in its appearance from a well-formed rectangle with sharp edges and corners when it was most clear to a nebulous elongated ellipse when it was least clear. The shape of the subjective figure never degraded to the point that its orientation was not discriminable, but as the quantitative estimates attest, the changes were large and consistent across observers. The quantitative estimates of clarity are summarized in Figure 27 where the mean clarity rating is plotted as a function of the ISI for the different dynamic displays. The results shown in Figure 27 were averaged across line element length and across subjective figure orientation since neither variable had a significant effect on the clarity of the subjective figure. Each function represents a different degree of frame displacement. As can be seen in Figure 27,the clarity of the subjective figure decreased as ISI increased [F (4, 20) = 44.9, $p <$ 0.001]. Also, the clarity of the subjective figure was less when the foreground area was displaced by the larger amount [F (1, 5) = 12, $p <$ 0.025].

The entire pattern of clarity results is consistent with those

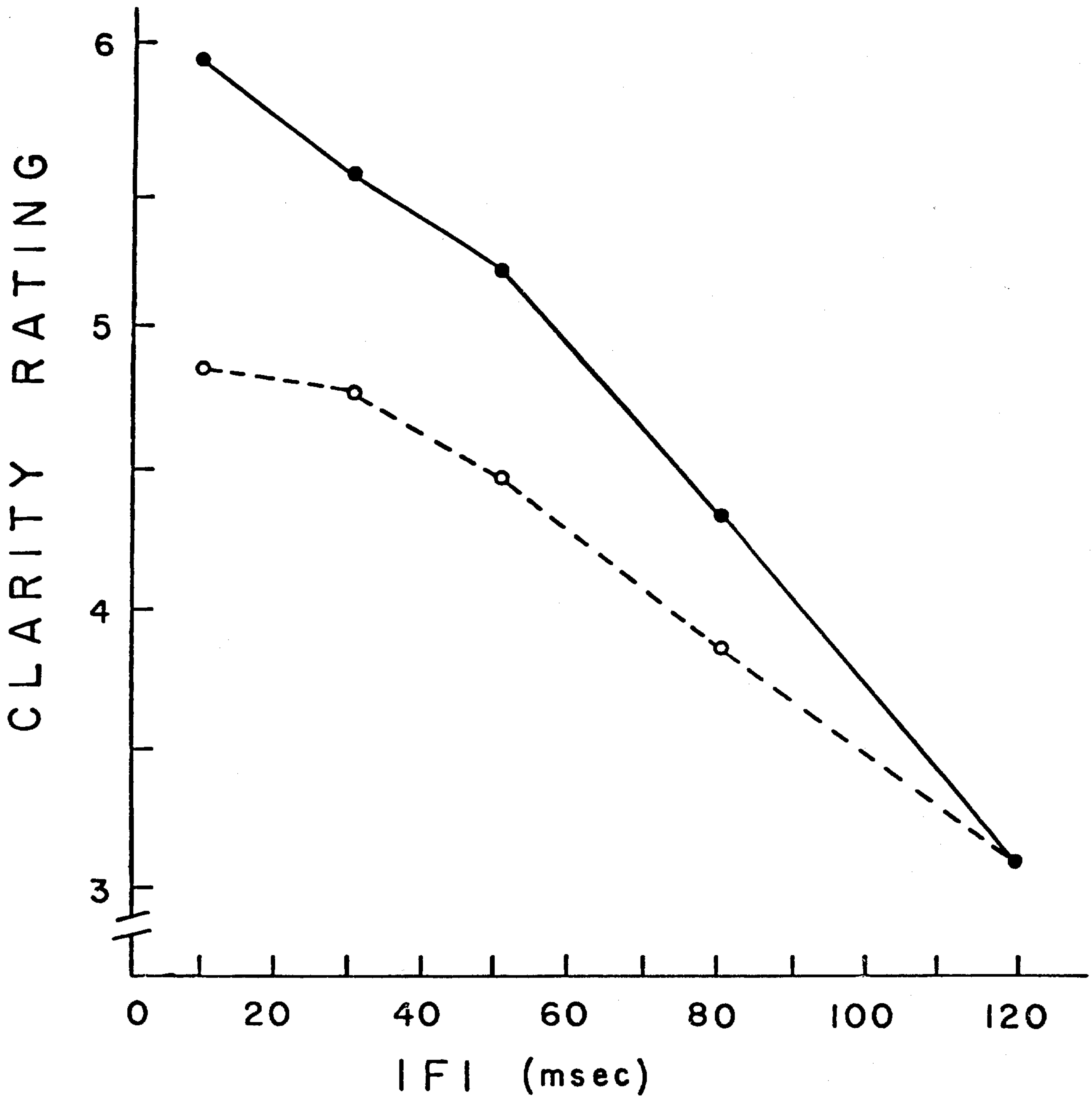


Fig. 27. Clarity of subjective figure as a function of interstimulus interval, or the time between stimulus frames (IFI).

reported by Braddick (1974), although the absolute values of our clarity ratings were higher at long ISIs. But again, our lower prevailing light level might have resulted in the higher absolute clarity values. The fact that line length does not affect the perception of the correlated areas means that, as long as line orientation remains constant across frames, displays with lines appear to have no real advantage or disadvantage over displays with dots or squares as elements. However, as the next experiment demonstrated, there is an advantage of using lines if one is trying to understand the basis for the local match-ups which result in the perception of a global subjective figure.

Experiment J: Element orientation

This experiment was designed to examine the basis for the local pairings of elements which contribute to the perception of a global subjective figure in dynamic random-line displays like that employed in Experiment I. For example, on the one hand, it is possible that the individual line elements are each treated as an amorphous blob of light when pairings of elements in corresponding positions of the successive frames are established. Or, the connections between elements in corresponding positions may be based upon the definition of one common point. In either case, the quality of the subjective figure should not be adversely affected by any change in shape of the elements across frames of the display. On the other hand, it may be that all points comprising the individual line elements enter into the determination of the local pairings of the elements. Or, the local pairings may be based upon the outputs of shape-sensitive mechanisms (e.g., line detectors). In the latter two cases, the quality of the global subjective figure in random-line displays may be adversely affected by a change in shape of the elements across frames. Specifically, local pairings of elements in correlated positions may occur only if the elements have identical or nearly identical orientations. If so, a subjective figure may not emerge when the orientation of elements in one frame of the display is very different from that of elements in the second frame.

The major independent variable in the second experiment was the degree of difference in the orientation of line elements in successive frames of the display. ISI and line length were also included as independent variables, the latter in order to determine in what way it might interact with orientation difference. Also, the experiment was run in a lighted room to determine whether an increase in the light level over that used in Experiment I would decrease discrimination accuracy and clarity ratings at long ISIs (> 50 msec) as suggested earlier.

Method. In general the stimulus displays, their method of generation, and the procedures followed during an experimental session were the same as in the first study with the exceptions described below. The magnitude of the shift in the position of the figure area was not a variable, but was kept constant at 13'. Only three ISIs were used: 10, 30 and 80 msec. A difference in the orientation of the elements, from one frame to the next, was introduced as a new variable. The line elements in one frame were always vertical, but all elements in the second frame were rotated clockwise about their center in the plane of the display through an angle of either 0^{o}, 30^{o} or 60^{o}. In all, there were 36 different types of displays or conditions which resulted from the factorial combination of the two global orientations of the figure area (vertical or horizontal), two line-element lengths (9' or 18'), three ISIs, and three differences of line-element orientation across the two frames of the dynamic display.

The experiment was run in a lighted room. The luminance of the long lines, regardless of their orientation, was 3.0 mL; that of the short lines, regardless of orientation, 3.6 mL. The luminance of the dark areas between elements on the CRT was 0.7 mL. It was due to the low ambient room illumination.

Subjects. Six students served as volunteer observers for the experiment. Two of the students were experienced psychophysical observers and had served as observers in Experiment I. All subjects either had uncorrected 20/20 visual acuity or were corrected to it with eyeglasses.

Results and discussion. Both the discrimination and clarity data were essentially identical for all six observers, and therefore only group data are reported. The discrimination data are given in Table 1, and the clarity data are given in Table 2. Each entry in both tables is the mean of the responses for the six observers.

Consider first the row means. Each row mean summarizes the results for a display with a different interstimulus interval. An inspection of the row means reveals that the ability of an observer to identify the orientation of the subjective figure and the clarity of the subjective figure both decreased as ISI increased. With an 80-msec ISI the average clarity rating (1.3) was near the minimum of one, and discrimination performance (56.1) was just above the chance level of 50%. The deterioration of discrimination performance and figure clarity with an 80-msec ISI is just as prominent in the data for the 0^0-orientation difference conditions by themselves. In general, then, unlike the ISI effect in

TABLE 1

SUBJECTIVE CLARITY OF FIGURE AREA AS A FUNCTION OF
LINE LENGTH, ORIENTATION DIFFERENCE, AND INTERSTIMULUS INTERVAL.
EXPERIMENT 3.

ISI	SHORT LINES			LONG LINES			MEAN
	ORIENTATION			ORIENTATION			
	0^{o}	30^{o}	60^{o}	0^{o}	30^{o}	60^{o}	
10 ms	5.9	5.5	5.2	5.9	4.7	2.1	4.9
30 ms	4.5	4.4	3.8	4.4	3.4	1.6	3.7
80 ms	1.4	1.5	1.2	1.5	1.4	1.1	1.3
MEAN	3.9	3.7	3.4	3.9	3.2	1.6	

TABLE 2

PERCENTAGE OF CORRECT DISCRIMINATIONS OF THE ORIENTATION OF THE FIGURE AREA AS A FUNCTION OF LINE LENGTH, ORIENTATION DIFFERENCE, AND INTERSTIMULUS INTERVAL.
EXPERIMENT J.

ISI	SHORT LINES			LONG LINES			MEAN
	ORIENTATION			ORIENTATION			
	0°	30°	60°	0°	30°	60°	
10 ms	100	100	100	100	100	93	98.9
30 ms	100	100	98	97	100	66	93.6
80 ms	58	51	50	66	56	55	56.1
MEAN	86	84	83	88	85	71	

Experiment I in a dark room, the ISI effect in Experiment J in a lighted room is in good accord with the results of Braddick (1974) both in relative and absolute magnitude. It can be concluded that whatever the mechanism by which the orientation of the subjective figure was identified, it operated more effectively at long ISIs if the observer was in the dark rather than in the light.

Now consider the column means. Each column mean summarizes the results for a display having a particular line-element length and difference of element orientation across frames. For both tables an examination of the column means reveals an interaction between the two variables of line length and orientation difference. The variation of column means due to a change of orientation difference is less for short line elements than for long elements. For both sets of data the interaction is statistically significant [F (2, 18) = 18.4, $p < 0.001$ for discrimination performance, and F (2, 18) = 67.0, $p < 0.001$ for clarity ratings]. The nature of the interactions can be more readily appreciated in Figures 28 and 29 where discrimination performance and clarity ratings, respectively, are plotted as a function of the magnitude of the orientation difference of the elements in successive frames with element length as a parameter. As can be seen in Figure 28, the ability of an observer to identify the orientation of the subjective figure decreased as orientation difference increased, but the decrease is much more pronounced with long line elements than with short ones. Similarly, as can be seen in Figure 29, the clarity of the subjective figure deteriorated more quickly for long lines than for short lines as orientation difference increased.

The across-frame shape or form required of elements if they are to

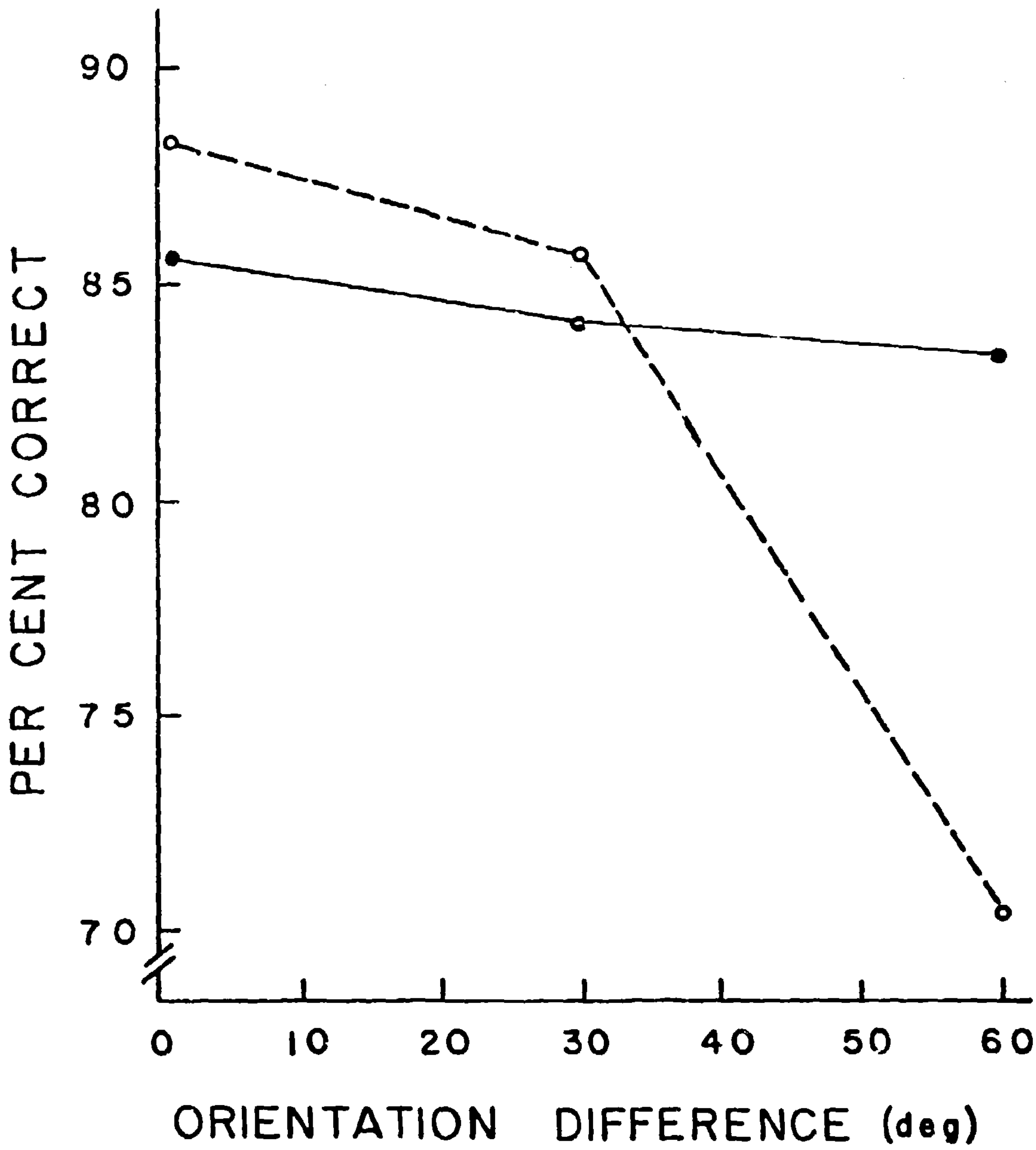


Fig. 28. Discrimination accuracy as a function of the difference of element orientation across frames.

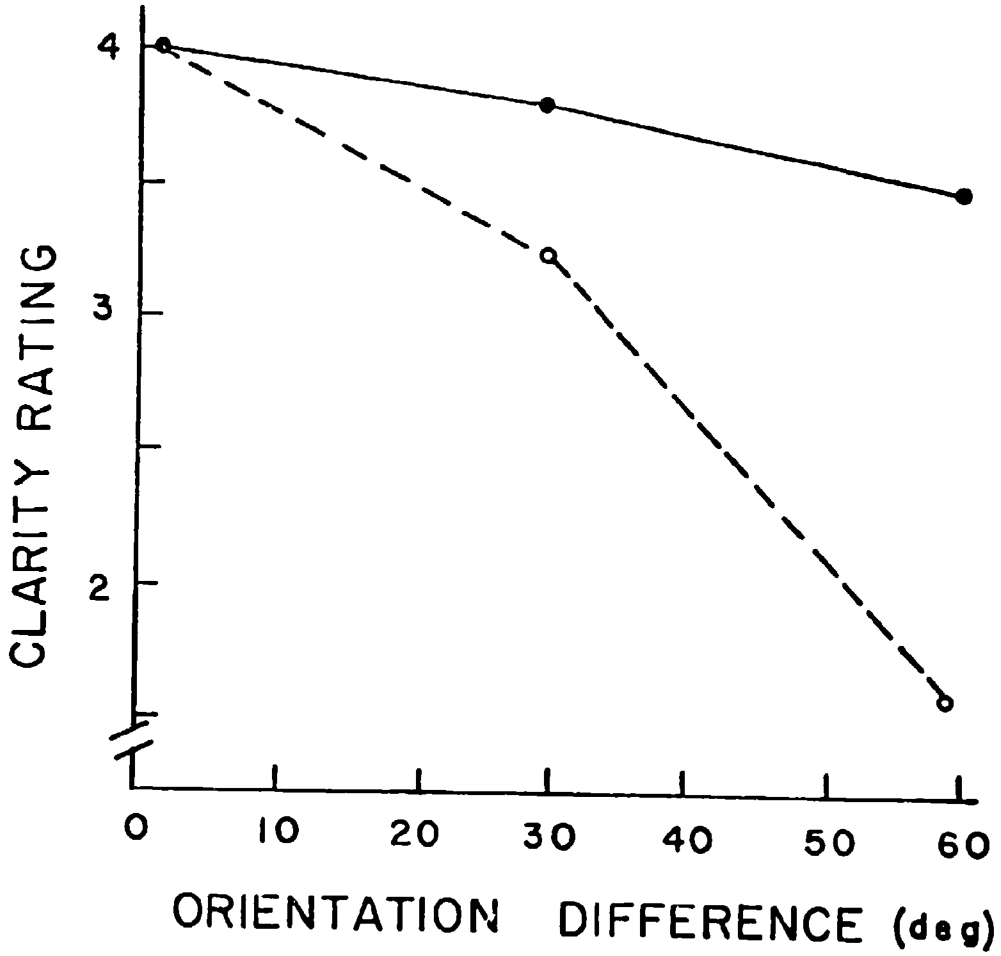


Fig. 29. Clarity of subjective figure as a function of the difference of element orientation across frames.

contribute to the emergence of a global subjective figure in a dynamic display (Experiment J) is surprisingly similar to that required of elements in the half-images of stereograms if they are to contribute to a global stereoscopic figure (Frisby and Julesz, 1975). Frisby and Julesz found that the depth percept obtained with a random-line stereogram collapsed gradually as differences in orientation were introduced between lines in the left and right half-images. The longer the lines in the stereogram, the greater was the rate of collapse of the depth percept with orientation difference. Frisby and Julesz emphasize the point that the amount of depth perceived between the global Cyclopean square and the background in their experiments was related in a gradual quantitative manner to events operating at a local level between elements. In the same way, the quality of the global subjective figure in our displays depended in a systematic way upon the local relationships of elements in successive time frames.

The <u>generation</u> of a subjective figure in random-element displays like that used in Experiment J demands that the spatial processing of the frames be carried out with a grain of the same order of magnitude as the spacing among the elements. Since the cells in the imaginary matrix used to generate the individual frames was 26', areas as small as this had to be compared for the presence or absence of a line element. If the grain of spatial processing were no finer than the matrix grain it would not matter what the orientation of the line elements was from one frame to the next because each element would be represented or treated as a blob only. The fact that orientation difference did have an effect in Experiment J means that the grain of spatial processing responsible for the generation of the subjective figure was <u>finer</u> than the matrix grain. Because the generation of a subjective figure depends at least in a first stage upon the processing of fine-grain spatial information (spatial frequency components greater than 2 c/deg) and because the generation of a subjective figure requires a short interval between frames, it is likely that the generation of the subjective figure begins with signal processing in sustained channels.

DYNAMIC TEXTURE PROCESSING

The experiments described in this section were designed to study the manner in which global texture information contributes to the perceptual grouping and movement of line elements in a dynamic visual display. One example of a display (Pantle, 1973) which has been used to demonstrate the role of global texture information is as follows. Line segments are positioned randomly (0.5 density) in the cells of a 20 x 25 imaginary array (see Figure 30). In a given pattern the elements (indicated by B's in Figure 30) which are used to fill a small subset (3 x 10 cell area) of the entire array differ from background elements (indicated by A's in Figure 30) in the remainder of the array. The A elements might be vertical line segments, and the B elements, horizontal line segments. A second pattern is generated in the same way except that the position of the 3 x 10 cell subset (texture cluster) is changed (see Figure 31). When the two uncorrelated patterns of line segments are alternately presented at a rapid rate, subjects see the texture cluster moving *in toto* back and forth. The perception of the apparently moving texture cluster is distinguished from other similar phenomena by two important characteristics. (1) The perception and movement of the texture cluster cannot be due to the processing of low spatial frequency luminance information because there is no average brightness difference between the cluster and background of each frame of the display. It is therefore not like the group movement sensation produced by the element-group display. (2) The perception of the texture cluster and its movement cannot arise from a spatiotemporal cross-correlation of the intensity distribution of successive frames because pairings of point-for-point intensities across the frames are random no

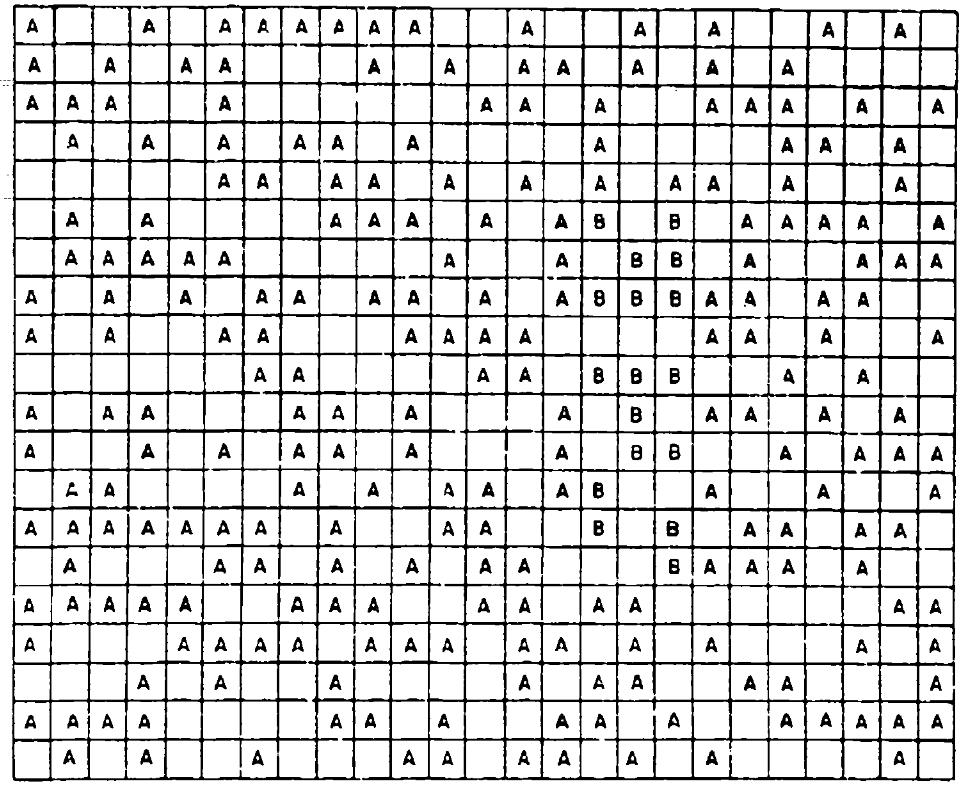


Fig. 30. A schematic representation of the spatial arrangement of elements in one of two stimulus frames used to study the apparent movement of a texture cluster.

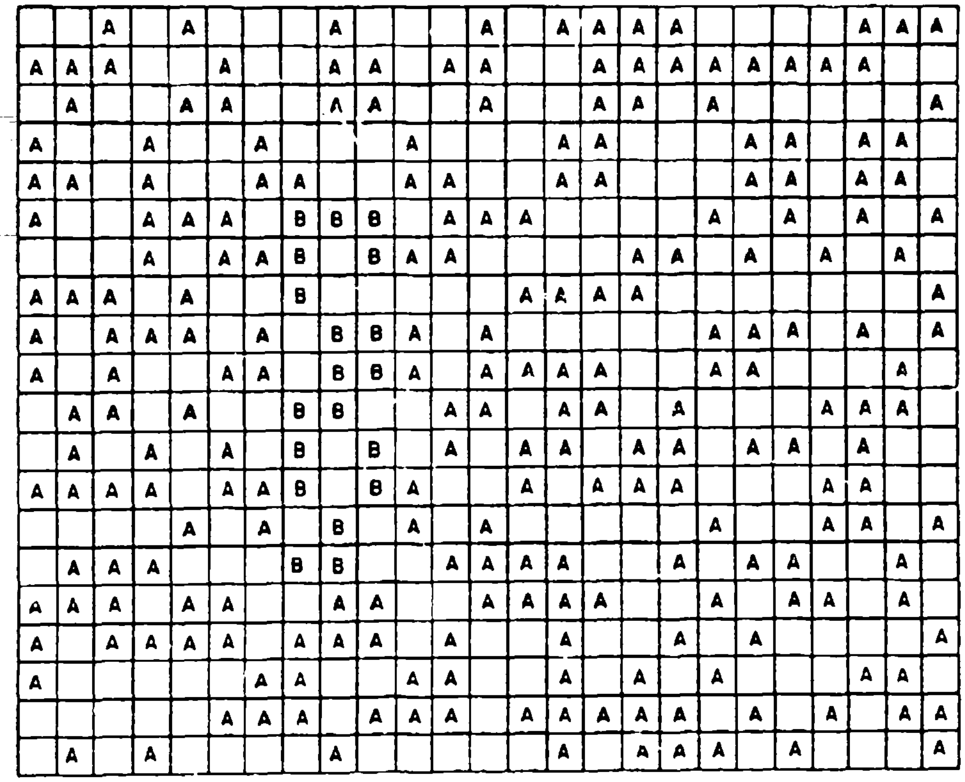


Fig. 31. A schematic representation of the spatial arrangement of elements in the second of two stimulus frames used to study the apparent movement of a texture cluster.

matter how the two patterns are aligned one with the other. The perception, therefore, is not like the perception of a displaced set of elements in alternating random-element patterns.

If the texture cluster display is viewed continuously and the frames are alternated at a rapid enough rate, the apparent movement of the texture cluster disappears (adapts) and oftentimes the texture cluster itself fragments perceptually. In the series of experiments described below we have (1) examined the time course and recovery of the adaptation process and (2) measured the amount of cross-adaptation that occurs between texture clusters defined by different texture cues.

Experiment K: Recovery from adaptation

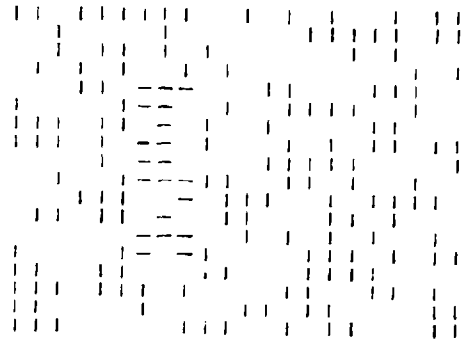
When the cluster movement sensation disappears or the texture cluster itself fragments after prolonged viewing, it is possible to restore it by looking away from the display for a few seconds and then looking back at the display. This observation has only been made informally, and it is the purpose of the present experiment to explore the "recovery" of the sensation systematically. To this end, the cluster movement display was viewed by an observer until the cluster movement or the texture cluster itself disappeared (hereafter called disappearance time), at which time the observer pushed a button which terminated the display. After a variable recovery interval, the same display reappeared and the observer viewed it again until the cluster movement or the cluster itself disappeared a second time. The second disappearance time provided a measure of the recovery from the adaptation produced by viewing the display the first time.

Stimuli and apparatus. All stimuli were generated in advance of the experiment and were stored on a disk by a PDP 11/10 computer. They were subsequently displayed on the face of an oscilloscope coated with a rapid-decay phosphor (P31) by the same computer.

The two frames of the cluster movement display used in the present experiment are shown in Figure 32. The display was viewed binocularly and without a fixation point from a distance of 103 cm. At this distance one of the frames (18 x 22 array) subtended a visual angle of $8^{0}14'$ vertically and $11^{0}06'$ horizontally. Individual line segments in each frame subtended 3'40" in width and 20'3" in length. The cluster of horizontally oriented line segments subtended 4^{0} vertically and 1^{0} 20' horizontally; the distance between the closest edges of the cluster in one frame and the cluster in the second frame was $3^{0}17'$. The luminance of the line elements was 1.8 mL; the luminance of the dark spaces bewteen elements, 5.5×10^{-2} mL.

Procedure. Observers served in one practice session and a number of experimental sessions, each conducted on a separate day. During the practice session, each observer viewed the apparent movement of the cluster that resulted from the alternation of the pair of stimulus frames. For each display sequence, the duration of each frame was 170 msec. The interval between frames (ISI) was 30 msec. The observer viewed each sequence until the cluster grouping and/or its movement disappeared. Almost all of the disappearance times were between 10 and 25 msec.

During each experimental session an observer viewed the display sequence twice on each trial. The observer pushed a button to terminate the display sequence when the cluster grouping and/or its movement disappeared the first time. After a variable recovery interval in which the display screen was blank for 10, 50, 100, 250, 500, 1000, 2000, 4000,



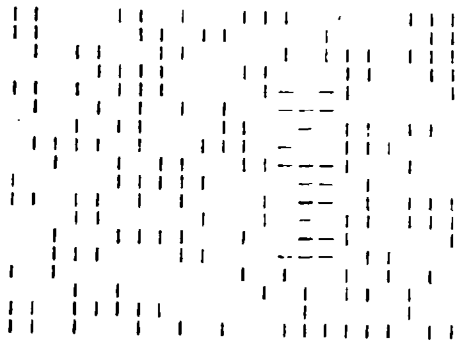


Fig. 32. Two frames of a cluster movement display containing horizontal cluster elements on vertical background elements (HV display).

8000, or 16000 msec, the observer viewed the display again until the cluster grouping and/or its movement disappeared a second time. The observer again pushed a button to terminate the display. Both the first and second disappearance times were recorded for each trial. During each display sequence and during the recovery interval, the observer directed his gaze toward the center of the display screen while attending to the entire screen. Enough experimental sessions (three or four) were conducted to obtain 9 pairs of disappearance times for each of the 10 different recovery intervals. The recovery intervals were run in blocks, and the order of presentation of intervals within blocks was random.

Three practiced psychophysical observers and three naive observers participated in the experiment. The results for the naive observers were identical to those for the trained observers in all important respects, and only the results for the trained observers are summarized below.

Results. A summary of the results of the experiment is given in Figure 33. Each point on the solid function in the top panel of the figure is the mean of 27 measurements (9 replications for each of the 3 trained observers) of the first disappearance time (t_1) of the display sequence. There is no reason to expect that t_1 should vary as a function of the recovery interval which follows the first display sequence, and as can be seen in the figure, t_1 remained constant within the limits of experimental error, across the various recovery intervals. The dashed function represents the mean of the second disappearance time (t_2) for each trial. As shown in the figure, t_2 increased monotonically with the length of the recovery interval inserted between the first and second display sequences. This means that the perceptual grouping and cluster movement

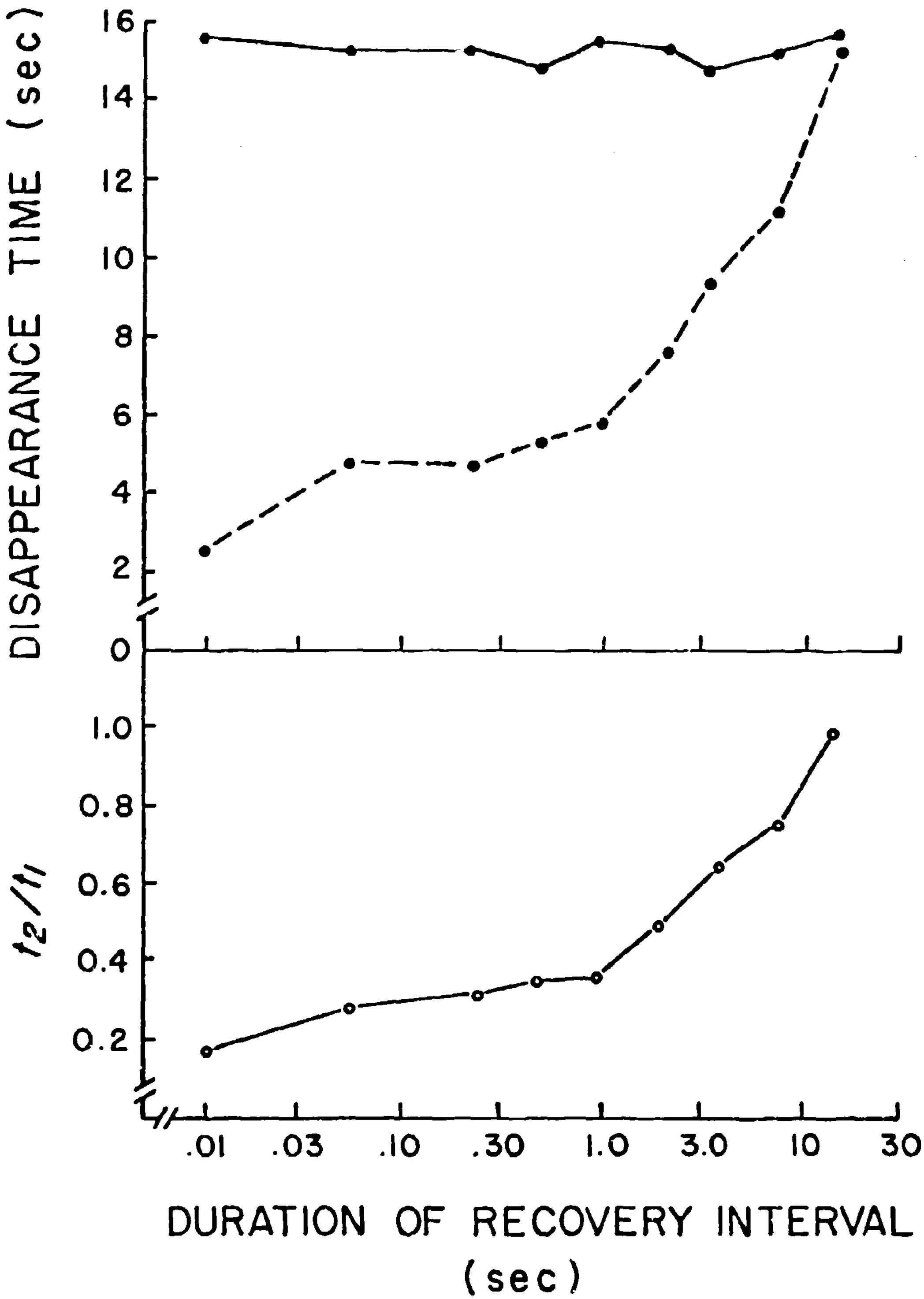


Fig. 33. Top panel: First (t_1--solid curve) and second (t_2--dashed curve) disappearance times as a function of the duration of recovery interval. Bottom panel: t_2/t_1 ratio as a function of the duration of recovery interval.

tendency was stronger and took a longer time to adapt after longer recovery intervals. The function in the bottom panel of Figure 33 gives the ratio t_2/t_1 for each recovery interval. If the processes responsible for perceptual grouping and movement were fully restored during the recovery interval, then t_2 should be equal to t_1 and the ratio would be equal to 1.0. As can be seen in the figure, full recovery from adaptation took approximately 16 sec. Recovery was fairly slow over the first 500 msec where t_2 was about one-third t_1, but increased rapidly over recovery intervals between 1-16 sec.

In the experiment just described the cluster movement display, when it is presented for the first time in a given trial, can be regarded as an adapting display, and when it is presented the second time, a test display. Viewed in this way, the experiment was an attempt to determine the effects of an adapting display on an identical test display. In the next two experiments, we had subjects view one type of cluster movement display (adapting) in order to determine what effect it had on the disappearance time measured with a different cluster movement display (test). Different types of adapting displays were used in different conditions of the experiment.

Experiment L: Components of adaptation to texture stimuli

When the inspection of one stimulus (adapting display) affects the perception of a second stimulus (test display), it is assumed that a common visual mechanism responds to both stimuli. If two entirely different mechanisms were responsible for the processing of an adapting and test display, the inspection of the adapting stimulus should have no effect upon the perception of the test stimulus. Using this logic, we conducted a cluster movement study in which observers inspected adapting displays having various degrees of similarity to a test display.

The test display was the same as the cluster movement display of the recovery experiment, i.e. contained horizontal cluster elements on vertical background elements. The adapting displays had at least six dimensions upon which they could be compared with the test display. The adapting displays and the "similarity dimensions" are summarized in Table 3. Either the displays possessed the following characteristics or they did not. A more complete description is given in the Stimuli and Apparatus section.

(1) CLUSTER--the display contained a cluster of like-oriented elements which were distinct from the background elements;

(2) BACKGROUND ELEMENT POSITION--line elements in the background were in the same position as background elements in the test display;

(3) CLUSTER ELEMENT POSITION--within each cluster the line elements were in the same position as those in the test display;

(4) CLUSTER ELEMENT ORIENTATION--within each cluster the orientation of the line elements was the same as that of cluster elements of the test display;

(5) BACKGROUND ELEMENT ORIENTATION--the background elements had the same orientation as the background elements of the test display;

(6) COMMON ELEMENTS (OTHER)--somewhere in the display there were elements with orientations the same as those found somewhere in the test display.

One simple prediction that one might make on the basis of a multi-stage model for the cluster movement sensation is that the effect of any adapting display would be directly proportional to the total number of dimensions it had in common with the test display, assuming that the dimensions were of equal importance in determining perceptual groupings and apparent movement. Referring to Table 3, the reduction of degradation

TABLE 3

SUMMARY OF ADAPTING DISPLAY TYPES AND DIMENSIONS OF SIMILARITY WITH TEST DISPLAY

	Adapting display*								
Dimension	Control (Blank)	OBOB	HH	VV	NH	PH	OB	VH	HV
Cluster					X	X	X	X	X
Background element position		X	X	X			X	X	X
Cluster element position						X	X	X	X
Cluster element orientation					X	X			X
Background element orientation				X					X
Common elements (other)			X	X	X	X		X	X
Total number of common dimensions	0	1	2	3	3	4	3	4	6

*Key:

OBOB: line elements all 45 deg clockwise off vertical

HH: line elements all horizontal

VV: line elements all vertical

NH: element positions in cluster negatively correlated with those of HV and of the same orientation, with blank background

PH: element positions in cluster positively correlated with those of HV and of the same orientation, with blank background

OB: cluster elements 45 deg clockwise off vertical on background elements 45 deg counterclockwise off vertical

VH: vertical cluster elements on horizontal background elements

HV: horizontal cluster elements on vertical background elements time would be predicted to increase from left to right across the table; i.e., displays on the right side of the table would be expected to produce short degradation times while those on the left, relatively long degradation times.

An alternative prediction might be based upon the assumption that some dimension or subset of dimensions was more important for adaptation than the others. With this assumption it would be predicted that adapting displays containing the more heavily weighted dimension(s) would reduce the degradation time of the test display substantially more than the other adapting displays. For example, if having a cluster and a background were critical, the OB, VH, and HV adapting displays would reduce test cluster degradation time significantly more than the remaining displays. Rather than a gradual difference in degradation time from the CONTROL to the HV adapting display, there would be a gradual decrease from the CONTROL to the PH display, followed by a sharp decrease in degradation time for the OB, VH, and HV adapting displays.

Subjects. Eleven subjects with normal or optically corrected vision served in the experiment either in partial fulfillment of course requirements or as paid volunteers. All subjects were naive with respect to the purpose of the experiment, and none were experienced psychophysical observers.

Stimuli and apparatus. All stimuli were generated in advance of the experiment and were stored on a disk by a PDP 11/10 computer. They were subsequently displayed on the face of an oscilloscope coated with a rapid-decay phosphor (P31) by the same computer. Each stimulus sequence consisted of two frames alternating in time. A frame consisted of line segments positioned randomly (0.5 density) in an 18 row x 22 column imaginary matrix (see Figure 30). The random positioning of line-elements in the first frame of each sequence was the same for all pairs of frames; likewise, for the second frame. The correlation between the element positions of the first frame and the second frame was zero, no matter how the frames were aligned.

Eight different pairs of stimulus frames (each pair used for a different display) were generated and classified into three categories: (a) no cluster, (b) cluster and background, and (c) cluster only. In the non-cluster frames, the line segments were all of the same orientation (all horizontal, HH; all vertical, VV; or all 45 deg clockwise from vertical, OBOB). In the cluster frames, a small area of like-oriented elements was positioned in each matrix, with the remaining elements (background) of a different orientation. In one frame the cluster (3 x 10 cell area) was positioned on the right half of the matrix and the other frame on the left (see Figures 30 and 31). In the HV frames, the cluster elements were horizontal and the background elements were vertical. For the VH frames, the cluster elements were vertical and the background elements horizontal. The third pair of cluster frames, OB, had elements 45 deg clockwise from vertical in the cluster and 45 deg counterclockwise from vertical in the background.

The third category of stimulus frames differed from the others in that a cluster appeared in each frame, but no background elements were present. In one stimulus of this type, PH, the horizontal line-element <u>positions</u> within the cluster were positively correlated (+1) with the positions of cluster elements in the test display, as were the positions of elements in the HV, VH, and OB displays. That is, the positions of all the cluster elements in the four adapting stimuli and in the test display were identical. The second cluster-only stimulus display, NH, had cluster elements whose positions were negatively correlated (-1.0 correlation) with those in the test display. In other words, the positions of the elements in the NH display were located in those imaginary cells in which no lines appeared in the test display and in the HV, VH, and OB displays.

The viewing distance, spatial dimensions of the displays and elements, and the luminance of the elements and the spaces between elements were the same as those of the last experiment.

Procedure. Subjects served in one practice session and three experimental sessions, each conducted on a different day. During the practice session, each subject observed the apparent movement of the cluster which resulted from the alternation of the two stimulus frames. Additionally, each subject was trained to make judgments about the perceptual degradation of the cluster that typically occurs after prolonged viewing. A variety of stimulus frame durations (FDs) and interframe intervals (ISIs) were used in training the subject.

Each experimental session consisted of nine trials, eight trials in which one of the eight stimulus displays (described above) was used and one control trial. A trial began with a 30-sec adaptation period followed immediately by the test display (HV). During the adaptation period one of the eight stimulus displays (or a blank screen, in the case of the control trial) was presented. The test display appeared on the screen until the subject indicated that the cluster or its movement had perceptually degraded. The adaptation frames had an on-time (duration) of 267 msec and an ISI of 117 msec. At this cycle rate the cluster, if present, did not perceptually degrade. The test sequence (HV) was always presented with a frame duration of 167 msec and an ISI of 67 msec. During each session the order of adapting conditions was randomly determined for each subject.

On each trial the subject sat facing an oscilloscope screen with his righthand resting on a teletype keyboard. The subject was instructed to view the screen with a passive "global stare," one that encompassed the entire screen. Furthermore, the subject was cautioned <u>not</u> to fixate the apparently moving cluster or any particular line segments. When the test cluster degraded and/or the apparent movement of the cluster became erratic, the subject pressed a key on the teletype in order to terminate the trial. The duration of the trial (from onset of test display to key depression) represented a single estimate of the subject's <u>degradation time</u> (DT). Three estimates of the DT were obtained for each of the nine conditions for each subject.

During the experimental sessions, the subject was instructed to request that a condition be repeated if he was not confident that the judgment made was accurate; e.g., he may have felt he blinked at a critical time or pressed the key prematurely.

<u>Results</u>. Each subject provided three estimates of degradation time for each of the nine conditions. The median DT was determined for each subject and condition. The medians were analyzed with a one-way repeated measures analysis of variance (see Table 4). There was a significant main effect due to adapting condition [F (8, 80) = 11.843, p < .001].

For each condition the individual median DTs were averaged across subjects. Figure 34 shows tha mean DT as a function of adapting condition.

TABLE 4

ANALYSIS OF VARIANCE OF INDIVIDUAL MEDIAN DTs:
EXPERIMENT L.

Source		df	MS	F
Adapting condition	(A)	8	114.710	11.843*
Subjects	(S)	10	238.498	
A x S		80	9.686	

*$p < .001$.

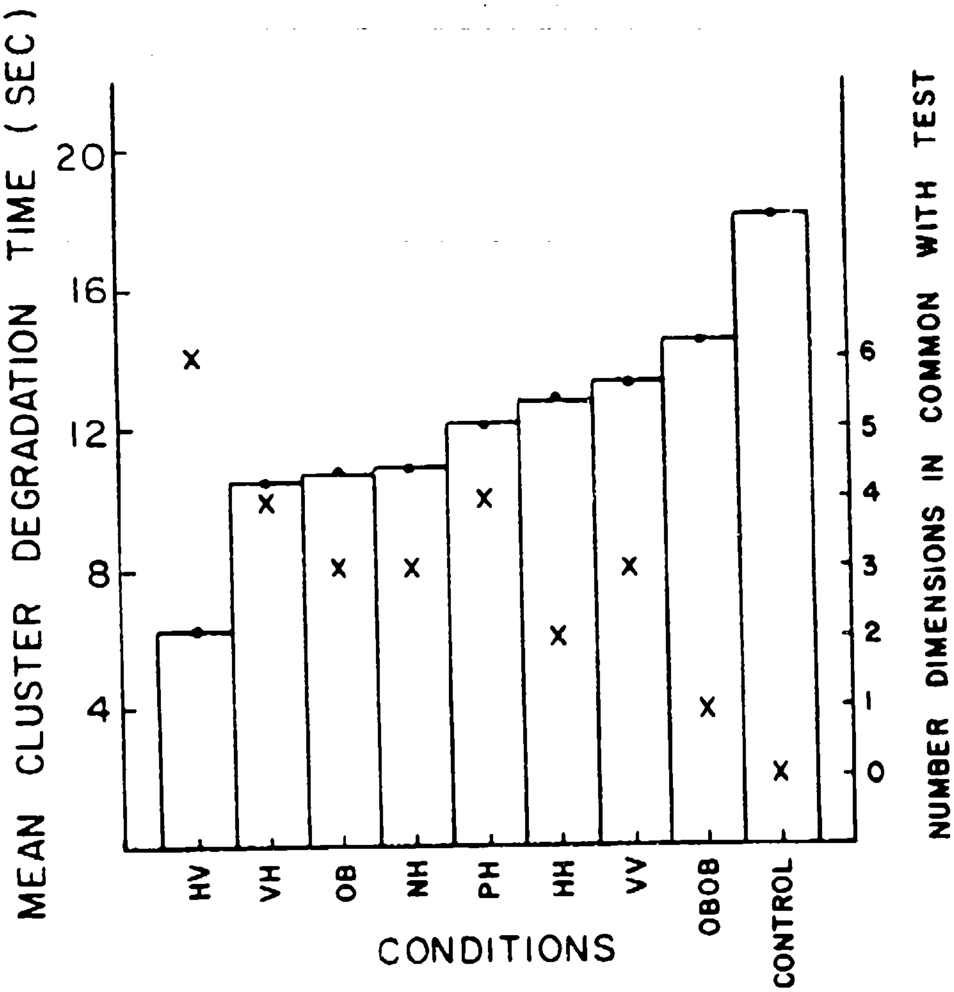


Fig. 34. Mean cluster degradation time (left ordinate) as a function of adapting condition. Right ordinate gives number of dimensions common to adapting and test displays.

The figure indicates that DT was inversely proportional to the number of dimensions in common between the adapting and test displays. A Newman-Keuls analysis indicated that the mean DT for the HV adapting condition was significantly less than that of all the other conditions, and that the mean DT for the control condition was significantly greater than all other mean DTs (all $\underline{p}$s $<$ .01). No other differences were significant (see Table 5).

Discussion. In many previous studies of object constancy and perceptual grouping using movement paradigms it has been found that visual mechanisms are quite "plastic" in what they will accept as one object in motion. Classical apparent movement experiments (e.g., Kolers, 1972; Kaufman, 1974; Navon, 1976) in which the stimuli are typically single isolated objects against a background of uniform intensity have shown that stimulus details are not critical for the perception of objects in apparent movement. However, the finding that specific detail information is not critical may, in part, be a result of the type of research paradigm used and the questions asked. Our cross-adaptation paradigm is more analytical with respect to the factors which contribute to the perception of a moving object and it provides quantitative information about the magnitude of the contribution of those factors.

Our cross-adaptation data support the following conclusions. (1) The mechanisms responsible for the perception of the moving texture cluster are to some extent affected by the detailed features of the texture cluster. There were differences in degradation time among adapting conditions which contained clusters defined by different elements. (2) At some stage in the processing of the texture cluster, there must be a representation of the cluster that is independent of the specific texture cues which define

TABLE 5

NEWMAN-KEULS ANALYSIS OF THE DIFFERENCE BETWEEN MEAN DTs
FOR VARIOUS ADAPTING CONDITIONS:
EXPERIMENT L.

Adapting condition	Adapting condition										
	HV	VH	OB	NH	PH	HH	VV	OBOB	Control	r	CR(.01)
HV	----	4.268*	4.604*	4.624*	5.847*	6.532*	7.033*	8.272*	11.844*	9	5.360
VH		----	0.336	0.356	1.579	2.264	2.765	4.004	7.576*	8	4.925
OB			----	0.020	1.243	1.928	2.429	3.668	7.240*	7	4.812
NH				----	1.223	1.908	2.409	3.648	7.220*	6	4.681
PH					----	0.685	1.186	2.425	5.997*	5	4.521
HH						----	0.501	1.740	5.312*	4	4.305
VV							----	1.239	4.811*	3	4.015
OBOB								----	3.572*	2	3.527
Control									----		

*$p < .01$.

the cluster. Otherwise, the presence or absence of a cluster in the adapting displays would not have been one of the factors which influenced degradation time. Taken together, these two conclusions suggest that the perception of the texture cluster and its movement may depend upon at least a two-stage process in which a low-pass spatial filter operation is performed on a topographic pattern of activity in arrays of feature (high spatial frequency) detectors.

Experiment M: Temporal requirements for texture processing

In Experiment L the dimensions which were used to define similarity between adapting and test displays were all spatial characteristics of the individual frames of the displays. In the present experiment on dynamic texture processing we examined the effects of the temporal characteristics of the adapting and test displays on the perception of the moving texture clusters. A second purpose of the present experiment was the introduction of a new dependent measure of cluster coherence and movement. Up to this point we employed cluster degradation time *per se* as our dependent measure. Because the degradation of the cluster sometimes appears to occur gradually over several seconds, a subject's ability to maintain a constant criterion for degradation is highly critical. Rather than ask subjects to make exact estimates of the point in time at which degradation occurred, test intervals of four different durations were used. For any given trial a particular test interval duration was chosen, and the subject rated the *degree* of degradation that had occurred within the test interval. It was felt that the new method of determining cluster degradation would be an easier task for the subject, be less susceptible to criterion shifts, and be more sensitive to small differences in degradation times across experimental conditions.

Subjects. Eight subjects with normal or optically corrected vision served in the experiment either in partial fulfillment of course requirements or as volunteers.

Stimuli and apparatus. All stimuli were generated and presented to the subjects in the same manner as in Experiments K and L. Two pairs of stimulus frames were generated, one for the adapting display and one for the test display. The HV test display was identical to that used in Experiment L. The line segments in the adapting display were in the same positions as those in the test frames. The cluster elements of the adapting display were vertical; the background elements were oriented 5 deg clockwise from vertical. The slight change in background element orientation allowed the subject to easily discriminate the change from the adaptation to the test display. The ISI was 67 msec for both adapting and test displays.

There were 12 conditions: 9 experimental and 3 control. The nine experimental conditions were made up of the factorial combination of adapting frame duration (100, 167, and 267 msec) and test frame duration (100, 167, and 267 msec). The three control conditions were similar to the control condition of Experiment L in that the adapting display was a blank screen. In the control conditions the test displays had FDs of either 100, 167, or 267 msec. The spatial dimensions of the stimuli were the same as those of Experiment K.

Procedure. Subjects served in one practice session and four experimental sessions, each 30 min in duration. The practice and experimental sessions were conducted in a manner similar to that used for

Experiment L. The major procedural change was the dependent measure used. Rather than using degradation time per se as the dependent measure, on each trial the subject was presented with one of four test display durations (5, 10, 15, or 20 sec). The subject's task was to rate the degree of degradation that occurred within each test interval using a three-point rating scale. If there was no change in the appearance of stimulus sequence during the test interval, a rating of "0" was given. If the subject was not sure, but thought that the cluster or its movement had begun to degrade or change, a rating of "1" was used. A rating of "2" indicated that the subject was fairly certain that the texture cluster or its movement had degraded.

Each experimental session consisted of 12 trials, chosen from the 48 total trials (12 conditions x 4 test interval durations). The trials presented in any session were randomly determined with the following constraint: each adapting and test frame duration and each test display duration occurred equally often in each experimental session. As in Experiment L, each trial began with a 30-sec adaptation period, followed immediately by the test display.

The experimenter initiated each trial and simultaneously started a stopwatch. The experimenter terminated the trial at the end of each test interval. After each test interval the subject gave his rating verbally.

Results. There were 48 conditions (12 adaptation-test conditions x 4 test intervals) for which each subject gave degradation ratings. Each subject's ratings were totaled over test interval duration to provide the new measure of degradation. A high total was comparable to a short degradation time in Experiment L. The individual ratings were totalled across the different test durations in order to provide a stable measure for the purpose of analyzing the main independent variables of adapting and test frame duration (FD). The degradation rating totals (DRTs) were analyzed with a 4 (adaptation) x 3 (test) repeated measures analysis of variance (see Table 6). There were significant main effects due to adaptation [F (3, 21) = 20.733, $p < .002$] and test condition [F (2, 14) = 25.517, $p < .001$]. There was no significant interaction.

For each of the 12 adaptation-test conditions the DRTs were averaged across subjects. Figure 35 shows the mean DRT as a function of adaptation and test condition. The figure indicates that all adapting conditions produced more degradation (higher DRTs) than the control conditions. Also, long FD adapting conditions tended to produce more degradation than the short FD adapting condition. However, a Newman-Keuls analysis did not show the trend to be statistically significant (see Table 7).

Figures 36 and 37 show the adaptation and test effects, respectively, as a function of the test display duration. Both figures show that more degradation was reported as the duration of the test display increased. Figure 36 also shows that adapting displays with long FDs (167 and 267 msec) produced more degradation than those with the short FD (100 msec). Figure 37 shows that the amount of degradation reported was inversely related to the duration of the frames of the test display.

The significant main effect of test FD and the tendency for adapting effectiveness to be greater with longer adapting FDs is evidence that the process responsible for the perception of the moving texture cluster is a slow-acting one. In addition, there is no evidence that the adaptation

TABLE 6

ANALYSIS OF VARIANCE OF INDIVIDUAL DEGRADATION RATING TOTALS: EXPERIMENT M.

Source	df	MS	F
Adaptation (A)	3	38.750	20.733*
Test (T)	2	98.156	25.517*
Subjects (S)	7	3.476	
A x T	6	3.156	0.671
A x S	21	1.869	
T x S	14	3.847	
A x T x S	42	4.704	

*$p < .001$.

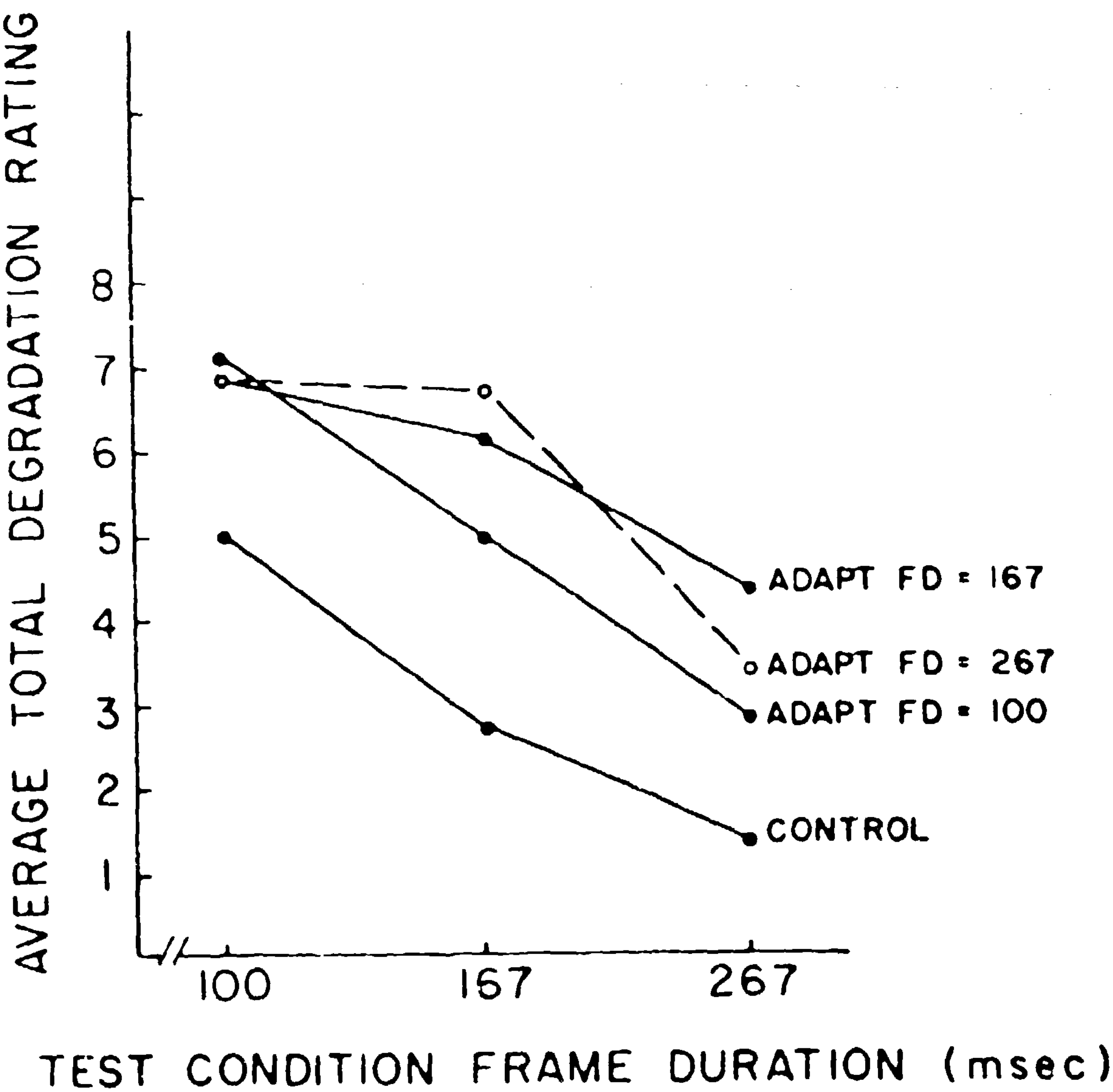


Fig. 35. Degradation rating as a function of the frame duration of the test display. Parameter for curves is the frame duration of the adapting display.

TABLE 7

NEWMAN-KEULS ANALYSIS OF THE DIFFERENCES IN DEGRADATION TOTALS FOR VARIOUS ADAPTATION CONDITIONS: EXPERIMENT M.

Adaptation frame duration (msec)	Adapting frame duration (msec)						
	Control	100	267	167	*r*	CR(.05)	CR(.01)
Control	-----	1.958**	2.625**	2.750**	4	1.105	1.401
100		-----	.667	.792	3	.999	1.295
267			-----	.125	2	.823	1.122
167				-----			

**$p < .01$.

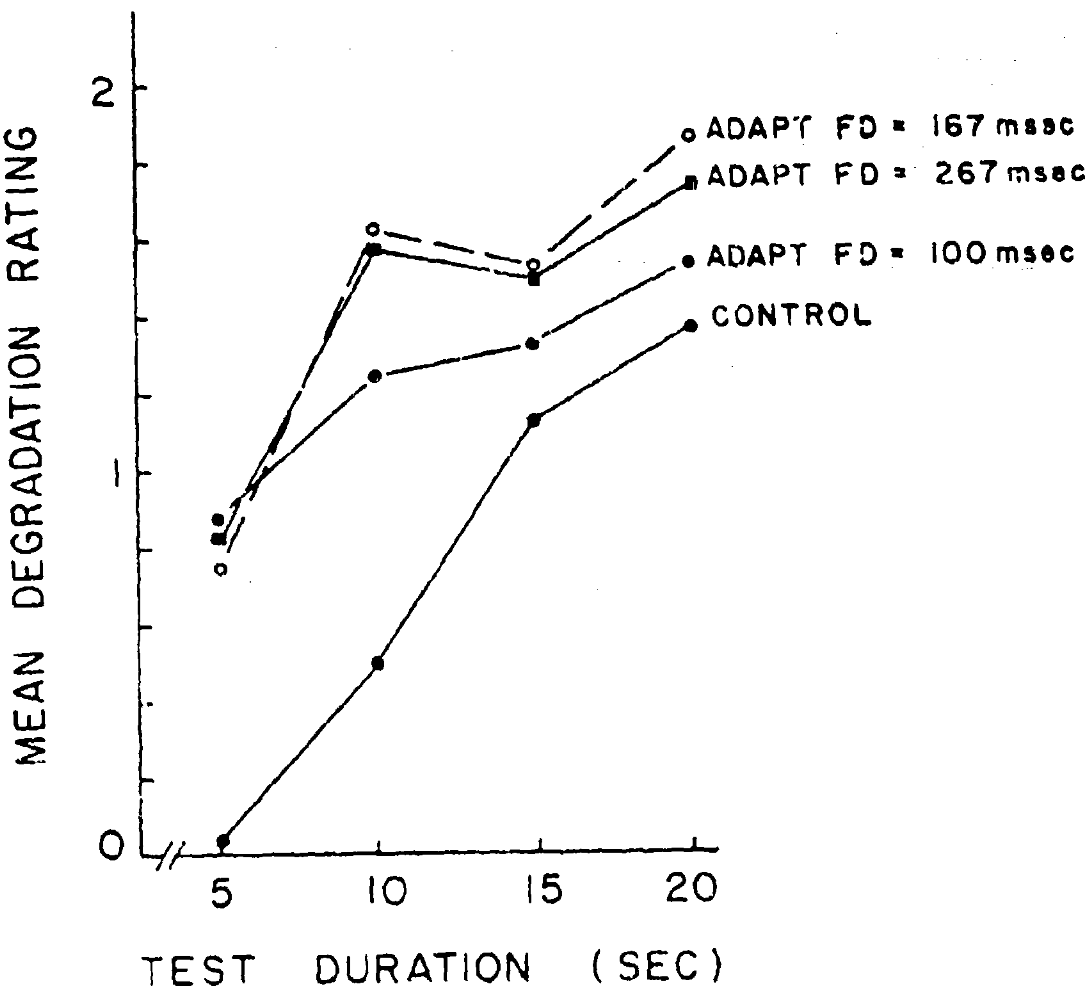


Fig. 36. Degradation rating as a function of the test interval duration. Parameter for curves is the frame duration of the adapting display.

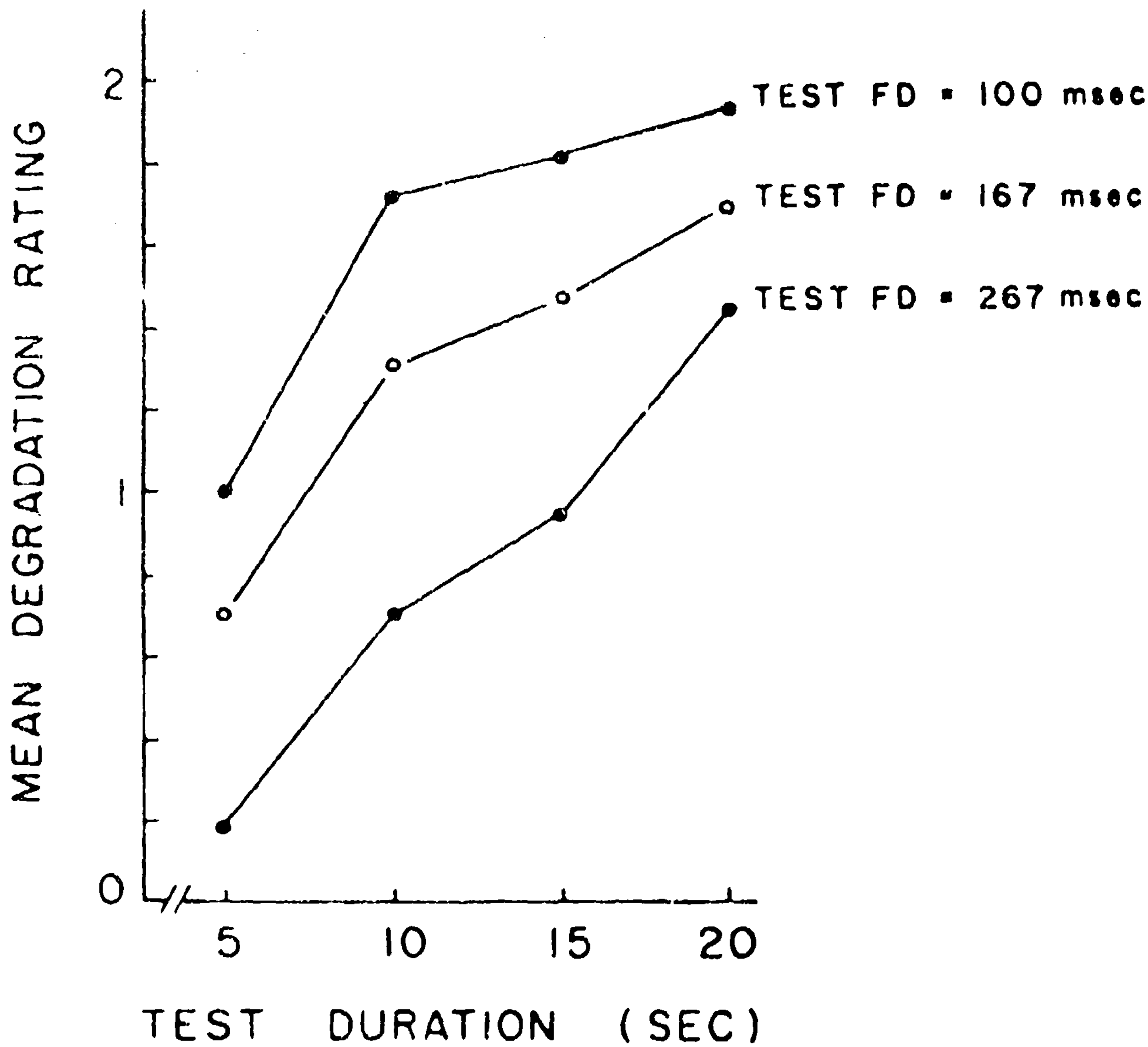


Fig. 37. Degradation rating as a function of the test interval duration. Parameter for curves is the frame duration of the test display.

produced by a moving texture is temporally selective, as is the case with a flickering disc (Pantle, 1971) or a moving sinusoidal luminance grating (Tolhurst, Sharpe, and Hart, 1973). There was no interaction between adapting and test FD, indicating that the effects of each variable were independent of the other one. The lack of temporal selectivity suggests that the displays with different temporal characteristics did not bring different dynamic texture processes into play.

CONCLUSIONS

1. Dynamic sine-wave masking experiments provide strong evidence for a sustained-transient model of visual information processing. Both qualitative and quantitative predictions of the model were verified, and unlike many previous tests of the model, the masking experiments do not depend upon the ability of an observer to maintain two separate threshold criteria.

2. The importance of the dynamic sine-wave masking results for applied problems is demonstrated by the finding that the pattern of masking effects of a background with a particular spatial frequency content upon a set of test targets cannot be predicted without knowing the temporal characteristics of both the background and the targets.

3. The shape of the overall spatial contrast sensitivity function of the human visual system has been known for some time to change as a function of temporal frequency and the level of light-dark adaptation. Our experiments demonstrate that the change of shape is at least in part due to changes in the spatial frequency response characteristics of both sustained and transient channels, and not simply a consequence of a changeover from one set of channels to the other.

4. Under conditions designed to be optimal for observing the spatial spread of an inhibitory effect of transient channels on sustained channels, we found none. The negative finding is a potential source of difficulty for some accounts of metacontrast based upon a sustained-transient model.

5. By means of a selective adaptation procedure with sine-wave

gratings, it was demonstrated that the two perceptual states evoked by a bistable motion display are attributable to the processing of different spatial frequency components. Evidence was most conclusive that low spatial frequency components processed by transient channels were responsible for the perceptual grouping and global apparent movement of the three lines in each frame of the display. If the result is generalized to other dynamic displays or to the constantly changing optic array produced by the real world, it means that some of the perceptual organization which occurs is simply a consequence of passive low-pass filtering of spatial frequency components by transient channels.

6. The visual system possesses the ability to extract or to construct a global subjective figure out of a set of correlated elements in alternating, Julesz-type random-element patterns. The results of our correlational movement studies, in which we used lines as elements, showed that the clarity of such a subjective figure decreases gradually as the orientation difference of the elements in successive frames of the display is increased. This result makes it unlikely that the first stage in the formation of the subjective figure consists of local point-by-point comparisons of the intensity distributions of the two frames. Taken together with the fact that the subjective figure emerges only when the interval between frames is short and the fact that the spatial frequency content of the frames is concentrated in the high-frequency region of the spectrum, the orientation result supports the idea that the first stage of the figure formation process involves the temporal integration of energy in successive frames by high spatial frequency, sustained channels.

7. The perception of a subjective figure based upon texture cues in

a dynamic display depends upon a process which consists of at least two adaptable components: one component involving a representation or coding of the spatial details of the individual texture elements themselves, and another component involving a representation or coding of the figure as a whole. Perhaps, the simplest integration of these two findings is to assume that the perception of figures based upon texture cues is the result of a two-stage process in which a low-pass spatial filter operation is performed on a topographic pattern of activity in arrays of feature detectors.

8. The adapting effects which are produced by the continued inspection of a moving texture stimulus, or the length of time that the coherence and movement of a texture stimulus are maintained, were both found to be directly related to the duration of the individual frames of a dynamic texture display. The time required to process a moving texture stimulus is considerably longer than that required to process a moving stimulus defined by a luminance difference between the stimulus and its surround.

9. The spatiotemporal properties of the grouping phenomena discussed under conclusions 5, 6, and 7 are different, and the steps by which perceptual organization is achieved in each case are probably different. At present the three types of phenomena can be used independently (a) to evaluate the quality of different types of dynamic displays and (b) to identify potential sources of success and failure in visual performance tasks involving human operators. More research is needed to understand the manner in which the different organizational tendencies interact and to specify more closely their relationship to a sustained-transient model.

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