Vision Res. Vol. 23, No. 7, pp. 735–744, 1983
Printed in Great Britain

0042-6989/83/070735-10$03.00/0
Pergamon Press Ltd

VISUAL MASKING BY FLICKERING SURROUNDS

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(*Received* 15 *December* 1981; *in revised form* 14 *July* 1982)

Abstract—Observers detected drifting sine-wave gratings presented in a circular 3° dia test field which was surrounded by a 3.25° wide annulus. Forced choice contrast thresholds were measured with surrounds consisting of a steady field of light or uniform sinusoidal flicker. The flickering surround raised detection thresholds only for gratings with spatial frequencies below 2–4 c/deg. Variations on the basic experiment revealed that: (1) low spatial frequency gratings drifting through the surround masked detection of uniform flicker presented to the center; (2) masking did not depend greatly on the drift rate of the test grating but could not be obtained with stationary targets; (3) flicker restricted to either the top or side borders of the test field was a sufficient condition to produce masking; (4) the size of the masking effect decreased with center–surround separation. These results suggest a destructive interaction between transient mechanisms subserving neighboring regions of the visual field.

Metacontrast   Masking   Spatial frequency   Sustained-transient

INTRODUCTION

The appearance of a visual target may be modified by the background against which it is viewed. The term "masking" defines a class of situations where the background exerts a destructive influence on some aspect of target visibility. This can occur when the target and mask occupy the same region of space or when the mask only surrounds the target. In the latter case, the paradigm is called "paracontrast" when the mask precedes the target and "metacontrast" when the target is presented first (Stigler, 1910). In the recent literature it has become increasingly common for "metacontrast" to be used as an umbrella term to refer to any situation in which mask and target do not overlap. To avoid confusion, "surround masking" will be employed here in this context.

In an early study, Werner (1935) noted that surround masking was readily obtained only with solid figures such as a disk or filled rectangle. When the target was a grating or other object with internal contours, masking was more difficult to obtain. Although Werner made no attempt to systematically vary the internal contours of the target, his results suggest that surround masking may be tuned to low spatial frequencies. Adding internal contours has the effect of removing the lowest spatial frequency components. Since this reduces masking, Werner's results might be explained by assuming that surround masking is limited to low spatial frequency components.

In this article I describe several experiments which were aimed at determining the spatial frequency tuning of surround masking. Observers viewed sine-wave gratings of different spatial frequencies which were presented within either a steady or flickering surround. Results showed that surround masking is obtained only with targets containing spatial frequencies below 2–4 c/deg.

METHODS

Observers

Four observers served as subjects during the study. All were partially aware of the purpose of the experiments.

Apparatus

Stimuli were presented by the standard television technique on the faces of two Tektronix 608 display scopes. The CRT's were placed at right angles to each other and viewed monocularly at a distance of 76 cm through a beam splitter in order to produce a single visual field. Black paper masked the displays so that one provided a central test field and the other a surround. Color and mean luminance (25 cd/m^2) of the unmodulated display rasters were matched to produce a field which was uniform except for a very fine dark line which delineated the center from the surround area and a small black circle (to aid fixation and accommodation) in the middle of the central test field. In spite of many attempts at different alignment procedures, we were never able to entirely eliminate the fine border between the target and mask. Figure 1 shows the spatial arrangements of center and surround areas used in the study. For most experiments, the central region was circular with a 3° dia and the surround was a 3.25° wide ring. A second arrangement is shown in Fig. 1B. The center and surround was adjacent but the dimensions were varied. The test field was rectangular with variable width and height maintained at 3°. In some experiments (Fig. 1C), black rings were inserted around the central area to separate it from the mask. In these cases, the center was always 3° and width of the annulus reduced.

The test stimuli were sine-wave gratings presented with no change in space-averaged luminance. Unmasked thresholds were obtained with a steady surround of the same mean luminance. Masks consisted of uniform flicker or drifting sine-wave gratings. The wave form of the flicker was either sinusoidal or noise. Noise flicker was created by randomly varying the luminance of the surround on each CRT sweep to produce an essentially flat temporal spectrum. With both classes of flicker, time-averaged luminance was the same as that of the unmodulated field. Unless otherwise stated, masks were set 1.5 log units above their own detection thresholds.

The present study resembles the more typical single-flash metacontrast and paracontrast experiment because target and mask contours do not overlap. In the single-flash experiment mask and target are presented as brief pulses separated by a fixed time interval. The paradigm used in the present study presents a more complicated temporal situation but can be related to single-flash experiments in the following way. Consider the case where the target is a drifting grating and the surround is sinusoidal flicker. A single retinal point viewing a drifting grating will see only a sinusoidal luminance modulation (flicker) as the grating moves past. If the temporal frequencies of the drifting grating and surrounding flicker are the same, then the luminance at each retinal point in the test area will be locked in phase with the luminance of the surround. The exact phase angle of the locking will vary at each horizontal location (because vertical gratings only vary in luminance along the orizontal axis). Some parts of the test field will lag behind the surround (paracontrast) in phase, some will be exactly in 0 or 180° phase while others will lead in phase (metacontrast).

Procedure

Contrast thresholds for detection of sine-wave gratings were measured by a two alternative forced choice staircase method which has been described elsewhere (Green, 1981). Briefly, each trial consisted of a pair of 2 sec observation intervals and the observers' task was to identify the correct interval. Following Wetherill and Levitt (1965), a staircase was used to produce a detection level corresponding to the 79.6% correct point on a pyschometric function. When an observer made three correct detections in a row, contrast was decreased by a 0.1 log unit step. An error at any time resulted in a one step increase in contrast on the next trial.

RESULTS

(A) Masking as a function of spatial and temporal frequency

The upper panels of Fig. 2 and 3 show the sensitivities of two observers for sine wave gratings drifting at a temporal frequency of 7.2 Hz. In the presence of a steady suround, contrast sensitivity functions for both observers exhibit only slight low spatial frequency attenuation. Introduction of 7.2 Hz sinusoidal flicker into the surround produced large changes in both the detection thresholds and suprathreshold appearance of low spatial frequency gratings. As has previously been reported by Tyler (1980), a uniform flicker annulus induced a complementary flicker into the central test field but did not cause the test area to appear different in brightness from the surround. This flicker was not restricted to the edge of the test field but appeared throughout the central area. The motion of low spatial frequency gratings drifting through the flicker appeared jerky and discontinuous while higher spatial frequency gratings drifted in smooth, continuous motion.

Reflecting this greater influence on coarse gratings, the flicker masks produced an exaggerated low spatial frequency attenuation in the sensitivity function of

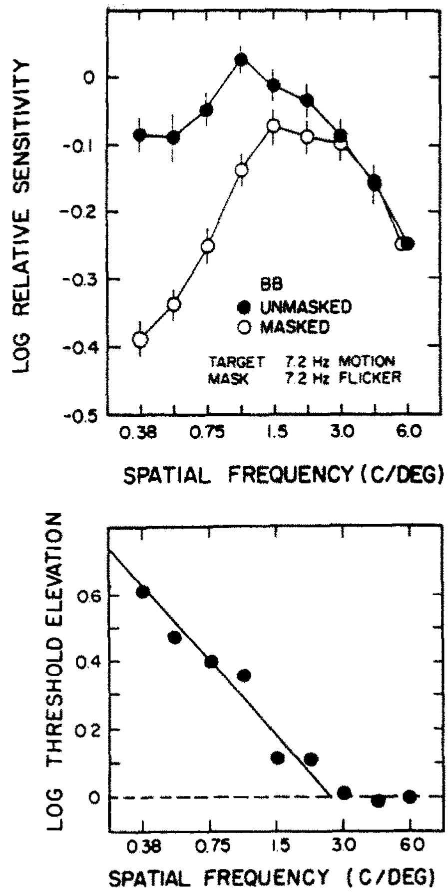

Fig. 2. *Upper panel:* sensitivity for drifting gratings as a function of spatial requency. Closed circles show data obtained with a steady surround and open circles the results obtained with a flickering surround. Vertical bars indicate ± 1 SE (estimated). Both target and mask were modulated at 7.2 Hz. *Lower panel* log threshold elevation produced by the flickering surround. The line through the data points was fit by the method of least-squares, with the thresholds from 4.2 and 6.0 c/deg excluded. Observer: BB.

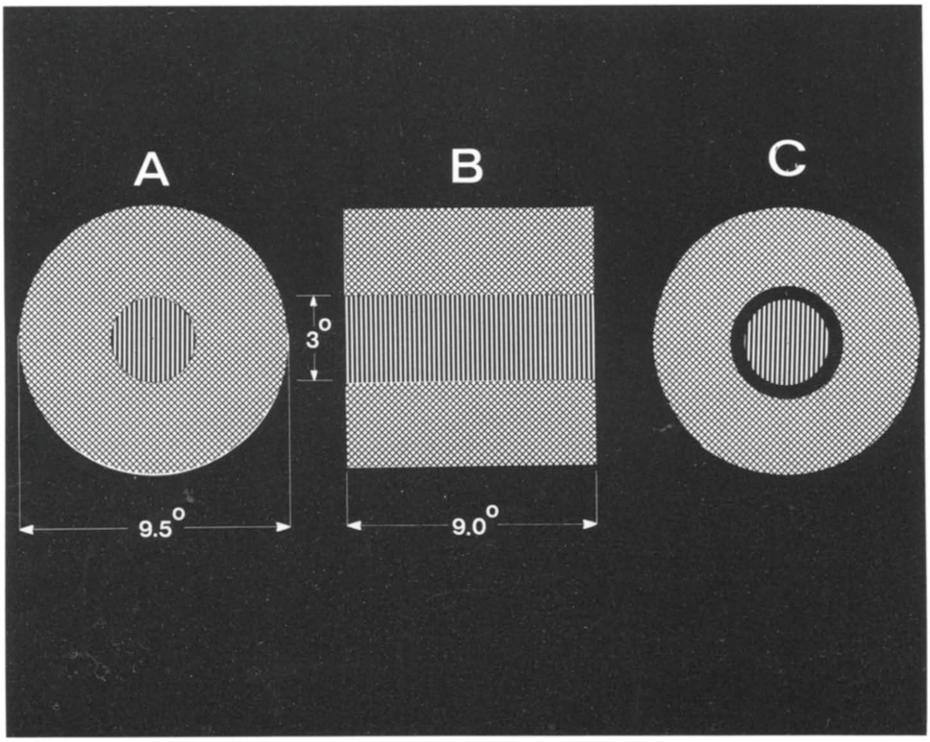

Fig. 1. Schematic representation of center–surround arrangements used in various phases of the study.

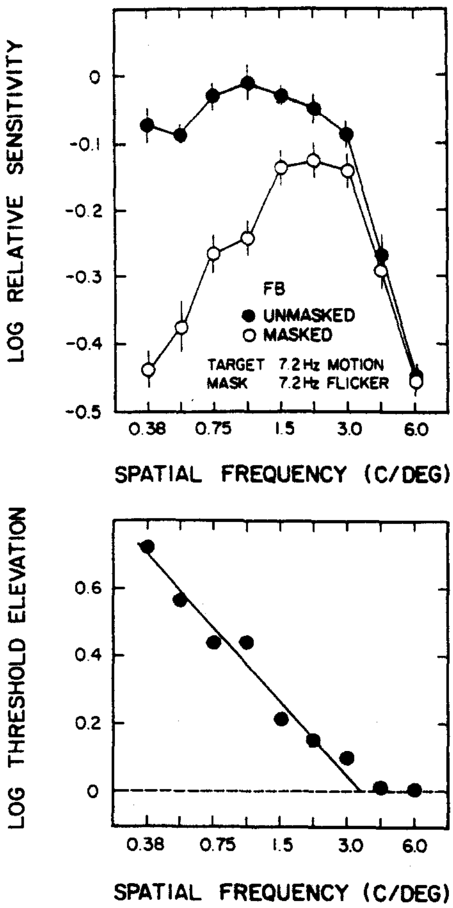

Fig. 3. Details same as Fig. 2 except that only the data point from 6.0 c/deg was excluded from calculation of the fitted curve. Observer: FB.

both observers. The effect of the mask on sensitivity diminished with increasing spatial requency. The bottom halves of the figures show the magnitude of the masking effect expressed in terms of the log of the ratio in contrast thresholds obtained with the steady and flickering surrounds. At the lowest spatial requency, the flickering surround exerted a 0.72 (FB) and 0.61 (BB) log unit masking effect. Size of the threshold elevation then decreased as a power function of the spatial frequency. Straight lines fit through the points by the method of least squares intersect the horizontal dashes, which indicate no masking, at 3.3 (FB) and 2.45 (BB) c/deg.

A similar experiment was performed with slower test gratings drifting at 3.0 Hz. Observer BB was tested with a 3.0 Hz sinusoidal flicker mask while FB viewed noise flicker. The threshold elevation curves for both observers are shown in Fig. 4. Although noise was slightly less effective than sinusoidal flicker, both types of mask produced spatial frequency tunings similar to those obtained with the higher temporal frequency. Threshold elevation curves were again decreasing power functions of spatial frequency and intersected the no-masking line at 2.4 (FB) and 3.5 (BB) c/deg. Reducing the temporal frequency did

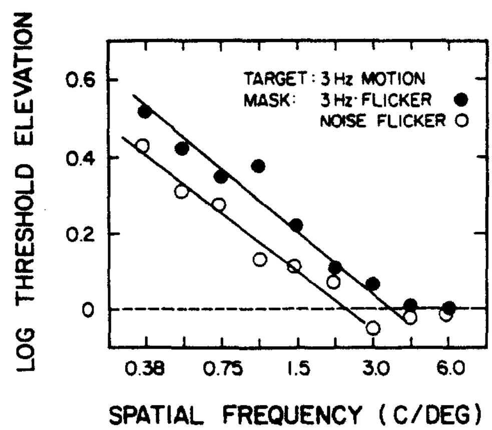

Fig. 4. Log threshold elevation produced by the mask as a function of spatial frequency. Test gratings drifted at 3.0 Hz. Closed circles show data for observer BB who was tested with a 3.0 sinusoidal flicker mask. Open symbols indicate threshold elevation produced by a noise mask viewed by FB.

not produce a systematic change in the upper spatial frequency limit for masking by the flickering surround.

In the next experiment, I examined the effect of adding internal contours to the mask. The reverse masking experiment was performed by determining depth of modulation thresholds for uniform flicker presented in the test field while the surround contained drifting sine-weave grating masks of different spatial frequency. The masking effect produced by gratings drifting at 7.2 Hz on the detection of 7.2 Hz sinusoidal flicker is shown in Fig. 5. Threshold elevation diminished as a power function of the spatial frequency of the masking gratings. The masking curve intersected the no-masking line at 4.3 c/deg. However, a comparison of Fig. 5 with Fig. 2 shows that gratings were less effective in masking flicker than flicker was in masking gratings. For example, flicker raised detection thresholds for a 0.38/deg grating by 0.61 log unit while the same frequency gratings raised flicker thresholds by only 0.38 log unit. This correlated with

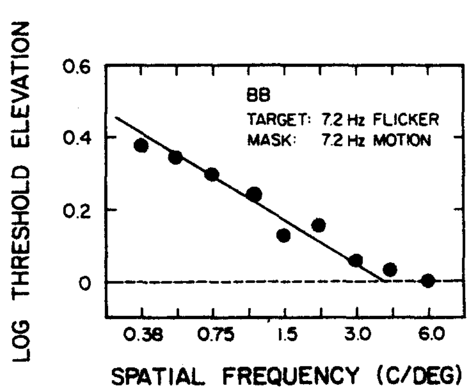

Fig. 5. Log threshold as a function of spatial frequency of drifting sine-wave grating masks. Rate of temporal modulation for grating masks and flicker targets was 7.2 Hz. Observer: BB.

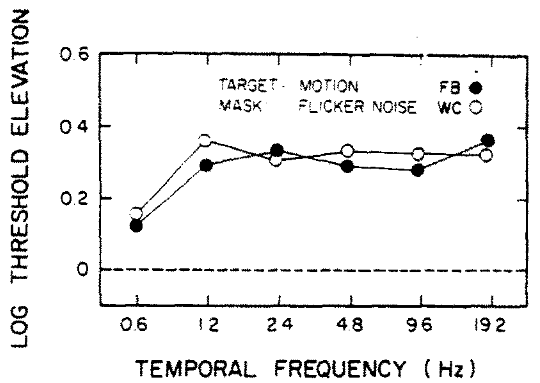

Fig. 6. Log threshold elevation as a function of temporal frequency of a target grating with a spatial frequency of 0.54 c/deg. Closed symbols show data obtained from observer FB and open symbols data from WC.

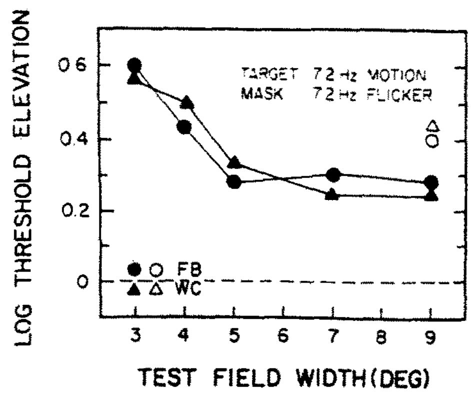

Fig. 7. Log threshold elevation for grating detection as a function of width of the test field. Vertical extend was maintained at 3°. Test grating spatial frequency was 0.54 c/deg and both target and mask were modulated at 7.2 Hz. Circles and triangles represent the data for two observers.

the observation that although grating surrounds induced apparent flicker into the center test field, its vividness was less pronounced than the flicker produced by modulation of a uniform surround. Moreover, the ability of gratings to induce flicker diminished with increasing spatial frequency.

I also examined the effect of noise flicker masks on the detection thresholds of gratings drifting at different temporal frequencies. Figure 6 shows the threshold elevations obtained with a 0.54 c/deg gratings drifting at temporal frequencies ranging from 0.6 to 19.2 Hz (1.1–35.5 deg/sec). Size of the threshold elevation was constant at about 0.3 log unit for all drift rates down to 0.6 Hz, where the masking effect began to decline. We also investigated whether motion of the target was a necessary condition for surround masking. Two observers were tested with stationary gratings switched on and off with a gradual cosine temporal envelope in order to avoid temporal transients. Flicker surrounds produced no masking effect in either observer. These observations show that motion of the test grating is necessary to obtain surround masking. However, the rate of motion need not be great.

(B) *Masking as a function of test field dimensions*

The results of the initial experiments demonstrate that surround masking is limited to test gratings below the 2–4 c/deg range. This result suggests that masking desensitizes only mechanisms tuned to low spatial frequencies. There is, however, an alternative explanation. Since test field size was kept constant, targets of different spatial frequencies contained different numbers of stripes: low spatial frequency targets consisted only of a few stripes while high spatial frequency targets contained a large number of stripes. It is possible that masking depends on the number of bars in the test field. This interpretation is plausible because the central and outer portions of a grating may not be equally affected by the surround. Tolhurst and Thompson (1975) concluded that the central area of a circular grating patch was less affected by the surround than was the portion immediately adjacent to the surround. When the target consists of many fine stripes (high spatial frequencies), the center may contain a few which are immune from masking and can be detected equally well whether or not the mask is present. If there are only a few coarse stripes (low spatial frequency) each stripe covers a large area of the test field and is not localized in the center. As a result, these would therefore be more susceptible to masking. In the next phase of the study, the field size was varied to alter the number of stripes in the target.

The previous experiments employed only test targets presented in a circular 3° dia test field. The central test region was enlarged, and the number of stripes in the target was increased by using the center–surround arrangement shown in Fig. 1B. The display was masked down to a 9° wide square and the test field height was maintained at 3° while its width was varied from 3 to 9°. Thresholds were measured for a 0.38 c/deg grating drifting at 7.2 Hz in the presence of a steady surround or a sinusoidal flicker mask of the same temporal frequency. Figure 7 shows the threshold elevations obtained with different width test fields. The maximal threshold elevation occurred with the narrowest test field. Enlarging the target to 5° reduced the masking effect by about one-half but further increases in width produced little additional change. Increasing the number of stripes weakened masking but did not abolish it. Therefore, the absence of masking with high spatial frequency gratings is not due to the increased number of stripes. Note that when the central test field was 9° wide, the flicker mask consisted only of 3 × 9° horizontal bars at the top and bottom of the target. Therefore, flicker at the vertical edges of the grating was not a necessary condition for surround masking. We also investigated a situation there the target was 3° wide and 9° high, so that flicker was present at the sides of the grating but not at the top and bottom. This condition (open symbols) also produced a threshold elevation which demonstrated that flicker on the sides of the target was a

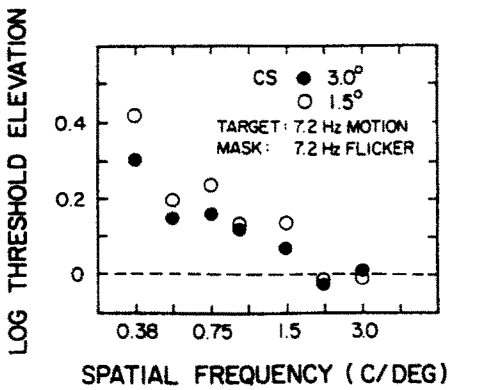

Fig. 8. Log threshold elevation for detection of sine-wave gratings as a function of spatial frequency. Gratings were presented in a field 9° wide and 3.0° (closed symbols) or 1.5° high (open symbols). Temporal frequency was 72. Hz. Observer: CS.

sufficient condition for masking. Although increasing the height to 9° also reduced the amount of the masking, the reduction was less than occurred when the width was expanded.

Enlarging the test field width, like increasing spatial frequency, had the effect of multiplying the number of stripes in the target grating. If magnitude of masking depended only on the number of stripes in the display, then masking should occur at lower spatial frequencies in a wide display than in a narrow one. To test this possibility, we redetermined spatial requency tuning of masking with a test field 9° wide (flicker only at the top and bottom) and 1.5° or 3.0° high. Results for this experiment are shown in Fig. 8. The data are qualitatively similar to those obtained with the smaller test field. Masking is greatest with the lowest spatial requency and dminished with increasing number of stripes. Although the shorter test field produced slightly greater masking, the threshold elevations produced with the wide field were smaller than those produced by the circular 3° field. The data are also noisier so that a line was not drawn through the data points. However, a curve computed by the least-square method would intersect the no-masking line at 1.88 c/deg for the 1.5° field and 1.95 c/deg for the 3.0° field. Even though obtained with a field three times the width, these values are only slightly lower than those obtained in Figs 2 and 3.

(C) *Masking as a function of center–surround separation*

Previous studies have shown that spatial separation of the target and surround may affect the strength of masking. Alpern (1959), for example, found that a 2° separation completely eliminated metacontrast. However, studies of the "periphery effect" (e.g. Valberg and Breitmeyer, 1980; Breitmeyer *et al.*, 1980) have demonstrated that masking of a central target may occur even when the surround is removed from the test field by distances much greater than 2°. In the next experiment, the center–surround separation was varied in order to determine whether the masking found here resembles metacontrats or the periphery effect.

The effect of separating the borders of the grating target and flicker surround was investigated by employing the display shown in Fig. 1C. Black rings of various widths were inserted around a 3° dia test field. This was accomplished at the expense of the surround width. Thresholds were measured for a 0.54 c/deg grating drifting at 7.2 Hz with and without sinusoidal masks of the same temporal frequency. Observer BB was tested with fixation directed at the enter of the target or at a mark located 4° below the center (to test for effects of retinal locus) while data were obtained from observer FB only with central fixation. The top panel of Fig. 9 shows that contrast sensitivity decreased as width of the dark rings increased. A ring 2° in width produced a 0.15–0.2 log unit loss compared to the sensitivity obtained with no ring. (Remember, however, that there was a fine dark line in the "no ring" condition.) Previous studies have likewise demonstrated that dark surrounds decrease sensitivity to low spatial frequency gratings. Estevez and Canonius (Estevez and Canonius, 1976), for example, showed that even a 12′ wide dark flank could cause a 0.4–0.5 log unit increase in contrast threshold. The size of their effect is considerably greater than the one found here. This difference may lie in the use of drifting gratings in the present study. All other studies which investigated the effects of sur-

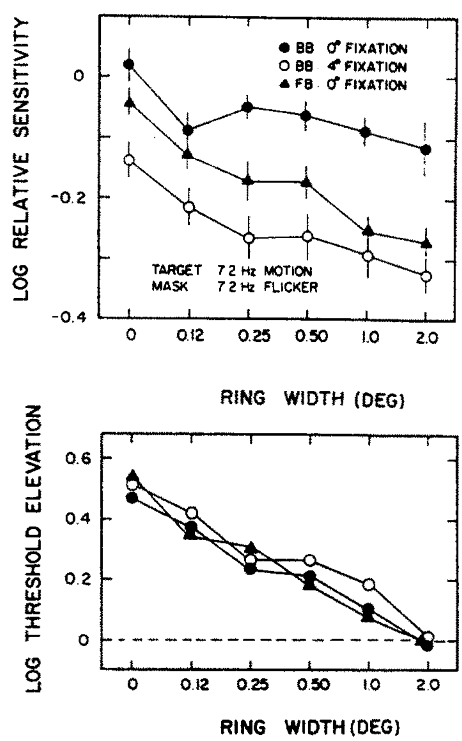

Fig. 9. *Upper panel:* sensitivity for drifting gratings as a function of the width of a surrounding black ring. Vertical bars indicate ± 1 SE (estimated). *Lower panel:* log threshold elevation as a function of width of the surrounding black ring.

round luminance on contrast sensitivity employed stationary gratings.

The lower panel of Fig. 9 shows the masking effect produced by flicker as a function of center–surround separation. Data for both observers and both fixation conditions are similar. Masking declined from a maximum in the no-ring condition to 0 when the target and mask were separated by 2°. In addition to a reduction of masking, widening the center–surround separation weakened the apparent strength of the induced flicker. Both observers noted that induced flicker was absent with a 1° separation, although this condition produced a measurable masking effect. In sum, the present data exhibit the same 2° critical separation found in metacontrast (Alpern, 1953). Masking only occurs between mechanisms subserving adjacent regions of the retina.

DISCUSSION

The results of the present experiment support Werner's (1935) observation that adding internal contours to the target reduces surround masking. While Werner's conclusion was based only on the comparison of a solid rectangle with a single grating, it was shown here that systematically adding stripes to the test field (increasing spatial requency) first weakened and then completely eliminated masking. The upper limit at which masking could be obtained fell in the 2–4 c/deg range. However, no masking occurred at any spatial frequency unless the gratings drifted. Werner's observations were further extended here by finding that the addition of internal contours to the mask also reduces masking: surrounding gratings masked a uniform test spot only when spatial frequency was below 4 c/deg. Therefore, high spatial frequency in either mask or target reduces or eliminates surround masking. Similar results have also been demonstrated in situations where the target and mask overlap. I have shown that overlapping flicker masks drifting gratings with spatial frequencies below 4 c/deg (Green, 1980, 1983; see also Breitmeyer and Levi, 1981; Stromeyer *et al.*, 1979; Green, 1981a), that prior adaptation to uniform flicker produces a loss of sensitivity to gratings below 4 c/deg (Green, 1981b) and that adaptation to drifting gratings below 4 c/deg produces a motion aftereffect in uniform flickering fields (Green *et al.*, 1983). Whether flicker is surrounding, overlapping or viewed prior to the target grating, similar spatial frequency tunings are seen.

A series of experiments by Dember and colleagues also demonstrate that adding internal contours decreases the effect of surround masking. In these studies, observers discriminate between a uniform black disk and a target disk which were presented immediately before a surrounding annulus (metacontrast). Targets consisted of disks divided into various numbers of alternating white and dark stripes (Dember *et al.*, 1974) or pie-shaped wedges (Cox and Dember, 1970; Dember *et al.*, 1973; Dember and Stefl, 1972; Arand and Dember, 1978). Unlike the present study where the observer was required to detect contrast, the task in Dember's studies was simply luminance discrimination. However, the results of these studies were similar to those reported here: masking was greatest with the coarsest patterns and declined with increasing number of target elements. With the very finest patterns either no masking or a facilitation was obtained.

One study in the literature, however, appears to suggest that high spatial frequencies play an important role in surround masking. Growny (1976) studied masking with unpatterned disks and annuli containing sharp or blurred (high spatial frequencies reduced) edges. The data showed that masking was much greater when target and surround edges were sharp than when blurred. This appears to contradict the present study since it apparently demonstrates that high spatial frequencies are critical for surround masking while we found low spatial frequencies to be of primary importance. One reason for the difference may be methodological. Both the present experiments and those of Dember used a forced-choice detection measure while Growny employed suprathreshold magnitude estimation. However, my results agree with those of Werner (1935), who also used suprathreshold judgements. Another explanation might be that I varied spatial frequency by altering the internal spatial structure of the stimuli, a procedure which had no effect on target–mask separation. The method used by Growny may have confounded spatial frequency and separation. Blurred stimuli in his study were created by removing light from the edges of the test disk and annuli and adding it to the center. This is effectively producing a partial separation between mask and target. The reduced masking with blurred targets may have resulted from greater target–mask separation and not the absence of high spatial frequencies.

To account for the loss of effect with addition of internal contours, Werner (1935) as well as subsequent authors (e.g. Growny, 1976; Growny and Weisstein, 1972; Weisstein *et al.*, 1975) have supposed that the surround masking effect is due to a local interaction between the outer edges of the target and the inner edges of the surround. By adding internal contours, edges are introduced at locations further removed from the surround. The greater separation between the inner contours and surround presumably weakens local interactions and masking is diminished. However, the results of the present study cast doubt on this explanation. Figure 8 shows that the low-pass spatial frequency tuning of masking was obtained even when flicker was restricted to the top and bottom of the target gratings. Since there is no flicker at the sides, increasing the number of stripes did not change the distance between the internal contours and the mask. Therefore, loss of masking with higher spatial frequencies cannot be due to increased edge–mask separation. Moreover, similar spatial frequency tuning was obtained when the center was a uniform flickering disk and the number of stripes in the surround was varied. The non-local nature of masking was also supported by the anecdotal reports of the observers. With such large test fields as were used here (at least 3° wide), it would be expected that local masking would not result in a uniform loss of contrast across the test field. Rather, the gratings would be more visible at the center than the edges of the target (cf. Tolhurst and Thompson, 1975). However, observers unanimously agreed that masking appeared uniform across the test field. It seems that surround masking involves spatially extended mechanisms rather than local interactions.

Other studies also support the view that surround masking is not due to local interactions between mask and target edges. First, the pie-shaped wedges used by Dember were designed so that all internal contours were equidistant from the mask, regardless of fineness of the pattern. In spite of this he found the best masking with targets containing the largest wedges. Second, in a study by Petry and Hood (1978), masking was measured with a test spot placed near the edges of the surround or in the center of the test area. The effects of the mask were identical for both targets, leading Petry and Hood to conclude that masking was not restricted to the edge of the surround but uniform throughout the test field. Third, the spatial frequency tuning obtained here is identical to that resulting from overlapping flicker (Green, 1980, 1982) or prior adaptation to flicker (Green, 1981b). Moreover, loss of sensitivity could not be obtained in many of these experiments if test gratings appeared stationary. The similarity of results obtained with surrounding and overlapping flicker suggests a common mechanism is involved in both situations.

An alternate hypothesis to account for the spatiotemporal properties of surround masking can be framed in terms of the sustained transient dichotomy. According to this model, the human visual system contains two separate mechanisms for the processing of spatiotemporal information (Keesey, 1972; Tolhurst, 1973; Kulikowsky and Tolhurst, 1973). The transient system is more sensitive at low spatial and high temporal frequencies. The role of this mechanism is to signal the presence of temporal change. The sustained system responds best to low temporal and high spatial frequencies and is presumably responsible for coding spatial pattern. Data from both the present and previous studies suggest that surround masking occurs under conditions where both enter and surround would likely stimulate the transient system. First, the range of gratings over which we obtained a masking effect matches previous estimates of the spatial frequency tuning of the transient system (Kulikowski and Tolhurst, 1973; Legge, 1978; Wilson, 1980; Green, 1980, 1981a,b). Second, several studies (Tolhurst and Thompson, 1975; Klein *et al.*, 1974) have failed to produce a masking effect by a steady presentation of a central target surrounded by a stationary masking grating. However, when the central and surround gratings are briefly flashed, (White and Lorber, 1976; Rogowitz, 1980) masking occurs. In the present study, no masking occurred unless the gratings moved.

The view that surround masking can be interpreted in terms of the sustained-transient dichotomy is not new. It has been proposed by Weisstein *et al.* (1975) that paracontrast occurs when sustained mechanisms stimulated by the surround inhibit transient mechanisms responding to the center. Breitmeyer and Ganz (1976) suggested that paracontrast is due to a sustained on sustained interaction while metacontrast represents inhibition of the sustained system by the transient system. Although the present paradigm does not fit neatly into the category of metacontrast or paracontrast, these explanations do not seem valid in the present situation since they all involved the sustained system. We only found masking with drifting low spatial frequency gratings which convey little form information and are poor at stimulating the sustained system. However, surround masking can occur with Vernier acuity targets (Breitmeyer, 1978), which presumably stimulate the sustained system, are employed. It is possible that surround masking can be produced by a variety of mechanisms, depending on the exact stimulus conditions which are chosen by the experimenter. For example, some metacontrast studies find monotonic backward masking functions while other studies produce U-shaped masking curves (Kahnesman, 1968). The monotonic curves may represent transient on transient interactions while the U-shaped functions may result from transient on sustained masking.

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