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SPATIAL FREQUENCY EFFECTS IN MASKING BY LIGHT*

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Abstract—Observers detected briefly pulsed sine-wave gratings presented with various asynchronies before, during or after a 700 msec conditioning flash. Although the conditioning flash raised increment thresholds for detection of both low and high spatial frequency gratings, shapes of the masking curves differed. Curves for low spatial frequency gratings exhibited peaks at the conditioning field on and offset, resembling data reported by Crawford (1947). However, when a high spatial frequency grating was detected, no on or offset peaks were found. These results are consistent with a model of the human visual system postulating the existence of separate sustained and transient mechanisms.

INTRODUCTION

Rapid variations in the mean luminance of a visual field can produce large changes in the sensitivity of human observers. Crawford (1947) determined the time course of such sensitivity changes by presenting a brief test spot at different intervals before, during or after a half-second flash of light, which he termed the "conditioning field". When increment thresholds for detection of the test spot were measured, two main effects were found. First, threshold was elevated even when the test spot preceded the conditioning field. Second, thresholds were highest when the spot was presented at the beginning or end of the conditioning field. The higher increment thresholds produced by the conditioning field was subsequently called "masking by light" (Boynton and Kandel, 1957; Kahneman, 1968) to denote the apparent loss of sensitivity to the test target.

Crawford considered the test spot to be an unobtrusive probe which simply allowed characteristics of the conditioning field to be revealed. Although a few studies (e.g. Boynton, 1961) have investigated the role of test target characteristics in masking by changing the relative sizes of test spots and conditioning fields, the importance of test target spatial properties has not been thoroughly studied. For example, it has previously been demonstrated that spatial frequency content of a pattern may greatly influence the speed with which it is processed by the visual system. While low spatial frequency gratings are detected with short latency, higher spatial frequency gratings are processed more slowly (Breitmeyer, 1975; Lupp *et al.*, 1976; Vassilev and Mitrov, 1976; Harwerth and Levi, 1978). It therefore seems possible that spatial frequency of the test target would affect the time course of masking by light. Further, a recent study by Kitterle and Leguire (1975) investigated sensitivity to test spots and high frequency gratings at the offset of a conditioning field. The usual "ear" in the masking function at conditioning field offset was found for test spots but not for gratings. Since spots contain most energy at low spatial frequencies, this result suggests that mechanisms detecting high and low spatial frequencies may be differentially sensitive to conditioning flashes. The present experiment investigated this possibility by determining sensitivity to low and high spatial frequency sine-wave gratings in a Crawford paradigm. The results are interpreted in terms of a model of the human visual system which postulates the existence of separate mechanisms for the detection of spatial and temporal stimulus characteristics.

METHODS

Observers

The author and a second, naive observer (SH) served as subjects.

Apparatus

Observers monocularly viewed gratings and conditioning field flashes in a modified Iconix 6137-4 four channel tachistiscope. The end-plate of one channel was replaced with the face of a Hewlett-Packard oscilloscope (P31 phosphor) upon which sine-wave gratings were displayed by the standard television technique. Conditioning flashes were presented by the simultaneous on and offset of fluorescent lamps (Sylvania F6TF/CW) in two other channels. The two conditioning channels were combined by a beam splitter and filtered in order to appear nearly the same color as the CRT screen. Conditioning and grating channels were superimposed by a second beamsplitter to form a single 4.5° dia circular visual field. Since the CRT raster was continuously present, conditioning flashes were seen as a luminance step over the mean raster

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luminance of $2.4\,cd/m^2$. Onset and offset of the stimuli were controlled by an Iconix 6255 timer with associated lamp drivers and relays.

Procedure

Observers detected a 30 msec grating presentation shown with various asynchronies before, during or after a 700 msec conditioning flash. Both observers initiated each session with 10 min of dark adaptation followed by 3 min of adaptation to the raster luminance. Different psychophysical methods were used to measure grating sensitivity in the two observers. SH was tested with a two alternative forced-choice staircase paradigm. A single trial consisted of two intervals separated by 7 sec. One interval contained the test grating and the conditioning flash while the other interval contained only the conditioning flash. The observer's task was to indicate which interval contained the test grating. Individual trials were separated by a 7 sec intertrial interval. If correct on three straight trials, grating contrast was reduced by one step (0.1 log unit). An error at any time resulted in an increase in contrast by one step. A single staircase consisted of tracking threshold through seven reversal points. The first point was discarded and the following six averaged to provide a threshold value, which corresponds to the 79.6% correct point on a psychometric function (Wetherill and Levitt, 1965). This procedure was employed with parametric variations of two spatial frequency test gratings (1.0 and 7.8 c/deg) and a large number of stimulus onset asynchronies. The particular spatial frequency values employed were chosen to cover the widest possible range in order to produce the greatest difference in test target latencies. In order to produce test targets with fairly discrete Fourier spectra, it was decided to use gratings with a minimum of 4 cycles. This limited the lowest spatial frequency to about one c/deg (since the test field was 4.5°). The 7.8 c/deg value was the highest spatial frequency for which the apparatus produced enough contrast to detect the target at maximum masking.

Conditioning flash luminances of 54.8, 27.4 and $13.7\,cd/m^2$ were paired with the 1.0 c/deg test grating while only the highest flash luminance was used with the 7.8 c/deg grating. Three staircases were run for each experimental condition. MG was tested with the same stimulus conditions by method of adjustment. Both test grating and conditioning flash were presented every 7 sec. The observer modulated grating contrast with a featureless 10-turn potentiometer until the target was just detectable. Plotted threshold determinations are the geometric mean of four settings.

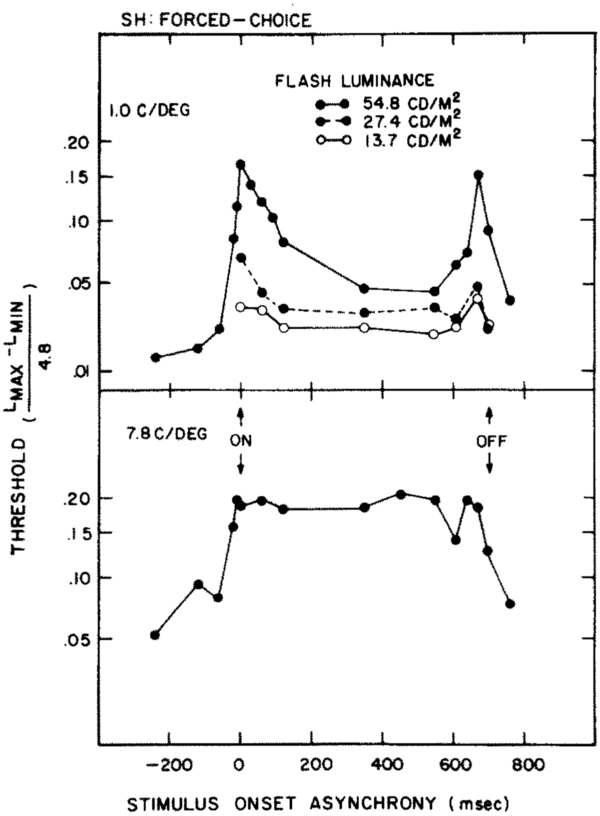

Fig. 1. Grating thresholds as a function of stimulus onset asynchrony between test target and conditioning field. The upper panel shows results for the one c/deg test grating while the lower panel shows thresholds for 7.8 c/deg test target. Data were obtained by the two-alternative forced-choice staircase method. Observer: SH.

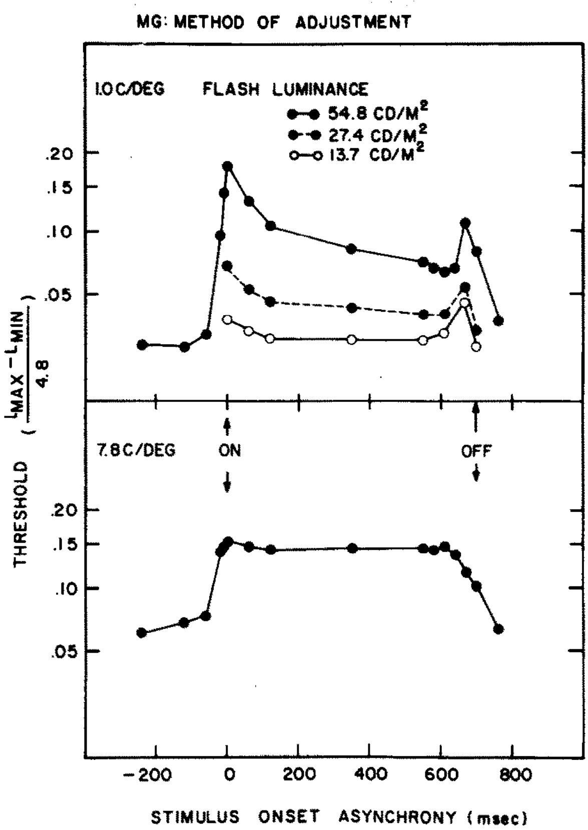

Fig. 2. Grating threshold as a function of stimulus onset asynchrony between test target and conditioning field. The upper panel shows one c/deg test grating thresholds and the lower panel 7.8 c/deg target results. Data obtained by the method of adjustment. Observer: MG.

RESULTS

Results are shown in Figs 1 and 2 where thresholds are plotted against stimulus onset asynchrony. Standard error for the most variable point was 8% for SH and 6% for MG. Negative numbers indicate the test grating preceded the conditioning flash. (Conforming to the convention used by Crawford (1947), sensitivity is plotted downward). Threshold is expressed in terms of contrast on the CRT screen as:

$$C = \frac{L_{max} - L_{min}}{4.8} \tag{1}$$

where L_{max} is peak luminance of the bright bars, L_{min} minimal luminance of the dark bars, and 4.8 is twice the mean luminance of the display. Note that the change in mean luminance produced by the conditioning flash is not taken into account. This dependent measure is therefore analogous to the ΔI measures used by Crawford because the denominator of Equation (1) is a constant.

Effects of the conditioning flash on detection of a 1.0 c/deg test grating are similar to those reported by Crawford using a 0.5° dia test spot. For both observers, thresholds peak at conditioning flash on and offset. The onset peak for observer MG was larger than the offset peak, agreeing with Crawford's data. However, the size of the peaks was similar for observer SH. This difference may reflect differences in the psychophysical procedures used with the two observers (*cf.* Teller, 1971). Two other effects reported by Crawford, backward masking beginning 100 msec before conditioning flash onset and the increased thresholds produced with increasing conditioning flash luminance, were also shown in the data of both observers. Curves obtained with 7.8 c/deg test gratings, however, were different in shape from those obtained with the lower spatial frequency test grating where threshold peaks were found at flash on and offset. Rather, threshold rises as SOA approaches zero and maintains a steady level until flash offset. Threshold begins to decrease for MG 60 msec prior to flash offset but the same effect was not demonstrated by SH. Failure to find an offset peak in the high frequency gratings has previously been reported by Kitterle and Leguire (1975). Interestingly, one of their observers shows the abrupt increase in sensitivity exhibited by SH at flash offset while a second observer resembles MG in that threshold begins to decrease well before the offset of the flash. Reasons for these individual differences are not clear.

Crawford (1947) suggested that the backward

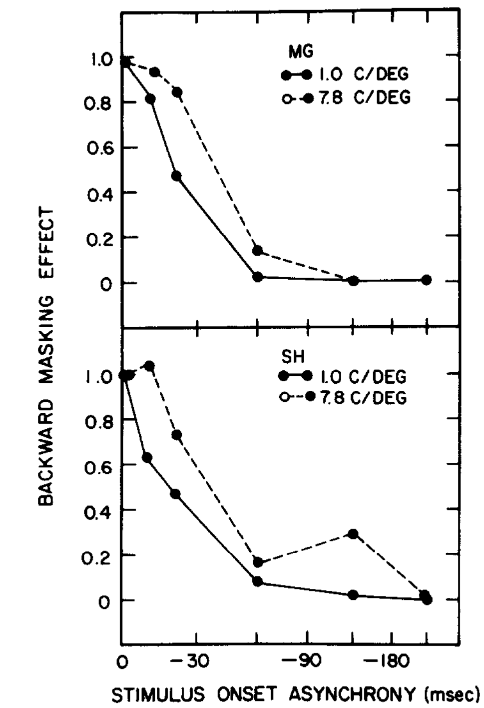

Fig. 3. Normalized backward masking effect as a function of stimulus onset asynchrony between conditioning field and test grating. Upper panel shows results for MG and the lower panel results for SH.

masking effect was caused by the conditioning flash "overtaking" the test target. Previous data (Breitmeyer, 1975; Lupp *et al.*, 1976; Vassilev and Mitrov, 1976; Harwerth and Levi, 1978) have suggested that low spatial frequency gratings are processed with shorter latency than are those of higher spatial frequency. If true, the conditioning flash should overtake the higher spatial frequency grating sooner than the lower spatial frequency grating (*cf.* Corwin, 1971). Figure 3 shows backward masking effects normalized by assigning the value zero to the threshold obtained at −240 msec and the value 1.0 to the threshold obtained at 0 SOA. For both observers threshold elevation obtained with the 1.0 c/deg test grating drops substantially when grating precedes the conditioning flash by only 10 msec. On the other hand, detection thresholds of the 7.8 c/deg grating are the same SOA at zero and −10 msec, suggesting that the conditioning flash has completely overtaken the test grating by −10 msec. Masking effects for the 1.0 c/deg grating drop to half amplitude at an SOA of about −20 msec while the 7.8 c/deg grating elevation is half at −40 msec. This 20 msec difference in processing time between these two spatial frequencies agrees well with the estimate obtained by Breitmeyer (1975) using a reaction time measure.

DISCUSSION

Previous experiments (Crawford, 1947; Baker, 1953; Boynton and Bush, 1953; Boynton and Kandel, 1957; Battersby and Wagman, 1959) which examined the effects of conditioning fields on visual sensitivity employed test targets consisting of spots of light. These studies obtained the well known "ears" in threshold curves at flash on and offset. The present study, however, found that the presence of ears depended on the spatial structure of the test target. Threshold curves for the 1.0 c/deg test grating showed peaks at conditioning field on and offset while no such peaks were found for the 7.8 c/deg test gratings. Therefore, the classic ears on the masking curve are not ubiquitous and can be obtained only under restricted stimulus conditions.

The difference in the threshold curves obtained with high and low spatial frequency test gratings might be explained by the hypothesis that different visual mechanisms mediate detection of spatial contrast and temporal change. The first idea of this sort was proposed by Sperling (1965), who suggested that the response of the visual system to luminance steps can be analyzed into two distinct components. The beginning of the step evokes an impulse response while the remainder of the flash produces a steady state response. The impulse (i.e. temporal) response produced by the briefly flashed target is drowned out by the impulse response produced by the conditioning field on and offset. Sperling supposed that the observers are therefore forced to rely on "spatial contrast" in order to detect the target at conditioning field on and offset. At other times, when the conditioning field produces a steady state response, observers can detect the "temporal pattern of illumination". Sperling is suggesting here that on and off transients mask temporal discriminations better than spatial ones. The implication is that these two classes of discrimination must be performed by different visual mechanisms.

This hypothesis is similar to the more recent notion that the human visual system contains separate mechanisms for the detection of spatial and temporal information (Keesey, 1972; Tolhurst, 1973; Kulikowski and Tolhurst, 1973). Briefly presented gratings stimulate both "transient" and "sustained" mechanisms. Since the transient system is relatively more sensitive at low spatial frequencies (van Nes *et al.*, 1967) detection of the briefly pulsed one c/deg test grating would normally be made as a "temporal discrimination". The temporal (impulse) response to the conditioning field onset and offset masked the temporal component of the grating response and forced the observer to rely on a sustained mechanism which had a higher threshold. The 7.8 c/deg test grating was presumably always detected by the sustained system and therefore showed no threshold peaks at conditioning field onset and offset. Test spots used as targets in previous Crawford paradigm experiments contained most energy at low spatial frequencies and therefore were likely detected by a temporal discrimination as were the low frequency gratings in the present experiment.

This interpretation is supported by anecdotal observations made by the observers. When presented well before, during the middle of or well after the conditioning flash, the one c/deg test grating was detected as a brief structureless flicker on the screen. When presented at conditioning field onset and offset, detection was made on the basis of the vertical striations in the target. This suggests that the temporal but not spatial properties of the test grating were masked by the conditioning field transients. On the other hand, the 7.8 c/deg test grating was always detected as a set of stationary stripes.

The explanation proposed above suggests that high spatial frequencies are detected by a mechanism which is insensitive to the transients produced by the conditioning field. However, thresholds for detecting the fine gratings were uniformly higher during the course of the conditioning flash. What caused this sustained masking effect? One possibility is that the higher mean luminance (Sperling's "steady-state response") produced by the conditioning flash decreased grating sensitivity. However, Patel (1966) has shown that higher mean luminance increases rather than decreases sensitivity. The reason for this apparent contradiction lies in the dependent variable used by different authors. Crawford and subsequent authors calculated thresholds in terms of luminance increment thresholds (ΔI) while Patel (1966) and most other authors employing grating stimuli used Michelson contrast as the dependent variable. The major difference between these measures is that contrast measures take into account change in mean luminance while increment threshold measures do not.

The analysis in Figs 1 and 2 followed Crawford's method of using a dependent measure, ΔI, which ignored the temporary change in mean luminance produced by the conditioning flash. Figure 4 shows the data for SH (data for MG are similar) replotted as a function of

$$C = \frac{(L_{max} + L_{cf}) - (L_{min} + L_{cf})}{4.8 + 2L_{cf}} \quad (2)$$

which reduces to

$$C = \frac{L_{max} - L_{min}}{4.8 + 2L_{cf}} \quad (3)$$

where L_{cf} is the luminance of the conditioning flash. This differs from equation (1) only in that the conditioning flash luminance has been added to the denominator. When gratings are presented before or after the conditioning flash, L_{cf} is 0, and thresholds are the same as in Fig. 1. (At SOA's of −20 and −10, gratings partially overlapped the conditioning flash and were arbitrarily plotted with L_{cf} as 0). Defined in this way, the contrast thresholds obtained when grat-

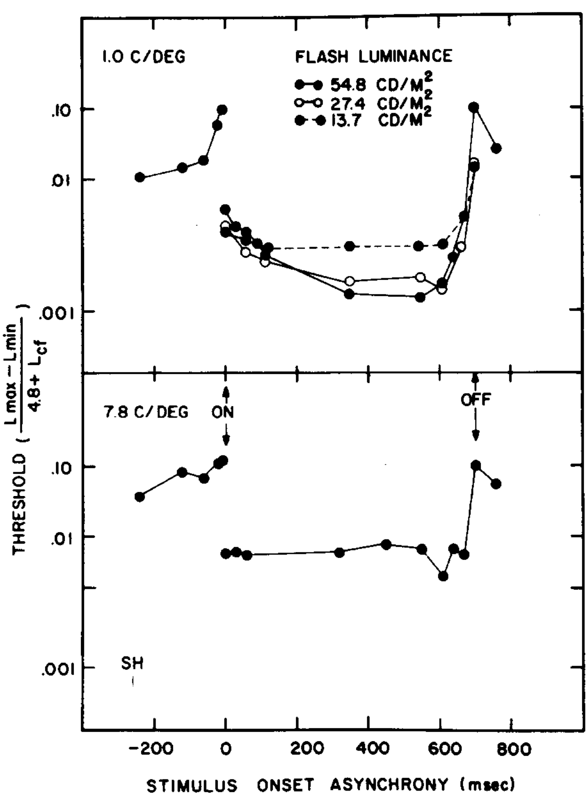

Fig. 4. Grating contrast thresholds as a function of stimulus onset asynchrony between test grating and conditioning field. Upper panel shows data for one c/deg test grating and lower panel for 7.8 c/deg test grating. Results are replotted from Fig. 1 with change in mean luminance produced by the conditioning field added to the numerator and denominator of the Michelson contrast equation. Observer: SH.

ings were presented during the conditioning flash, i.e. $L_{cf} > 0$, are lower than those obtained before or after the conditioning flash. In sum, calculating sensitivity in terms of contrast rather than increment threshold reverses the apparent effect of the conditioning field on grating detection. With low spatial frequency targets, a genuine masking effect at conditioning field on and offset is superimposed on a stronger facilitation effect due to the higher mean luminance. With high spatial frequency gratings, only the facilitation is seen.

This interpretation predicts that temporal transients produced with no change in adaptation level should mask low spatial frequency targets but have no effect on detection of high spatial frequency gratings. Several studies employing uniform fields flickered with no change in time-averaged luminance have found results consistent with this prediction. It has been demonstrated that uniform flicker masks moving but not stationary low spatial frequency gratings (Klein *et al.*, 1977), drifting gratings with spatial frequencies only as high as 4 c/deg (Green, in preparation), and wide flickering bars but not narrow ones (Stromeyer *et al.*, 1979). Green (1981) has further found that prior adaptation to flickering fields raises detection thresholds for temporal change but has no effect on detection of spatial change.

The results of the present experiment support the view that the effects of a luminance step on visual sensitivity can be decomposed into two components. One is a transient at the on and offset which masks the transient system but has no effect on the sustained system. The second is a steady state response to the higher mean luminance level. This component produces an improvement of contrast sensitivity analogous to that found when a higher luminance steady background is employed (Patel, 1966). Masking theories (Kahneman, 1968; Fox, 1978) have attempted to account for a *loss* of sensitivity produced by a luminance increment. However, conclusions about the effect of a luminance step on threshold depend on how visual sensitivity is defined.

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