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A binocular site for contrast-modulated masking

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Abstract

Contrast-modulated (CM) gratings, composed of two luminance-modulated sinusoids of similar spatial frequency, mask the detection of test sinusoids at the difference frequency. However, the mechanism underlying masking by CM gratings remains poorly understood. In this paper, we aimed to determine whether the masking of 1 cycle deg^{-1} LM test gratings by a 1 cycle deg^{-1} beat (formed from a pair of carriers at 8 and 9 cycles deg^{-1}) occurs in monocular channels or after the site of binocular combination, or both. Threshold elevations for the detection of a 1 cycle deg^{-1} test grating were obtained for a number of stimulus conditions, including: (1) dichoptic CM (both 8 and 9 cycles deg^{-1} mask components presented to one eye, with the 1 cycle deg^{-1} test grating to the other); (2) dichoptic variant (8 and 9 cycles deg^{-1} mask gratings presented to separate eyes, with the 1 cycle deg^{-1} test grating presented to one eye); (3) binocular CM (all mask and test gratings presented to both eyes). As a control, masking magnitude was also measured for LM mask gratings of similar frequency (1 cycle deg^{-1}) and effective contrast (3%) to that of the beat. For both LM and CM masks, the dichoptic condition yielded threshold elevations that were similar or greater than the binocular condition. When 8 and 9 cycles deg^{-1} mask components were presented to separate eyes (the dichoptic variant condition), no beat pattern was visible and no elevations in detection threshold occurred. The results demonstrate that, like LM masking, detection of a target in the presence of a CM mask does not involve purely monocular mechanisms. Further, that the site of CM masking must occur beyond the stage at which monocular matching for stereopsis takes place. This is consistent with other studies which suggest that dichoptic masking is contingent on stereo matching, and thus occurs relatively late in the hierarchy of binocular visual processing.

Keywords: Dichoptic; Binocular; Masking; Contrast-modulation

1. Introduction

The technique of contrast masking has been used extensively to explore early visual processing. Under this paradigm, observers are asked to detect a test stimulus in the presence of a pedestal, or mask, pattern: if detection thresholds increase when the mask is present, it is reasoned that the same psychophysical channel processes both the test and the mask (see Graham, 1989). Findings that threshold elevation is maximal when mask and test gratings are of similar spatial frequency, for example, provided evidence for the existence of independent channels in the visual system selective for narrow ranges of image spatial frequency (e.g. Stromeyer & Julesz, 1972; Legge & Foley, 1980).

Models of masking based on this paradigm (Wilson & Bergen, 1979; Wilson, 1980; Wilson, McFarlane, & Phillips, 1983) cannot, however, be used to explain human perceptual performance for masking experiments when the stimuli are more complex than single sinusoids. For example, Foley (1994) found results that were inconsistent with the standard models when he added a second mask component with a different orientation. Ross and Speed (1991) found inconsistencies when using masks with orientation or spatial frequency differences between mask and target. Further, masking by contrast-modulated (CM) patterns, composed of two or three high spatial frequency sinusoids typically results in threshold elevation, at a frequency corresponding to the contrast modulation of the CM pattern, despite no Fourier components of that frequency being present in the pattern (Henning, Hertz, & Broadbent, 1975; Nachmias & Rogowitz, 1983).

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Henning, Hertz, and Broadbent (1975), and subsequently several others, suggested that CM masking might be explained by the presence of a 'distortion product' of the same frequency as the contrast modulation, generated by a nonlinearity prior to the stage of contrast masking. This would allow an 'almost' linear channels model to be upheld. However, several studies have found features of CM masking that are inconsistent with this idea (e.g. Badcock & Derrington, 1989; Daugman & Downing, 1995; Cropper, 1998; Willis, Smallman, & Harris, 2000). In particular, the prediction that CM mask gratings should have the same effect as LM masks of similar frequency and effective contrast has not been borne out by recent work, suggesting the simple 'distortion product' hypothesis cannot explain masking by CM patterns. Willis et al. for example, have recently reported that while the effects of masking by low contrast LM gratings are highly dependent on the relative spatial phase between mask and test patterns, no such phase dependence exists for CM masks whose envelopes are modulated at the same frequency. No current model of masking can explain these results (but see Akutsu & Legge, 1995; Daugman & Downing, 1995 for alternative ideas).

A first step in arriving at an alternative explanation for CM masking is to find out where in the visual hierarchy the masking occurs, using traditional psychophysical methods to probe the putative site of masking. Here, we aimed to determine whether CM masking occurs in purely monocular channels, or in a binocular mechanism, or both. We know that LM masking occurs in binocular channels (Legge & Foley, 1980), and indeed, that it may occur after the stage at which depth matches are assigned (McKee, Bravo, Taylor, & Legge, 1994). This issue has not previously been explored for CM masks. It has however, been suggested that the visual processing of contrast-modulated patterns may occur within monocular channels. Badcock and Derrington (1987) reported that discrimination sensitivity for beat displacement is significantly reduced when the two carriers are presented to separate eyes, suggesting that observers are detecting the displacement of one of the components, and not the envelope, in order to complete the task. They interpreted the result as suggesting that CM stimuli are processed within monocular channels. However, their data do not conclusively demonstrate that CM patterns are processed in purely monocular channels. The data are compatible with the possibility that the process occurs within a binocular mechanism, but at a relatively high level of processing — in particular, beyond the site of stereo matching, where the beat components might be combined in such a way that a modulation at the beat frequency is no longer present in the effective stimulus. If this were the case, the stimulus would be perceived as a single-frequency surface, sloping slightly in depth (Blakemore, 1970). Here we use a masking study that allows us to distinguish between these two interpretations.

We start by clarifying what is meant by monocular and binocular mechanisms: A monocular mechanism is one which receives input from a single eye and which is unaffected by stimulation of the other eye. A binocular mechanism is one which can receive a signal from either eye or from both eyes. It is not necessary for a stimulus to be present in both eyes for a binocular mechanism to respond. However, the mechanism may respond differently for monocular or binocular visual input: e.g. binocular performance in contrast detection and discrimination tasks (where both eyes view both mask and test patterns) is typically better than monocular performance (where only one eye views both mask and test patterns) by a factor of roughly the square root of 2 (e.g. Blake & Levinson, 1977; Legge & Foley, 1980; Foley & Legge, 1981; Wilson, 1980). There are several suggestions for how monocular signals might be combined to account for this finding (see Campbell & Green, 1965; Green & Swets, 1974). One that accounts well for a body of data on sinusoid detection and discrimination is the quadratic summation model (Legge, 1984b). According to this model, monocular signals are squared before they are summed within a binocular mechanism. If this model is correct, it leads to a powerful prediction: that dichoptic masking conditions, where mask and test gratings are presented to separate eyes, should yield much greater masking than monocular or binocular conditions. This prediction provides a simple explanation for previous empirical studies: dichoptic masking of sinusoidal test gratings by masks of the same spatial frequency and phase, is considerably greater than equivalent monocular masking (Legge, 1979; Levi, Harwerth, & Smith, 1979; Legge, 1984a). Importantly, these empirical findings, in conjunction with Legge's model, provide compelling evidence that masking by single sinusoidal gratings occurs primarily after the site of binocular combination (Legge, 1984a).

A comparison of dichoptic and binocular masking can thus be used to test whether a particular masking phenomenon occurs in purely monocular or in binocular channels. Broadly, if dichoptic masking conditions yield greater masking than equivalent binocular or monocular conditions, the site of masking must be binocular. The rationale for this prediction is as follows. Consider first what would be expected if a target was detected by purely monocular channels. Dichoptic presentation of mask and test patterns should yield no further masking than a control condition in which the mask stimulus is absent. This is because the monocular channel responsible for detecting the test pattern would not be influenced by the mask, as by definition it would have no link with the other eye. If the target was detected only in purely binocular channels, after the site at which left and right eye signals are combined, the dichoptic condition should produce at least as much masking as the binocular condition. If signals from the right and left eye are combined linearly, dichoptic and binocular conditions should produce very similar threshold elevations, because it will not matter whether the mask and test stimuli passed through the same or different eyes. If the combination is nonlinear, masking may be much greater, as Legge and others found for single component sinusoidal masking (Levi et al., 1979; Legge, 1984a,b).

In this paper, we describe a set of experiments designed to reveal the stage of processing at which CM masking occurs. Our first aim was to determine whether masking of a sinusoidal test grating by a CM mask grating (specifically a beat, composed of two gratings of similar spatial frequency) occurs in monocular or binocular channels, or both. Our first study was based on a clear prediction (from Legge, 1984a,b): if purely monocular channels are involved in the detection of a sinusoidal target on a CM mask, dichoptic viewing (test and mask gratings presented to separate eyes) should result in very little masking compared with a binocular condition. If the site of masking is binocular, dichoptic masking should be as great, or greater, than binocular masking. If both binocular and monocular channels are involved, but the visual system cannot access them independently, we expect the level of masking to be somewhere in between.

The results from the first study showed that the site of CM masking is indeed binocular. Our second step was to determine the approximate stage at which CM masking occurs within binocular visual processing, and, specifically, whether masking occurs before or after the site at which left and right eye signals are combined for stereo matching. There is some hint from the literature that many masking effects may occur at a relatively late stage of binocular processing. Binocular masking, for example, is reduced when the test signal is presented at a different disparity from the noise mask. This has been demonstrated for the detection of sinusoidal test gratings (Henning & Hertz, 1977) and for more broadband luminance test patterns in noise (Henning & Hertz, 1977; Moraglia & Schneider, 1990, 1992). Further, dichoptic masking with simple bar stimuli can be dramatically reduced by stereo matching. For example McKee et al. (1994) asked observers to detect a monocular bar target, in the presence of a bar mask, presented to the other eye. When binocular disparity was introduced between the mask bar and an additional bar, presented adjacent to the test bar (and in the same eye as the test), thresholds for test detection were reduced to values very similar to absolute detection threshold. This was interpreted as indicating that dichoptic masking occurs within disparity tuned mechanisms, at a site beyond stereo matching.

We devised a 'dichoptic variant' condition, in which one eye received the test grating, plus one high spatial frequency mask component, and the other eye received the second mask component alone. We wanted to test whether the effect of the CM mask would be reduced when the components of the mask were presented to different eyes, and where there would then be an opportunity for stereo matching. The rationale for this stimulus arrangement is based on the well-known result that when a pair of sinusoids of slightly different frequencies are presented, one to each eye (such as the 8 and 9 cycles deg^{-1} gratings used here), the visual system interprets the differences between the two patterns as binocular disparity, stereo matching occurs, and the observer sees a single slanted surface in depth (Blakemore, 1970).

We asked whether the introduction of binocular disparity, by presenting the two mask components to separate eyes, results in a reduction in masking. If masking takes place before stereo matching occurs, CM masking should still occur, whether or not observers perceived the beat pattern. If masking occurs after the site of stereo matching, we would expect a reduction in masking because the mask pattern is transformed by stereo matching, so that it is no longer modulated at a low frequency.

2. Methods

Contrast thresholds were measured for the detection of test gratings in the presence of a mask. The test stimulus was always a 1 cycle deg^{-1} luminance-modulated (LM) sinusoidal grating. The mask stimulus comprised various combinations of two LM gratings (8 and 9 cycles deg^{-1}, each of 20% contrast[2]) which, when viewed simultaneously with both eyes, appeared to 'beat' at the difference frequency of 1 cycle deg^{-1}. As a control, detection thresholds were also measured for test gratings in the presence of a mask composed of a 1 cycle deg^{-1} LM grating of 3% contrast, together with an 8 cycles deg^{-1} LM grating of 20% contrast. In previous experiments this stimulus was shown to produce similar levels of masking as the 1 cycle deg^{-1} CM mask described above, and was thus judged equivalent in terms of 'effective' frequency and contrast (Willis et al., 2000). The spatial phase of each mask component was constant, while that of the test stimulus was randomised on each trial. This was deemed necessary to reduce additional cues from local contrast or luminance (e.g. Badcock, 1984a,b).

[2] Note that the contrast reported are those measured from the monitor after spatial and temporal interleaving of the signals has taken place.

2.1.1. Observers

Three observers took part in the study: JH, one of the authors, and SA and SM, who were both naïve to the purpose of the experiments. All had normal or corrected-to-normal (6/6 or better) visual acuity.

2.1.2. Stimulus generation and display

Gratings were generated using a Cambridge Research Systems (CRS) VSG2/4 gratings generator with 12-bit DACs, and displayed on an Nanao T2 17-inch monitor. The resolution of the display was 1008 pixels by 414 lines. Vertical gratings were presented within a rectangular patch of 4.3° height and 3.6° width at a viewing distance of 3 m. The screen luminance surrounding the grating patch was matched to that of the mean luminance of the stimulus (52 cycles deg^{-1} m^{-2}).

A combination of spatial and temporal interleaving was used to present grating patches for the various stimulus conditions. Pairs of frames, each containing two spatially-interleaved grating patches (where alternate rows of the display screen corresponded to one of the gratings), were temporally interleaved at a frame rate of 118 Hz. Frame 'A' contained two gratings, spatially interleaved; frame 'B' contained a further grating spatially interleaved with a blank (mean luminance).

For the dichoptic viewing conditions, a VSG ferroelectric stereo-goggles unit (Cambridge Research Systems) was used to present frames 'A' and 'B' to right and left eyes separately (59 Hz per eye). No beat was perceived when 8 and 9 cycles deg^{-1} mask components were presented to separate eyes, indicating that the phosphor persistence of the display was minimal. Seven mask conditions were employed (see Fig. 1 for a schematic representation):

(a) *Binocular CM:* CM mask and LM test gratings viewed binocularly. Frame A contained the test grating (1 cycle deg^{-1}), plus one mask component (8 cycles deg^{-1}, 20% contrast); frame B contained the other mask component (9 cycles deg^{-1}, 20% contrast). Temporally interleaving the two mask components and presenting them to both eyes simultaneously results in the percept of a contrast modulation, or 'beat' at 1 cycle deg^{-1} (Fig. 1a).

(b) *Dichoptic CM:* CM mask and LM test presented to different eyes. Frame A contained both mask components (8 and 9 cycles deg^{-1}); frame B contained the test component (1 cycle deg^{-1}). The stereo-goggle unit was used to present frame A exclusively to one eye and frame B exclusively to the other, so that one eye saw only the test stimulus, and the other only the 1 cycle deg^{-1} CM mask (Fig. 1b).

(c) *Dichoptic CM variant:* CM mask components presented to separate eyes. Frame A contained one mask component (8 cycles deg^{-1}) plus the test (1 cycle deg^{-1}); frame B contained the other mask component (9 cycles deg^{-1}). The stereo-goggle unit was used to present frames A and B to separate eyes, so that one eye saw one mask component, and the other the second mask component plus the test (Fig. 1c).

In order to control for the effects of masking by either of the high spatial frequency mask components alone, contrast thresholds were obtained for the detection of 1 cycle deg^{-1} test gratings in the presence of a single mask grating of 8 cycles deg^{-1}, for both binocular and dichoptic viewing conditions:

(d) *Binocular control:* 8 cycles deg^{-1} mask component only. Frame A contained a single mask component of 8 cycles deg^{-1}; frame B contained the test (1 cycle deg^{-1}). The temporally-interleaved frames were shown to both eyes simultaneously (Fig. 1d).

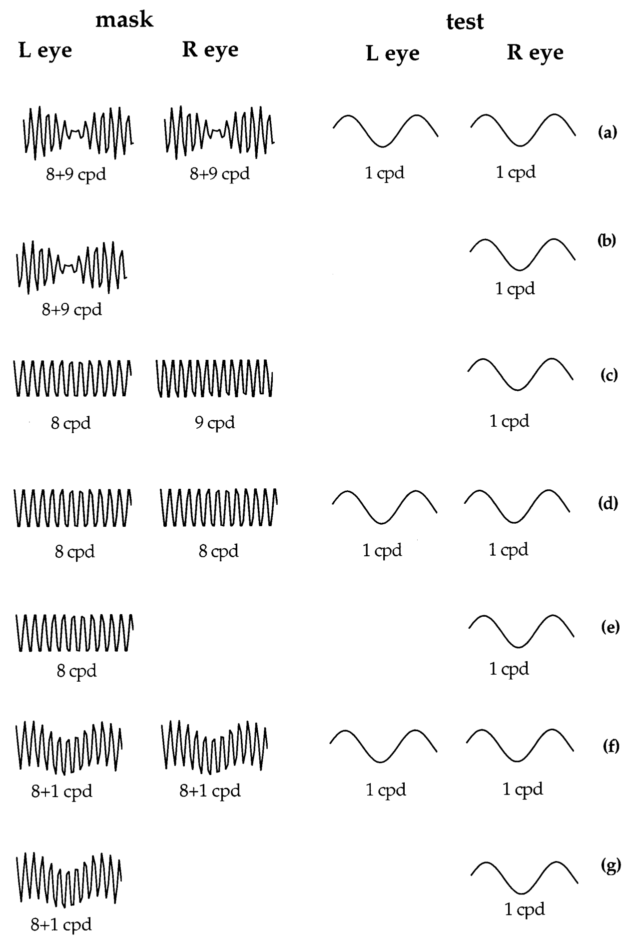

Fig. 1. Schematic diagram showing the signal received by each eye in each of seven experimental conditions, as described in the text (Section 2). Stimuli were presented using a combination of spatial and temporal interleaving. Dichoptic presentation was controlled via a VSG stereo-goggles unit (Cambridge Research Systems) yoked to the frame rate of the display. Under dichoptic conditions, the eye receiving each signal was randomised from trial to trial. cpd = cycles deg^{-1}.

(e) *Dichoptic control:* 8 cycles deg^{-1} mask component only. Frame A contained a single mask component of 8 cycles deg^{-1}; frame B contained the 1 cycle deg^{-1} test. Stereogoggles were used to present frame A to one eye and frame B to the other, so that one eye saw only the mask component, and the other only the test (Fig. 1e).

Note, in this study we were interested in masking above and beyond any residual masking due to a single 8 cycles deg^{-} component. Thus, we compare masking in conditions (a), (b) and (c) with these two controls, rather than comparing them with absolute threshold.

In order to compare the effects of masking by CM and LM gratings, the experiment was repeated using an LM mask of equivalent effective frequency (1 cycle deg^{-1}) and contrast (3%) to that of the 8 plus 9 cycles deg^{-1} CM mask (see Willis et al., 2000).

(f) *Binocular LM:* LM mask and test gratings viewed binocularly. Frame A contained one component of the mask (1 cycle deg^{-1}, 3% contrast); frame B contained the other mask component (8 cycles deg^{-1}), plus the test. The temporally-interleaved frames were shown to both eyes simultaneously (Fig. 1f).

(g) *Dichoptic LM:* 1 cycle deg^{-1} mask and test gratings presented to separate eyes. Frame A contained both mask components (1 and 8 cycles deg^{-1}); frame B contained the 1 cycle deg^{-1} test. The stereo-goggle unit was used to present frames A and B to separate eyes, so that one eye saw the test stimulus, and the other the 1 cycle deg^{-1} mask (Fig. 1g).

2.1.3. Procedures

A temporal two-interval, forced choice procedure (2-AFC) was used to estimate contrast threshold for the detection of LM test gratings in the presence of a mask. Observers were asked to identify in which of two sequential intervals, presented at random, the test grating was presented. The 'test' interval contained both the mask and test gratings: the 'non-test' interval contained the mask alone. Each interval, lasting 1 s (with smooth onset and offset achieved using a temporal cosine window), was accompanied by an audible tone. The end of the trial was signaled by a third tone, after which observers communicated their response to the computer via a button box, which then initiated the next trial. No feedback was given.

Contrast thresholds (75% correct) were calculated from a Probit fit of the data. Each experimental run, or 'block', contained 50 stimulus trials. Within each block of trials, five test contrasts were randomly interleaved. Data were collected for no longer than an hour at a time over a period of 2–3 weeks.

3. Results

3.1. Experiment 1: monocular or binocular?

Our first aim was to examine whether or not CM masking, like LM masking, takes place primarily after the site of binocular combination, or whether it occurs in purely monocular channels. We used the rationale that if the target grating could be detected at a monocular site, a CM mask presented to one eye should not mask the detection of the target LM grating presented to the other (dichoptic CM, condition (b)).

First, we sought to test whether dichoptic presentation of LM mask and test gratings of 1 cycle deg^{-1} yields greater masking than binocular viewing. The 1 cycle deg^{-1} LM mask of 3% contrast was chosen because it yielded similar elevations in threshold to that of the 1 cycle deg^{-1} CM mask used in this study (see Willis et al., 2000). In order to control for the effects of either of the high spatial frequency components of the CM mask alone, a single LM sinusoid of 8 cycles deg^{-1} and 20% contrast was also presented.

Fig. 2 shows contrast thresholds for detecting the 1 cycle deg^{-1} test grating in the presence of the 1 cycle deg^{-1} LM mask, presented either binocularly (condition (f)) or dichoptically (condition (g)). Dichoptic presentations of test and mask (solid grey bars) tended to result in similar or greater masking than binocular presentations (hatched bars), although for one observer there was slightly less masking in the dichoptic condition.

Legge's (Legge, 1984b) quadratic model was originally developed to model data from experiments in which mask and test patterns are identical in spatial frequency and phase. The mask and test gratings used here were different along both dimensions. It is perhaps not surprising, therefore, that the model would predict much greater differences in threshold elevation between the dichoptic and binocular conditions than those observed here. Our results show that dichoptic masking produces broadly similar threshold elevations to binocular masking for the low-contrast, phase-randomised LM mask we used, and suggests that Legge's model cannot be simply applied to more complex stimuli than those he used.

Next, we sought to extend this paradigm to the CM domain by comparing binocular with dichoptic masking by contrast modulated patterns composed of two high spatial frequency LM sinusoids (conditions (a) and (b), respectively). Fig. 3 shows contrast thresholds for the binocular condition (binocular CM condition (a), hatched bars) and dichoptic condition (dichoptic CM condition (b), solid grey bars) compared with the appropriate controls (8 cycles deg^{-1} binocular and dichoptic; conditions (d) and (e), respectively; black/white bars).

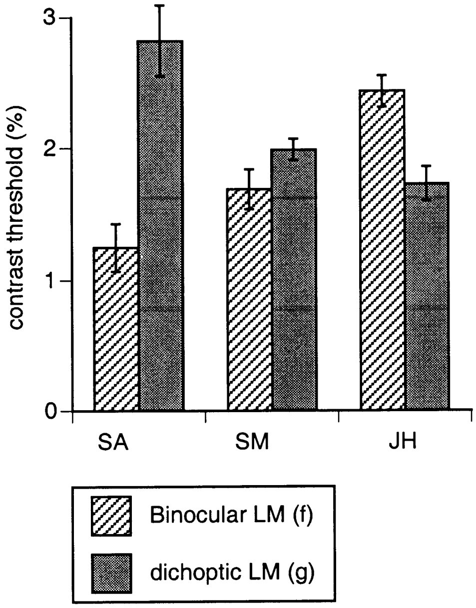

Fig. 2. Contrast thresholds (%) for the detection of 1 cycle deg^{-1} LM test gratings in the presence of an LM mask for three observers. Hatched bars show thresholds for the 'binocular LM' mask condition (f), in which both eyes viewed an LM mask composed of a 1 cycle deg^{-1} (3% contrast) plus an 8 cycles deg^{-1} (20% contrast) grating, and the 1 cycle deg^{-1} test. Grey bars show thresholds for the 'dichoptic LM' mask condition (g), in which one eye viewed the LM mask, and the other the 1 cycle deg^{-1} test. Note that dichoptic masking is similar to binocular masking. Error bars indicate 1 SE. Details of mask conditions (a)–(g) are provided in Section 2.

As expected, thresholds were very low in the control conditions. However, the dichoptic presentation of CM mask and test (dichoptic CM condition (b), solid grey bars) yielded as much, or more, masking than binocular presentation (binocular CM, condition (a), hatched bars). This result shows that CM masking must take place at a binocular site, And that there is essentially no contribution to target detection from purely monocular channels.

3.2. Experiment 2: before or after stereo matching?

With a binocular site for CM masking confirmed, we next sought to find out whether masking by CM gratings occurs early or late in binocular visual processing. Earlier research on luminance-defined stimuli has shown that the binocular disparity of a test or mask can affect the amount of masking that occurs (Henning & Hertz, 1977; Moraglia & Schneider, 1990, 1992; McKee et al., 1994). This makes phenomenal sense. For example if a mask stimulus is given binocular disparity by providing a matching stimulus at a different location in the other eye, the binocular visual direction of the mask will be different than if the matching bar were not present. The mask and test will no longer be superimposed and a 'release' from masking occurs (McKee et al., 1994). We might expect something similar to occur here. When the two high frequency components of a beat pattern are presented to separate eyes, no beat pattern is perceived (Badcock & Derrington, 1987). Instead, observers typically perceive a surface sloping in depth (e.g. Blakemore, 1970), because stereoscopic matching of elements within the pattern takes place. If CM masking occurs before this matching process has taken place, we might expect the dichoptic presentation of the two component gratings of the CM beat to mask the detection of a test grating at the difference frequency, despite the observation that no beat pattern is perceived. If CM masking occurs after the matching process, no such masking should occur, as the 'effec-

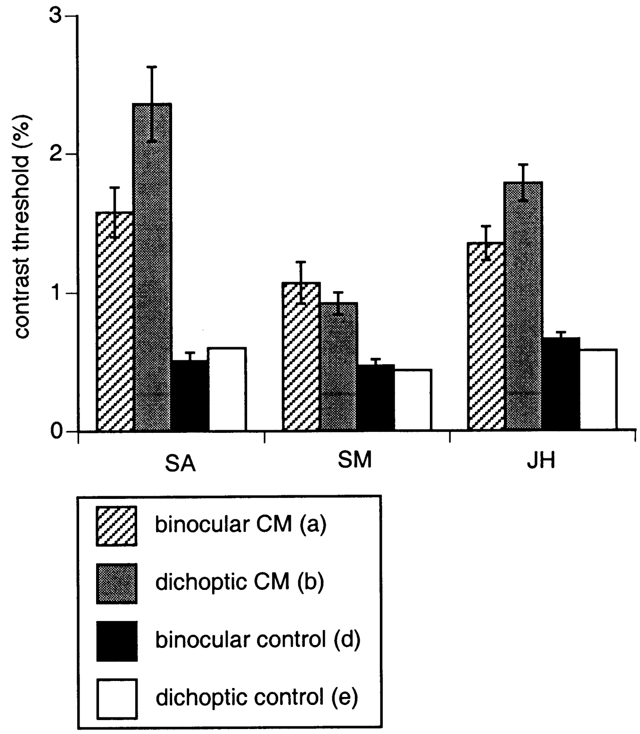

Fig. 3. Contrast thresholds (%) for the detection of 1 cycle deg^{-1} LM test gratings in the presence of the high spatial frequency components of a CM mask. Hatched bars show thresholds for the 'binocular CM' mask condition (a), in which both eyes viewed the 1 cycle deg^{-1} CM mask (composed of an 8 plus a 9 cycles deg^{-1} grating, each of 20% contrast), and a 1 cycle deg^{-1} LM test grating. Grey bars show thresholds for the 'dichoptic CM' mask condition (b), in which one eye viewed the test and the other viewed the CM mask. Solid black and white bars show, respectively, thresholds for a 'binocular control' condition in which both eyes viewed a single mask component at 8 and the 1 cycle deg^{-1} test. Condition (d) and a dichoptic control condition (e), where one eye views the test and one the mask. Note that, for all observers masking is significantly greater for the CM conditions than for the controls. Error bars indicate 1 SE. Details of the experimental conditions are provided in Section 2.

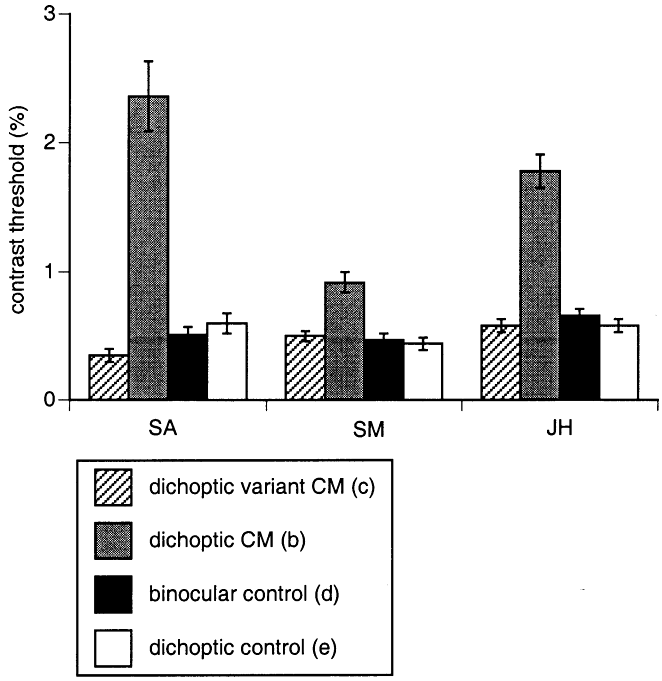

Fig. 4. Contrast thresholds (%) for the detection of 1 cycle deg^{-1} test gratings for four experimental conditions. Hatched bars show thresholds for the 'dichoptic CM variant' mask condition (c), in which one eye views one of the high spatial frequency mask components, and the other eye the other mask component plus the test. Grey bars show thresholds for the 'dichoptic CM' mask condition (b), redrawn from Fig. 3. Solid black and white bars show data for the binocular condition (d) and dichoptic condition (e) control conditions, respectively. Note that a large amount of masking is only found for the 'dichoptic CM' condition (grey bars). When the mask components are shown to different eyes (hatched bars) masking is reduced to that which occurs when there is only a single high spatial frequency mask component present. Error bars indicate 1 SE. Details of the experimental conditions are provided in Section 2.

tive' mask will have a similar contrast profile to a mask composed of a single 8 or 9 cycles deg^{-1} grating.

Fig. 4 shows contrast thresholds for the detection of the test stimulus for the dichoptic CM variant condition (condition (c), hatched bars), with the standard dichoptic CM condition (condition (b), solid grey bars), and with the control conditions in which the mask consisted of a single 8 cycles deg^{-1} grating, either presented to a different eye to the test (dichoptic control, condition (e); white bars), or presented simultaneously with the test grating to both eyes (binocular control, condition (d); black bars). There is a dramatic reduction in masking in the dichoptic variant condition, the threshold elevation is similar to that found when the mask is a single sinusoidal component of 8 cycles deg^{-1}. Following the logic outlined above, we interpret this as showing that the masking is occurring at a relatively late stage of binocular processing, beyond the point at which stereo matching occurs.

4. Discussion

The well-known observation that CM gratings, mask the detection of LM test gratings near the modulation frequency has long presented a problem for the classical linear channels theory of spatial vision. Explanations based on an early nonlinearity have now been effectively ruled out (Daugman & Downing, 1995; Cropper, 1998; Willis et al., 2000). However, despite several alternative explanations being proposed (such as observers' use of local luminance differences to solve the detection task; Badcock, 1984a,b), no current model is able to explain all the features of masking by CM patterns. Here, we aimed to elucidate the possible site of CM masking, as well as comparing masking by CM patterns with those of LM patterns of similar effective frequency and contrast.

4.1.1. CM masking is binocular

In the first experiment, we tested whether a sinusoidal target could be independently detected in a monocular channel by comparing binocular with dichoptic masking. The rationale was as follows. Consider the possibility that both binocular and purely monocular channels exist. If the visual system were able to independently monitor the output of the purely monocular channels, then dichoptic presentations of mask and test gratings would not result in elevations in threshold, because the monocular channels receiving the test signal would not receive the mask. If purely monocular channels do exist, but the visual system does not have independent access to them, we might expect to find threshold elevation somewhere between that for the binocular condition and the controls. This would occur because the monocular channels would not be masked and the binocular channels would be. Thus the perceptual decision would be based on some unkown combination of the outputs of these parallel channels.

Our results were not consistent with either of the above predictions. Instead, we found that masking is typically as large as, or larger, in the dichoptic condition than in the binocular condition (Fig. 3), a result not unlike that found for LM masking (Fig. 2). This suggests that target detection in the presence of a CM mask occurs within a binocular visual mechanism — i.e. one that receives a signal from either eye, or from both eyes, but that doesn't necessarily require signals from both eyes in order to function. Importantly it also suggests that the visual system does not have independent access to information from monocular channels, which would be providing an unmasked signal.

This result appears to be in conflict with a study that has explicitly looked at the detection of displacement of CM patterns (Badcock & Derrington, 1987). The authors interpreted their findings that sensitivity to beat displacement is reduced when the two carriers are presented to separate eyes, as suggesting that CM processing occurs in monocular channels. As in our study, their subjects did not perceive a beat pattern when the carriers were presented dichoptically. Badcock and Derrington's data are, however, compatible with the possibility that the CM patterns are processed in a binocular mechanism, at a site beyond that of stereo matching, where the components might be combined in such a way that a modulation at the beat frequency is no longer present in the effective mask.

4.1.2. CM masking occurs after stereopsis

There is some evidence to suggest that dichoptic masking of luminance-defined bar targets occurs at a site beyond stereo matching (see McKee et al., 1994). We wanted to test whether the same is true in the CM domain. To test this idea, we measured the extent of masking for a 'dichoptic variant' condition (c), in which each eye received one of the mask components, and one of the eyes received the test. If masking took place at a binocular site, but before the site of stereo matching, levels of masking for this 'dichoptic variant' condition should be similar to both the binocular mask condition (a) and the standard dichoptic condition (b). If masking took place after stereo matching, then the small differences in position between the mask components in the left and right eye (due to the components being slightly different frequencies) would be interpreted as disparity, and the resulting visual pattern would have the appearance of a single-component mask, sloping in depth. We would then expect masking to be greatly reduced.

If masking does take place in binocular channels tuned for specific disparities, the amount of dichoptic masking might depend on the phase relationship between the test and mask. It was not our intention to address this issue here. In this study, we randomly varied this phase relationship from trials to trial to reduce the possibility that observers performed the task based on local luminance differences (Badcock, 1984a,b). Considering the effects of phase would be an interesting focus for future study.

Observers perceived a pattern that appeared to be similar to a single mask component, rather than a CM beating pattern. One observer reported a consistent slope in depth of the pattern, but this was not always reported by the other observers. Because the local image differences between right and left eye were small (approximately 0.8 arc min) and well within the fusable range, we did not expect observers to perceive rivalry, and indeed, none of the observers reported a rivalrous percept for this stimulus.

For all observers, the 'dichoptic variant' condition was associated with a dramatic reduction in masking (Fig. 4), compared with the standard dichoptic (both mask components in the same eye) and the binocular conditions. Indeed, performance was very similar to that for the control conditions (in which the mask was a single high spatial frequency sinusoid). The results provide strong evidence that masking occurs after stereo matching. Left and right eye mask signals are combined at the stereo matching stage as if they corresponded to a surface slanting in depth. The resulting effective stimulus does not beat at the modulation frequency of the original CM pattern, and thus produces very little masking, rather like the single component mask. Whatever mechanism is responsible for the detection of a test sinusoid in the presence of a CM mask, it appears not to act at the very earliest stages of visual perception.

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