

# Masking with minimal contours: Selective inhibition with low spatial frequencies

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Paracontrast and metacontrast magnitudes were measured in a target identification task. A particular class of illusory contours is described that did not mask in the paracontrast condition but did show a large metacontrast magnitude. The discontinuity in the masking function is interpreted in terms of the Fourier decomposition of the visual scene that is performed by cells selectively responsive to discrete bands of spatial frequencies. The class of contours that we describe can only mask through inhibition generated by their low spatial frequencies. These results are consistent with recent models of masking based on two independent modes of inhibition—within sustained visual channels, and between sustained and transient visual channels.

One of the most important developments in visual psychophysics has been the discovery and classification of cells that are selectively responsive to different bands of spatial frequencies. Psychophysical and electrophysiological measurements (for reviews, see Breitmeyer, 1984; De Valois & De Valois, 1980; Graham, 1981; Shapley & Lennie, 1985; chap. 4) give evidence that the visual scene is represented in early vision in terms of a coarse Fourier decomposition, and that different pieces of the spectrum are processed by independent channels. Recently these ideas have been introduced into a theoretical framework for visual pattern masking (Breitmeyer, 1984; Breitmeyer & Ganz, 1976).

Pattern masking is a phenomenon in which perceived contrast or clarity of contour for one stimulus decreases as a result of the presentation of a second stimulus. In paracontrast (mask precedes target) and metacontrast (target precedes mask) masking, there is no overlap between mask and target contour. In this paradigm, it is generally possible to identify that a target has been shown, even when the target suffers contrast reduction and blurring (Breitmeyer, 1984). The loss of contour detail and contrast without complete elimination of stimulus detection suggests that masking operates by differentially affecting the processing of the high-spatial-frequency content of the stimulus. The central idea of Breitmeyer and Ganz's (1976) theory is that there are two independent modes of inhibition acting on the channels that process high spatial frequencies. According to this theory, paracontrast masking is achieved primarily by intrachannel inhibition caused by an antagonistic center-surround interaction within the

receptive field of a single cell. It is theorized that metacontrast masking is produced by center-surround interactions (as in paracontrast) and by an additional interchannel inhibitory interaction in which cells receptive to low spatial frequencies inhibit cells tuned to higher spatial frequencies. The proposed distinction between paracontrast and metacontrast is accounted for by the different temporal properties that characterize cells tuned to different bands of spatial frequency; shorter latencies and more rapid decays are associated with cells processing low spatial frequencies. Thus when mask precedes target, the cellular activity associated with the low-spatial-frequency content of the mask will decay before the high spatial frequencies of the target are processed.

The motivation for the present study arose from the notion that metacontrast operates via two modes of inhibition, whereas paracontrast operates via a single mode. The presence of an interchannel mode in metacontrast suggests the existence of masks that operate in a single direction, that is, masks that work only when the target is shown first. Such a one-way mask would be unable to use its high spatial frequencies for masking.

Contour elements can be arranged so that there is a minimum of within-channel inhibition on enclosed targets. Since cells sensitive to high spatial frequencies have physically small receptive fields, minimizing the degree of adjacency between target and mask decreases the strength of antagonistic center-surround interactions. Several studies have shown that metacontrast magnitude decreases with contour separation between mask and target (Alpern, 1953; Breitmeyer & Horman, 1981; Breitmeyer, Rudd, & Dunn, 1981; Growney, Weisstein, & Cox, 1977; Kolers, 1962; Kolers & Rosner, 1960; Weisstein & Growney, 1969).

We consider here masks that have contours that terminate on the target boundary but are everywhere orthogonal to the boundary. Masks that have this property are all of one class, and we will call them *minimal contour* masks. Examples of minimal contours are well

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known in the illusory contour literature; they take the form of radiating spokes that terminate on the illusory contour that they suggest (see Halpern, Salzman, Harrison, & Widamen, 1983; Kanisza, 1976; Stevens, 1983; for examples of this illusion).<sup>1</sup> The illusory contour shown in Figure 1A (adapted from Kanisza, 1976) is minimal and is expected to elicit a minimum of intrachannel inhibition in sustained cells. Consequently, this mask should be unable to produce paracontrast masking in tasks in which edge discrimination is required. The completed contour mask in Figure 1B has contour adjacent to the target (Figure 1C) and should show masking in both the paracontrast and metacontrast conditions.

The notion of using incomplete contours in masking is not novel. Sherrick and Dember (1970) showed that incomplete contours could produce metacontrast masking, and that the masking magnitude grew monotonically with contour completion. We extend this work to show that a similar result is not obtained in paracontrast and that this asymmetry can be interpreted in terms of the spatio-temporal properties of the inhibiting cells.

The spatial constraints on mask and target contour separation that are so critical for within-channel inhibition are considerably relaxed when the inhibition is between low- and high-spatial-frequency channels. Cells responding to low spatial frequencies are primarily sensitive to overall contrast changes; the spectral power at zero frequency is, in fact, the average contrast.<sup>2</sup> Within large limits, virtually any contrast in the mask may be available for reduction of edge detail or brightness in the target.

The relaxation of geometric constraints in interchannel inhibition has been observed in studies that have focused on the interaction between target-mask spatial separation and the retinal locus of stimulation. These studies have taken advantage of the gradient in average recep-

tive field size across the retina, which is reflected in a trend for intrachannel inhibition to dominate in the fovea and for interchannel inhibition to dominate in the periphery. Consequently, small separations dramatically reduce foveal metacontrast (Kolers & Rosner, 1960), whereas in the periphery, strong metacontrast is observed with separations up to 2° (Alpern, 1953; Growney et al., 1977).

Minimal contours can act as masks through the interchannel mode of inhibition simply because their elements have an overall positive contrast. In this sense the only difference between the minimal and completed masks in Figure 1 that is relevant for interchannel inhibition is that there is more overall stimulation in the completed contour mask. The detailed masking function of a minimal contour mask is distinctive because it operates only in the metacontrast regime. In terms of the detailed masking function, minimal contour masking should show a mathematical discontinuity at the juncture of the paracontrast and metacontrast regime, where time order of mask and target is reversed.

## METHOD

### Subjects

Two graduate students at the University of Virginia participated in the study. Both subjects had normal acuity and were experienced psychophysical observers. H.H. was a male aged 25; E.M. was a female aged 25. The subjects were paid participants and were naive as to the purpose of the study.

### Stimuli and Apparatus

The stimuli are shown in Figure 1. The stimuli were viewed binocularly at a distance of 127 cm. The diameter of the completed and illusory contours was .72°, and the diameter of the target disks was .58°. The distance between the centers of the two circular contours (real contours in the completed contour mask and illusory contours in the minimal contour mask), and between the centers of the target disks, was 1.48°. From each disk a .08° chop from the edge was deleted. The thickness of the real contour and of all lines in the masks was .03°. All stimuli were black figures on a white background. The masks and targets were drawn in black ink. Each target card consisted of two disks from which chops had been deleted (i.e., there were no complete disks). An example is shown in Figure 1C. All 16 possible combinations of chops were used in the study. These targets are similar to those used by Lyon, Matteson, and Marx (1981) and Breitmeyer (1978). The luminance of both targets and masks was 17.1 cd/m<sup>2</sup>. The interstimulus interval (ISI) was dark. The fixation field was on continuously at 17.1 cd/m<sup>2</sup>, except when an ISI, target, or mask was being shown. All stimuli were presented centrally on a Scientific Prototype (Model GB) three-channel tachistoscope.

### Procedure and Design

Upon entrance to the laboratory, the subjects were adapted to the completely darkened room for about 15 min. During this time the subjects aided in adjusting the masks in the tachistoscope so that the targets were appropriately centered, and several practice trials with the stimuli were conducted.

Each experimental trial was initiated by the subject with a hand-held switch. A trial consisted of fixation, target, ISI, and mask (metacontrast condition), or fixation, mask, ISI, and target (paracontrast condition). It was the subject's task to indicate after each tar-

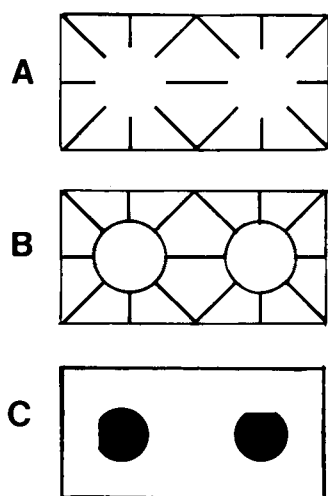


Figure 1. The masks (A and B) and an example of a target (C). A and B are identical except that the illusory contour suggested in A is explicitly drawn in B. Angular dimensions of the display are given in the Method section of the text.

get-mask (metacontrast) or mask-target (paracontrast) sequence from what side the chops had been deleted on both target disks. The dependent variable was the number of correct identifications in each condition.

In this study there were three independent variables: temporal ordering of mask and target, type of mask (minimal or complete), and ISI. Each of the five experimental sessions consisted of presentation of all 16 targets for each ISI in all combinations of mask and target order and mask type. Before the experimental sessions were conducted, the subjects participated in two practice sessions. The three ISIs (5, 25, and 50 msec) were blocked but presented in random order in each session. (Note: ISIs in the paracontrast condition are denoted as negative numbers.) The difficulty inherent in maintaining precise registration of the targets in the mask contours required that masks be alternated only after an entire ISI sequence was completed. Between sessions, the order of presentation of masks was varied. In this within-subjects design, each subject contributed 80 measurements for each ISI in each condition.

The mask duration in all conditions was 100 msec. The target duration for any experimental session was determined by performance in a calibration condition. The calibration condition was: completed contour mask/ISI = -5 msec. The target duration was adjusted so that the subject responded with an average of 66% accuracy in this condition. Subject H.H. started with a target duration of 10 msec and decreased to 7 msec over the five experimental sessions. Subject E.M. started with 7.5 msec and decreased to 5.5 msec. The calibration condition allowed assessment of the masking functions without the interactions introduced by subject practice.

In addition to the experimental trials, both subjects were run in a condition in which a blank white card was given as a mask. This was necessary in order to establish a baseline performance rate that could be differentiated from any masking the contours might produce. One session of 32 trials was run for each ISI in both paracontrast and metacontrast conditions. In this series, the target duration was maintained at 5 msec and the mask duration at 100 msec.

## RESULTS AND DISCUSSION

Experimental determinations of masking magnitude have generally yielded two distinct functional forms. Idealized versions are illustrated in Figures 2A and 2B. Appreciation of the mathematical properties of these functions is critical for understanding the unusual behavior of minimal contour masks. In this sequence of figures, the masking magnitudes are plotted as a function of some time interval. In the metacontrast condition, the time interval is the stimulus onset asynchrony (SOA), whereas in the paracontrast condition, the time interval used is the ISI.<sup>3</sup> In Figure 2A the masking function resembles a cusp and is associated with target identification tasks. The metacontrast and paracontrast portions, taken separately, monotonically decrease as the absolute value of the SOA (ISI) increases. For any given value of SOA (ISI), the paracontrast and metacontrast magnitudes are comparable. In Figure 2B the metacontrast and paracontrast portions appear quite different. Both are nonmonotonic, with maxima occurring at an offset on the order of 100 msec, but the metacontrast magnitude is much larger than the paracontrast magnitude. This function is associated with a brightness discrimination task. Although the functional shapes represented in Figures 2A and 2B have almost nothing in common, they share a fundamental attribute:

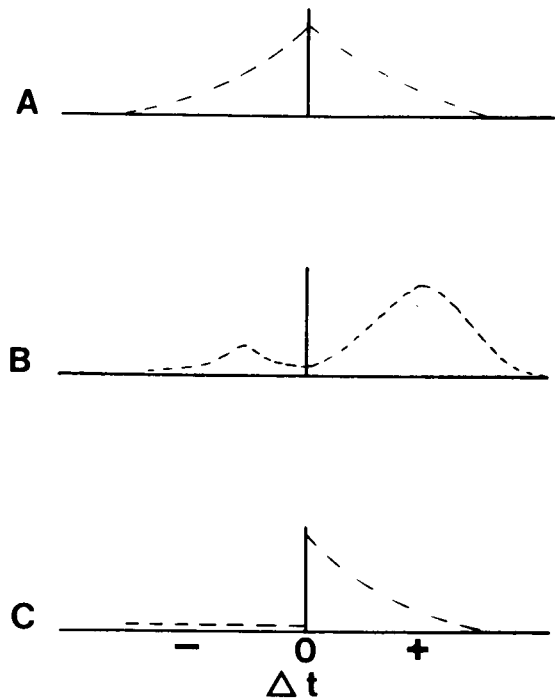


Figure 2. Idealized masking functions. A shows a typical monotonic masking function that might be obtained in a target identification task. B shows a nonmonotonic masking function that might be obtained in a target brightness rating task. C shows the masking function that is introduced by minimal illusory contour masks when used in an identification task.

the functions are continuous at the origin (ISI and SOA  $\rightarrow$  0). It is this feature that can be violated by minimal contour masks. We report here masking functions that are discontinuous at the origin by virtue of the mask's inability to operate when it precedes the target. An idealized function of this sort is depicted in Figure 2C. The data that we present here resemble the idealized functions depicted in Figures 2A and 2C for completed and minimal contour masks, respectively.

The results for both subjects are shown in Figure 3, in which masking magnitudes, measured as the proportion of incorrect target identifications for both completed and minimal contour masks, are plotted as a function of ISI in the paracontrast condition and as a function of mean SOA in the metacontrast condition. In analyzing these results, the metacontrast and paracontrast conditions were treated separately. Quadratic polynomials were fit through the set of three ISI (SOA) measurements for each condition that constituted an experimental session. The 2 subjects were analyzed separately. Thus polynomial coefficients were computed for both mask types, for both the metacontrast and paracontrast functions, and for each experimental session separately. These coefficients were then submitted to an analysis in which the main effects of mask type and the significance of the polynomial coefficients were evaluated, using a multivariate analysis of variance for repeated measures (O'Brien & Kaiser, 1985).

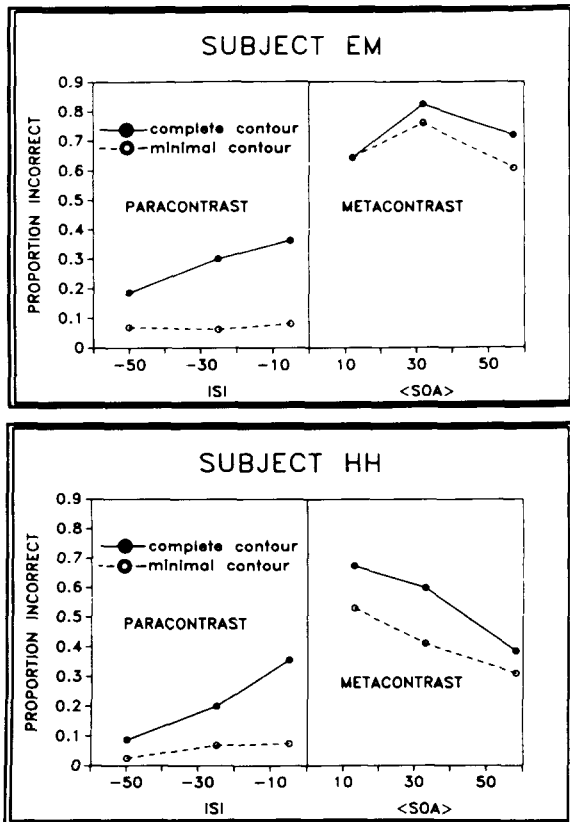


Figure 3. The data for Subjects E.M. and H.H. The continuous line shows the proportion of incorrect target identifications for the real contour mask; the dashed line shows corresponding data for the illusory contour mask. In the paracontrast condition, time is measured in terms of the interstimulus interval (ISI). In the metacontrast condition, time is measured in terms of the mean stimulus onset asynchrony (<SOA>). The mean SOA is the sum of the mean target duration and the ISI. The mean target duration was 7 msec for E.M. and 8 msec for H.H.

In the paracontrast condition, the data for both subjects were found to have a significant linear component [for H.H.,  $F(1,8) = 97.77, p < .0001$ ; for E.M.,  $F(1,8) = 16.33, p < .004$ ] and a quadratic component that did not reach significance [for H.H.,  $[F(1,8) = 0.60, p < .46$ ; for E.M.,  $F(1,8) < .01, p < .99$ ]. There was a significant main effect for mask type on the computed slopes [for H.H.,  $F(1,8) = 44.59, p < .0002$ ; for E.M.,  $F(1,8) = 12.63, p < .008$ ]. Finally, there was also a significant main effect for mask type for the overall average performance in the paracontrast condition [for H.H.,  $F(1,8) = 16.48, p < .004$ ; for E.M.,  $F(1,8) = 32.06, p < .0005$ ].

To determine whether the computed slopes for each mask were significantly different from zero, we performed  $t$  tests on the data from the paracontrast condition [for H.H., completed contour mask  $t(4) = 9.43$ , minimal contour mask  $t(4) = 3.34$ ; for E.M., completed contour mask  $t(4) = 3.84$ , minimal contour mask  $t(4) = 1.47$ ]. For the familywise Type I error to be maintained at 0.05, the in-

dividual tests are significant if  $p < .013$ . At this level, only the slopes of the masking functions for the completed contour mask were significantly different from zero.

In the metacontrast condition, we found robust masking for both mask types. Only for subject H.H. was there a significant main effect for mask type on the average metacontrast masking amplitude [for H.H.,  $F(1,8) = 20.17, p < .002$ ; for E.M.,  $F(1,8) = 0.88, p < .3745$ ]. Quadratic polynomials were again computed for both subjects in both masking conditions. For Subject H.H. only the linear component reached significance [ $F(1,8) = 57.47, p < .0001$ ], whereas for E.M. only the quadratic component was significant [ $F(1,8) = 19.11, p < .002$ ]. For neither subject was there a significant main effect for mask type on the computed polynomial coefficients.

The performance of both subjects was nearly perfect in all conditions when the mask was a blank field. The error rates for both subjects were less than 2% for the blank field trials. The baseline error rate for this experiment is probably determined by fluctuations in motivation and interest. The masking magnitudes reported in this study are thus not produced by the complexity of the task, or by any effect such as contrast reduction from temporal summation over the luminance of the mask.

The statistics confirm what is evident at a glance from Figure 3: (1) Completed contours have a greater paracontrast masking amplitude than minimal contours. (2) The paracontrast slope is greater for completed contours. (3) In the metacontrast condition, when there is a significant linear polynomial coefficient (H.H.) or a significant quadratic polynomial coefficient (E.M.), the value of the coefficient is independent of the mask type.

Our main results can be summarized as follows:

*Minimal contours did not show paracontrast.* Minimal contours induced very few errors at any ISI in the paracontrast condition, and performance did not significantly depend on ISI. Completed contours, however, did mask in paracontrast and performance significantly improved with increasing ISI.

*Minimal contours did show metacontrast.* The error rate in the metacontrast condition was only slightly greater for completed contours. We also found that the shape of the metacontrast function did not depend on mask type. These two features of minimal contour masking generate the expected discontinuity at the juncture between paracontrast and metacontrast.

## SUMMARY

We posed a relatively straightforward test of the existence of two independent modes of inhibition by constructing masks that are sensitive to the time ordering of target and mask presentation. The independence of paracontrast and metacontrast was established by constructing masks that show a strong discontinuity at the paracontrast-metacontrast juncture. The independence of these two masking conditions is taken as evidence that there are two independent modes of inhibition. These modes operate in

a fashion that can be interpreted in terms of the spatial frequency decomposition that occurs within early vision: (1) Paracontrast is observed with completed contours, but not with minimal contours, implying that the inhibitory mode in paracontrast occurs via cells with small receptive fields—the high-spatial-frequency channels. (2) Metacontrast is observed with both completed contours and minimal contours, implying that the inhibitory modes in metacontrast include an interchannel mode in which the inhibiting cell has a large receptive field—the low-spatial-frequency channel.

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## NOTES

1. It has been suggested that illusory contours can mask real contours (Weisstein, Matthews, & Berbaum, 1974). This is, in fact, true, and is in a sense the subject of this paper. However, illusory contours mask because their inducing elements generate cellular inhibition, not because the illusory contour is perceived. It is irrelevant for masking that the arrangement of inducing elements generates an illusory contour. This was shown in pilot studies in two different ways. First, completion of the inducing elements is known to destroy the perception of the illusory contour (Kanizsa, 1976). Adding lines to our illusory contours always increased the masking magnitude. Second, the perception of illusions as illusions takes time (on the order of 100 msec; Reynolds, 1978) and the perception of illusory contours apparently requires effortful attention (Pritchard & Warm, 1983). One way of assessing whether naive subjects are perceiving illusory contours is to establish whether they see depth separation or a brightness change (Parks & Prendergrass, 1982; Rock & Anson, 1979). It was quite clear that for the mask durations used in our experiments (100 msec) neither of these features was perceived. If it were true that the perception of the illusory contour was requisite for masking, this would be a most surprising result, since the perception of illusory contours is apparently organized at or beyond area 18 in striate cortex (Heydt, Peterhans, & Baumgartner, 1985).

2. In defining a target:mask energy ratio, it is necessary to specify what mode of inhibition is relevant. The desired quantity is the amount of light that is available for cell activation. If the receptive fields of cells processing target and mask are not comparable in size, then it is necessary to take into account spatial summation within a receptive field in order to estimate how much photic energy is available for neural processing. What is generally taken in the literature to be an energy (Breitmeyer, 1984, and references therein; Fox, 1978; Weisstein, 1972) is in fact an energy per unit area. This quantity is formed from the product of the stimulus intensity (ergs cm<sup>-2</sup> sec<sup>-1</sup>) and stimulus duration. In order to transform this product into an energy it must be multiplied by an area. The absolute value of this area is not necessary in forming the target:mask energy ratio; the ratio of the receptive field areas processing target and mask, respectively, is sufficient. This ratio may be near unity in intrachannel inhibition, in which the target-mask interaction is produced by a center-surround inhibition. However, in interchannel inhibition, the inhibiting cells (which are sensitive to low spatial frequencies) have large receptive fields compared to the cells processing the target (which are sensitive to high spatial frequency), and the areal ratio may be much less than unity. In this case the product of mask in-

tensity and mask duration does not give any indication of the relevant mask stimulation.

3. In this study we were especially interested in the behavior of minimal contour masks at the boundary between paracontrast and metacontrast. Consequently, the appropriate time parameterization in the two regimes is of central concern. There is no continuous variable that generates a transformation of paracontrast into metacontrast. Paracontrast and metacontrast are distinguished by time ordering, and this is intrinsically represented as a discrete variable. What this means is that there is no unit of time that appropriately measures time intervals in both the paracontrast and metacontrast regimes. It appears to be an historical accident that because metacontrast has been more intensively studied, the appropriate time parameterization for it (SOA) has been extended to paracontrast. In general, experimenters plot both paracontrast and metacontrast results on the same graph, and it is natural to use the same parameter for the abscissa with a simple change of sign to indicate the

paracontrast regime. As Lefton and Newman (1976) noted, early studies of paracontrast were part of larger studies of metacontrast. However, it is clear that SOA is *not* the appropriate time parameter for paracontrast, and paracontrast masking functions that use SOA as an argument may be distorted, especially if long mask duration times are used. This distortion will be most severe near the origin, where the finite mask duration will cause a uniform shift of the function to larger negative values. Turvey (1973, Experiment 13) showed that SOA is an invariant in metacontrast; the time interval to evade masking depends only on the SOA and is independent of the target duration. This law does not hold for paracontrast; SOA is, in fact, irrelevant for paracontrast. In this paper we use ISI to measure time intervals in paracontrast and SOA to measure time intervals in metacontrast.

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