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Facilitation of Luminance Grating Detection by Induced Gratings

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Grating induction causes a homogeneous test field surrounded by sinewave gratings to possess an induced counterphase grating [McCourt M. E. (1982). *Vision Research*, *22*, 119]. There is currently no consensus about the stage of visual processing at which illusory phenomena such as simultaneous brightness contrast are signaled. We measured the masking efficacy of induced gratings by measuring contrast detection thresholds for targets (sinewave luminance gratings) added in phase to both real and induced gratings which were matched in apparent contrast. At spatial frequencies below *c*. 0.5 c/deg, target detection and discrimination were comparably facilitated by both real and induced low-contrast pedestals (0.5–2%). At higher spatial frequencies (above 1.0 c/deg) facilitation continued to be observed for targets added in-phase to real grating pedestals, but occurred only for targets added out-of-phase with induced pedestal gratings. Higher inducing frequencies by themselves were not responsible for the observed phase shift of facilitation, however, since both real and induced pedestals produced similar target contrast discrimination functions when inducing frequency was varied by manipulating viewing distance (which holds the ratio of inducing grating period and test field height constant). The results imply the existence of at least two types of lateral interactive processes: one producing in-phase facilitation, and a second producing out-of-phase facilitation. The relative contribution of each process depends upon the ratio of inducing grating period and test field height. Copyright © 1996 Elsevier Science Ltd.

Grating induction   Brightness contrast   Brightness matching   Increment threshold   Sensitivity

INTRODUCTION

Grating induction (McCourt, 1982) is a brightness illusion in which an illusory (induced) sinewave grating is seen within a physically homogeneous test field which cuts through a sinewave inducing grating. Induced gratings are a low-pass function of inducing grating frequency and do not depend on eye movements for their production (Foley & McCourt, 1985; McCourt *et al.*, 1995). The stage of visual processing at which illusory brightness phenomena such as simultaneous brightness contrast or grating induction arises is unknown, although there is mounting physiological and psychophysical evidence that illusory contours are signaled as early as V1 (Peterhans & Van der Heydt, 1991; Grosof *et al.*, 1993; Dresp & Bonnet, 1991, 1993; McCourt & Paulson, 1994). The present experiments were designed to quantify the efficacy of induced gratings as masking stimuli by measuring contrast detection thresholds for sinewave luminance grating targets added in-phase to both real and induced gratings which were themselves matched in apparent contrast.

How "real" are induced (illusory) gratings?

The striking perceptual similarity between induced gratings and the luminance gratings which induce them [see McCourt (1994) for a detailed analysis of the induced grating waveform] raises the question of whether the neural mechanisms which signal phenomena such as induced gratings, illusory contours and the like are the same as those which signal their real counterparts. The identification of a common underlying mechanism would imply that these illusory phenomena are the consequence of operations performed by relatively early visual processes, and are not the result of higher-level interpretive processes. The principal item of evidence consistent with the idea that induced gratings are signaled by luminance grating detectors is that the two types of grating interact strongly. That is, the appearance of an induced grating can be partially or completely canceled by the addition of a real luminance grating of opposite spatial phase. Such a canceling procedure was first used to measure the magnitude of grating induction (McCourt, 1982). Some degree of cancellation would, however, be expected even if induced and real gratings were signaled by separate mechanisms. A useful analogy can be drawn here with findings from depth perception. The various

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cues to depth such as shading, texture gradient, motion parallax, binocular parallax, etc. are believed to be preliminarily extracted by independent mechanisms. These are subsequently combined to produce a fused depth percept in which perceived distance reflects some weighted nonlinear function of the depth signals provided by individual cues (Davis *et al.*, 1994)

Masking vs facilitation paradigms

An arguably more stringent test of whether two (or more) distinct stimuli share a common low-level processing mechanism is to determine whether the presence of one stimulus facilitates the detection of the other(s). Perhaps the most celebrated example of such facilitation is the "dipper" portion of the contrast discrimination function, which plots the threshold increment in target grating contrast (ΔC) as a function of the contrast of a pedestal grating (C). Detection threshold is equal to discrimination threshold when pedestal grating contrast is zero. With increasing pedestal grating contrast ΔC decreases to a minimum, which defines the point of maximum facilitation. With increasing pedestal contrast facilitation segues to masking such that discrimination thresholds exceed detection threshold. The dipper portion of the contrast discrimination function has been interpreted to reflect the existence of an accelerating nonlinearity, or a threshold, in contrast transduction within individual spatial channels (Legge & Foley, 1980; Wilson, 1980; Yang & Makous, 1995).* Evidence of such facilitation implies that both target and pedestal stimuli are processed by a common mechanism. Similar facilitation effects have been demonstrated for a variety of stimulus types in addition to gratings, including spots of light presented against various light backgrounds (Barlow, 1972), difference-of-Gaussians patterns (Wilson, 1980), and triphasic stimuli (Burton, 1981).

The present series of experiments sought to determine whether, and under what conditions, an *induced* grating pedestal might facilitate the detection of superposed luminance gratings. At issue here is whether a stimulus which is not itself physically present is nonetheless capable of reducing the detection threshold for a target grating added to it at similar spatial phase. Contrast thresholds were also measured in the presence of induced gratings whose perceived contrast might be expected to mask, rather than facilitate, the detection of target gratings. While masking paradigms have been widely employed to measure the spatial and orientation tuning of contrast processing mechanisms (on the assumption that masking occurs maximally when the mask and test are processed by the same mechanism), it is more difficult to support a claim for the common processing of real and illusory gratings based on masking data alone. Masking could, for example, be explained on the basis of the presence of the flanking inducing gratings themselves, which might elevate contrast thresholds for target gratings positioned in the test field, independent of any indirect effect via the illusory gratings they induce. On the other hand it is far more difficult to construe a plausible rival explanation for how the detection of target gratings would be *facilitated* by presenting them out-of-phase with the inducing grating, given the more parsimonious prediction would be that facilitated by an in-phase induced grating pedestal.

Paradoxical effect of high frequency inducing gratings

Another motivation of the present study follows recent findings on the effects of high frequency inducing gratings on target detection. Using a stimulus configuration similar to those employed in grating induction experiments, Takahashi and Ejima (1985) measured contrast thresholds for a 3 c/deg sinewave target grating patch (2.67 deg wide by 0.67 deg in height) presented either in-phase or out-of-phase with peripheral inducing gratings. For target gratings presented *in-phase* with the peripheral gratings, a dipper-function was observed, such that target grating threshold was reduced when peripheral grating contrasts were below *c.* 1%, and was elevated at higher contrasts. For target gratings presented *out-of-phase* with the peripheral gratings, however, only a masking effect was found, except perhaps for a small facilitation at the highest contrast (64%). Similar results have been reported by Cannon and Fullencamp (1993) for 8.0 c/deg grating patches (0.5 deg in dia) surrounded by annuli containing gratings of equal spatial frequency and orientation. These results are intriguing in that they suggest that target increment thresholds vary in the opposite direction from that which might be expected if induced gratings (which are out-of-phase with the inducing grating) acted like pedestals to facilitate the detection of superposed like-phase target gratings. It should be noted, however, that inducing gratings above 3.0 c/deg do not produce robust induced gratings except in very narrow (e.g. 0.1 deg) test fields (McCourt, 1982; Foley & McCourt, 1985). The results of Takahashi and Ejima (1985) and Cannon and Fullencamp (1993) nevertheless point out the need to measure target grating contrast thresholds in conjunction with inducing grating spatial frequencies and test field heights for which induced gratings are adequately visible.

Brief reports of the results of these experiments have been given elsewhere (Kingdom & McCourt, 1993; McCourt & Kingdom, 1994).

METHODS

Subjects

The authors (MM and FK) served as subjects. Both were experienced psychophysical observers and possessed normal vision.

*Stimulus uncertainty has been proposed as an alternative explanation for the facilitation of target detection when presented on like-phase pedestals (Lasley & Cohn, 1981; Pelli, 1985). Uncertainty does not account, however, for the elevation of target threshold (i.e. the "bumper" effect) for targets presented out-of-phase with pedestal gratings (Kulikowski, 1976; Bowen & Cotten, 1993; Yang & Makous, 1995), making the concept of an accelerating nonlinearity the generally preferred explanation.

Stimuli

Stimuli were generated using a VSG2 Digital Signal Generator (Cambridge Research Systems) and were displayed on a Barco CCID RGB monitor operating in yoked-gun (white) mode. Stimulus images were generated using a linearized 12-bit look-up-table constructed by suitable selection from 14-bit digital-to-analog converters.

The Digital Signal Generator produces waveforms which are modulated at right angles to the direction of the raster. It was necessary therefore that the test field run vertically from the top to the bottom of the screen at right angles to the raster scan.* For consistency with previous descriptions of grating induction displays and for clarity of presentation, examples of the three types of stimulus display used in these experiments appear rotated by 90 deg in Fig. 1.

The display subtended 23 deg in width by 16 deg in height at the standard viewing distance of 74 cm. In the "induced pedestal" condition [Fig. 1(a)] a sinewave inducing grating occupied the display except for a uniform test field which traversed the inducing grating. In the "real pedestal" condition [Fig. 1(c)] a sinewave luminance grating served as a pedestal and occupied the region of the test field in Fig. 1(a). The surrounding inducing region was uniform. From the standard viewing distance of 74 cm test field dimensions in both the induced and real pedestal conditions were 23 deg in width by 1 deg in height. The space-average luminance of the test field was equal to that of the surround at 37 cd/m^2. Inducing and pedestal grating spatial frequencies were always identical at 0.0625, 0.125, 0.25, 0.5, 1.0, and 4.0 c/deg. The target gratings which were added to the induced and real pedestal stimuli are schematically illustrated in Fig. 1(b) and (d). Note that only grating contrast, and not luminance offset, was added. These target gratings were always of the same spatial frequency as the induced or real pedestal gratings. In the induced pedestal condition, as illustrated in Fig. 1(a) and (b), target gratings were always added to the test field 180 deg out-of-phase with the inducing gratings; that is, they were added in-phase with any induced grating that might occupy the test field. In the real pedestal condition, illustrated in Fig. 1(c) and (d), target gratings were always added in-phase with the pedestal grating.

*We found that there was a small amount of "bleeding" from the inducing grating into the test field which presumably occurred because the signal defining the inducing grating was incompletely gated at the test field during each raster sweep. Microphotometric measurements with a small (<0.5 cm) aperture established that this bleeding did produce a luminance modulation in the test field whose contrast was *c.* 5% that of inducing grating. The artifactual grating was in-phase with the inducing grating and its contrast was constant across the test field. This grating was canceled by adding an opposite-phase grating of appropriate contrast into the test field. This canceling grating was subsequently added to all target gratings introduced into the test field. Following the addition of the canceling grating no remaining luminance modulation across the test field could be measured by microphotometer for any spatial frequency or contrast of the inducing grating. As an additional check we measured the detectability of a target grating added into the test field over a range of contrasts between 0.0 and 32% of the inducing grating. The inducing grating was physically occluded by an opaque screen. If the artifact was effectively canceled, as indicated by the microphotometric measurements, then the detectability of the target grating should be unaffected by the contrast of the occluded inducing grating. Variations in inducing grating contrast had no effect on target detection thresholds under these conditions. Hence, the effects of inducing grating contrast on target grating detection which we report must possess a perceptual, and not a physical, basis. As a final precaution the results for observer MM were successfully replicated in experiments performed on an independent display system, in which the raster sweep was not at right angles to the test field.

Procedure

Measurement of target grating detection thresholds. Target grating contrast thresholds were measured using a two-interval forced-choice adaptive staircase procedure. On each trial two stimuli were presented and observers selected the temporal interval judged to contain the target grating. Each stimulus consisted of the entire display as illustrated in Fig. 1(a) or (c). Between stimulus presentations the display was a uniform field of equal mean luminance. Thus, in the case of the induced pedestal condition of Fig. 1(a), both intervals contained the inducing grating; the target grating [Fig. 1(b)] was added to the test field in one of the intervals. The uniform field between stimulus presentations was inserted to reduce the effect of long-term adaptation to the inducing grating. Total stimulus duration was 400 msec; display contrast rose and fell under a raised cosine envelope. Onset and offset ramps each lasted 100 msec and stimuli were displayed at full contrast for 200 msec. The staircase procedure employed established the 70.7% correct level (Wetherill & Levitt, 1965). An experimental run was terminated after ten reversals, and thresholds were calculated as the geometric mean of target grating contrast over the last eight reversals.

Measurement of induced grating contrast. In order to meaningfully compare target detection thresholds across the real and induced pedestal conditions, a matching procedure was used to assess induced grating contrast for each inducing grating spatial frequency at each level of inducing grating contrast. Conceptually, each level of inducing grating contrast thus gave rise to an "equivalent real pedestal contrast".

The matching procedure established the point of subjective equality determined by method of adjustment under stimulus presentation conditions identical to those employed in the detection threshold experiments (i.e. using exactly the same temporal parameters of stimulus exposure). The inducing [Fig. 1(e)] and pedestal [Fig. 1(f)] stimuli were temporally alternated while the contrast of the real pedestal was adjusted to match that of the induced grating. No time limit was imposed; when a satisfactory match was obtained the sequence terminated and the observer's adjusted equivalent real pedestal contrast was logged by computer. Five such measurements were made for each condition of the experiment (inducing grating contrasts of 1, 2, 4, 8, 16, 32, and 64%

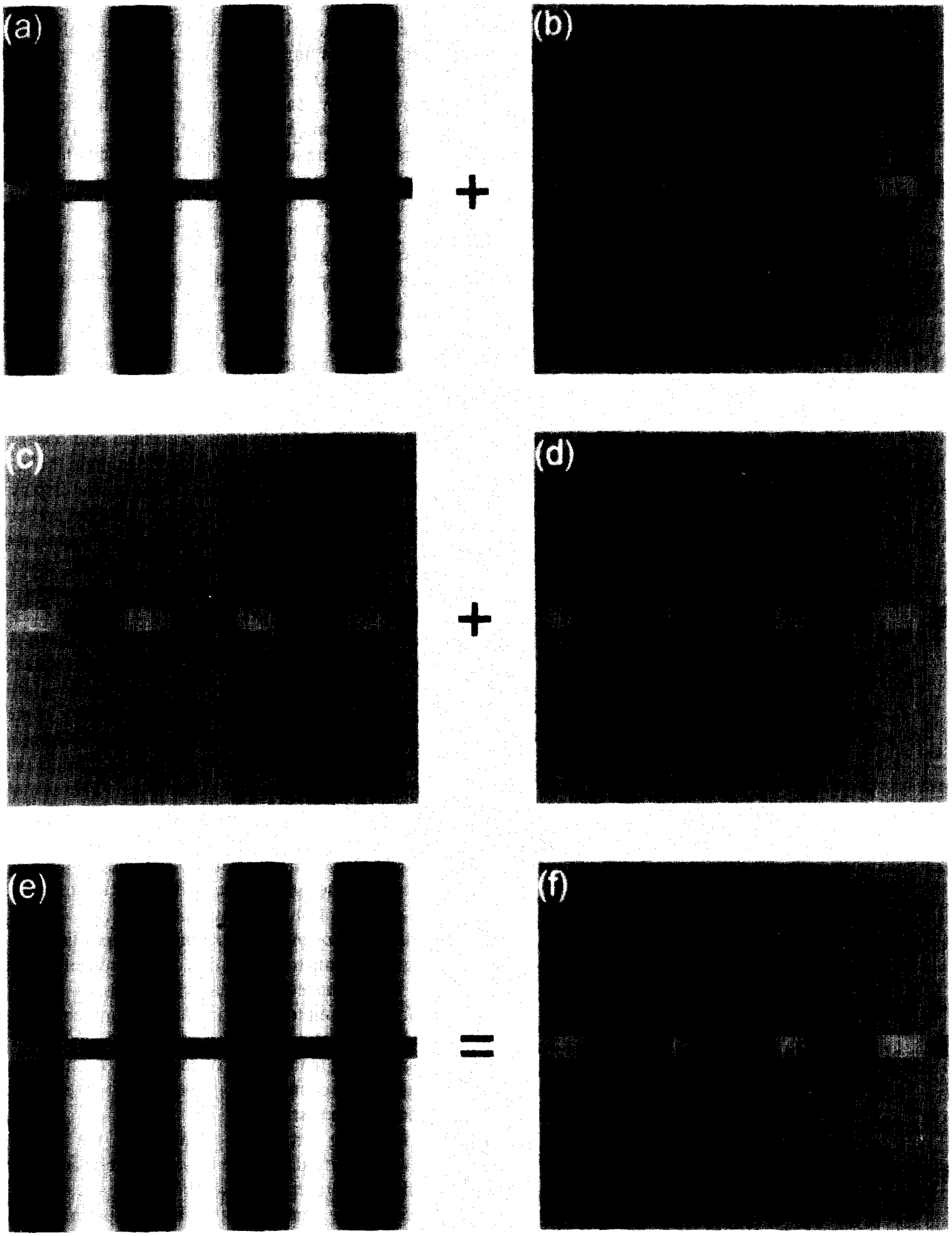

FIGURE 1. Examples of the three types of stimulus displays used in the present experiments. (a) The "induced pedestal" condition in which a sinewave inducing grating occupied the display except for a uniform test field which traversed the inducing grating. (b) A target luminance grating added in phase synergy to the "induced pedestal" of (a). (c) The "real pedestal" condition in which a sinewave luminance grating served as a pedestal and occupied the region of the test field in (a). The surrounding inducing region was uniform. (d) A target luminance grating added in phase synergy to the real pedestal of (c). From the standard viewing distance of 74 cm test field dimensions in both the induced and real pedestal conditions were 23 deg in width by 1 deg in height. Inducing and pedestal grating spatial frequencies were 0.0625, 0.125, 0.25, 0.5, 1.0, and 4.0 c/deg. (e, f) In order to compare the detection thresholds for targets (b and d) across the real and induced pedestal conditions (a and c), a matching procedure was used to assess the perceived contrast of induced pedestals at each inducing grating spatial frequency and level of inducing grating contrast.

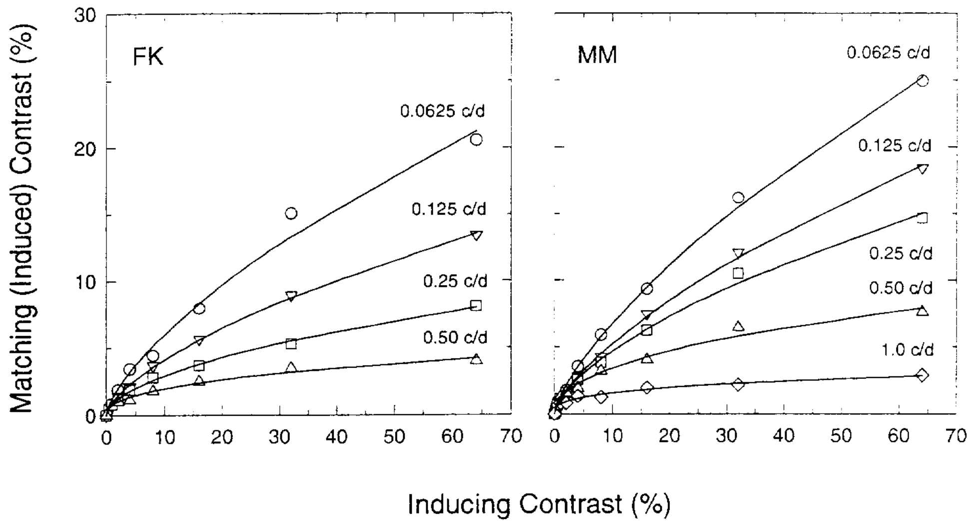

FIGURE 2. The mean percent contrast of real pedestal gratings [Fig. 1(f)] which matched the contrast of induced pedestals of the same spatial frequency [Fig. 1(e)] is plotted as a function of percent inducing grating contrast. Different inducing grating spatial frequencies are shown as parameters. There is no matching function for observer FK at 1.0 c/deg because the magnitude of grating induction was too weak at any inducing grating contrast to enable a match to be made. Smooth curves through the data represent the best-fitting power functions as determined by least-squares optimization. The matching functions allowed inducing grating contrast to be converted into "induced" pedestal contrast.

were used), and geometric means were computed. A schematic diagram of the appearance of the matched induced and real pedestal displays at the conclusion of the procedure is shown in Fig. 1(e) and (f), respectively.

RESULTS

Figure 2 plots the mean contrast of real pedestal gratings [Fig. 1(f)] which matched the contrast of induced gratings of the same spatial frequency [Fig. 1(e)] as a function of inducing grating contrast. Recall that these measurements were made using a homogeneous 1 deg test field, i.e. in the *absence* of any added target grating. Different inducing grating spatial frequencies are shown as parameters. There is no matching function for observer FK at 1.0 c/deg because the magnitude of grating induction was simply too weak at any inducing grating contrast to allow matches to be made. Confirming earlier reports (McCourt & Blakeslee, 1993) matching contrast is well described as a power function of inducing grating contrast with an exponent <1. The smooth curves through the data represent the best-fitting power functions (constrained to pass through the origin) as determined by least-squares optimization. The power law relationship between inducing contrast and matching (induced) contrast allowed the analytic conversion of inducing grating contrast into units of "equivalent real pedestal contrast". For simplicity we will refer henceforth to "induced" pedestals.

Figure 3 plots target grating detection thresholds as a function of real (solid symbols) or induced (open symbols) pedestal contrast. Absolute target grating threshold is indicated by dotted horizontal lines. Contrast discrimination functions for spatial frequencies ranging from 0.0625 to 0.5 c/deg appear in separate panels, as labeled. Again, in the induced pedestal conditions target gratings were added to the test field 180 deg out-of-phase with the inducing grating, and were thus in-phase with the induced gratings. The abscissae of Fig. 3 are plotted in terms of pedestal contrast for the real pedestal condition, and equivalent real pedestal contrast for the induced pedestal condition, the latter having been calculated from the results of the contrast matching functions of Fig. 2.

Figure 3 reveals a number of important points. First, target grating detection was facilitated by both real and induced grating pedestals. This is revealed by the "dipper" shape of the discrimination function. Second, the magnitude of facilitation in the induced pedestal condition, and the range of pedestal contrast over which it occurs, diminishes with increasing spatial frequency. Third, the pattern of facilitation and masking is most similar for the induced and real pedestal conditions at 0.0625 and 0.125 c/deg, and progressively diverges at higher spatial frequencies. The increasing compression of the induced pedestal functions (open symbols) along the abscissa as spatial frequency increases is due to the diminishing strength of induction at these higher inducing grating frequencies (see Fig. 2).

What accounts for the observed divergence, with increasing spatial frequency, of contrast discrimination functions measured on real vs induced pedestals? One possibility is that the high levels of inducing grating contrast required to produce the various levels of induced pedestal contrast at high spatial frequencies are exerting lateral masking effects. One way to test this hypothesis would be to produce induced pedestals at high frequencies without increasing inducing contrast. This can be accomplished by taking advantage of the fact that grating induction strength is constant for a constant product of inducing grating frequency (ISF) and test field height (TFH). Increasing viewing distance increases inducing grating spatial frequency while proportionally decreasing test field height and thus holding grating

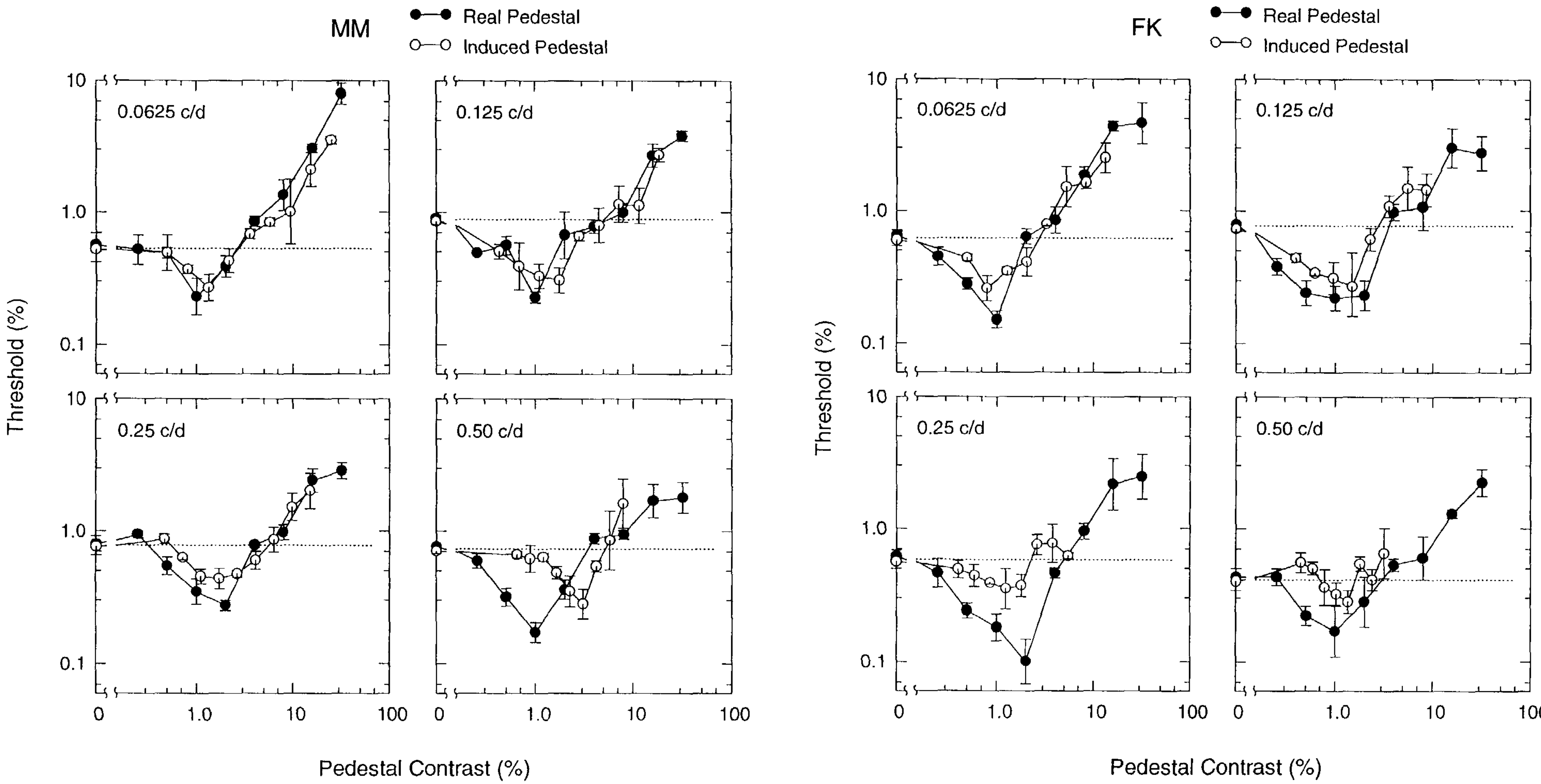

FIGURE 3. Target grating detection thresholds are plotted as a function of real (●) or induced (○) pedestal contrast for observers (MM) and (FK). Absolute target grating threshold is indicated by dotted horizontal lines. Contrast discrimination functions for spatial frequencies 0.0625–0.5 c/deg appear in separate panels, as labeled. Target detection is facilitated by both real and induced grating pedestals, as revealed by the "dipper" shape of the discrimination function. The magnitude of facilitation by induced pedestals declines with increasing spatial frequency. The overall shapes of the discrimination functions are nearly identical for low frequency induced and real pedestals, but diverges increasing spatial frequency.

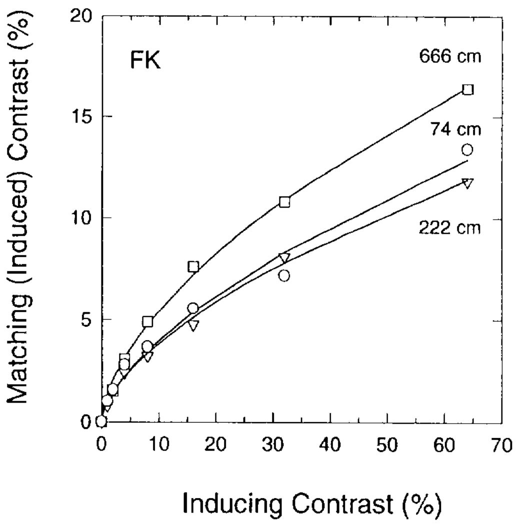

FIGURE 4. Induced pedestal contrast is plotted as a function of 0.125 c/deg inducing grating contrast (1 deg test field height) for observer FK. Viewing distance is shown as a parameter. Varying viewing distance manipulates inducing grating spatial frequency while preserving a constant ratio of inducing frequency to test field height. Induced pedestal contrast in this "constant ratio" condition, unlike the "constant test field height" contrast matching data of Fig. 2, displays no systematic variation with inducing grating frequency.

induction magnitude (i.e. induced pedestal contrast) constant (Foley & McCourt, 1985). Variations in viewing distance, therefore, can be used to manipulate inducing grating spatial frequency independently from inducing grating and induced pedestal contrast.

A control experiment was run on one observer (FK), whose results are shown in Figs 4 and 5. Figure 4 plots matching contrast at three viewing distances, shown as parameters, as a function of inducing contrast for a 0.125 c/deg inducing grating in conjunction with a 1 deg test field. Unlike the contrast matching data of Fig. 2, variations of spatial frequency consequent to changes in viewing distance are here shown to have no systematic effect on grating induction magnitude.

Figure 5(a) shows contrast discrimination functions measured on real (●) and induced (○) pedestals measured at the standard viewing distance of 74 cm. These data constitute an exact replication of the 0.125 c/deg condition of Fig. 3 for observer FK, and are in good agreement. Figure 5(b) and (c) present contrast discrimination functions measured at viewing distances of 222 and 666 cm, respectively, at which distances stimulus spatial frequencies were 0.375 and 1.125 c/deg. Note that despite the nine-fold increase in spatial frequency, contrast discrimination functions on real and induced pedestals nearly superimpose. Compare, for example, the induced pedestal condition of Fig. 5 (c) with those for 0.5 c/deg in Fig. 3.

Finally, as noted earlier, a number of investigators (Takahashi & Ejima, 1985; Cannon & Fullencamp, 1993) have reported that phase-aligned inducing gratings facilitate the detection of high frequency (3.0–8.0 c/deg) target gratings, whereas thresholds are elevated for targets presented in the context of opposite phase inducing gratings. Given the opposite pattern of results

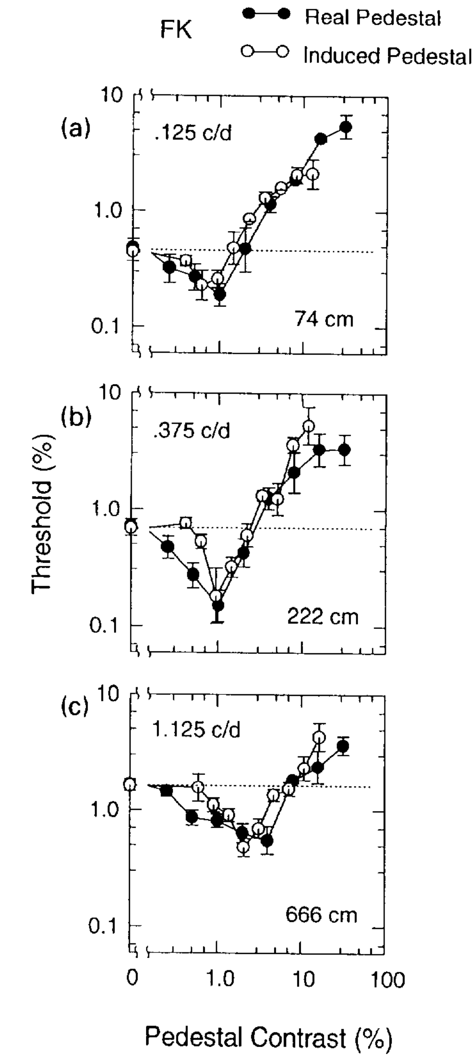

FIGURE 5. Contrast discrimination functions measured on real (●) and induced (○) pedestals measured at three viewing distances, shown as parameters in the three panels. The data in (a) are an exact replication of the 0.125 c/deg condition of Fig. 3 (FK). (b) and(c) are discrimination functions measured at viewing distances of 222 and 666 cm, respectively, at which distances stimulus spatial frequencies were 0.375 and 1.125 c/deg. Despite the nine-fold increase in spatial frequency, contrast discrimination functions on real and induced pedestals nearly superimpose.

(described above) for low frequency inducing gratings, target detection thresholds were also obtained in conjunction with both phase-aligned and opposite phase inducing gratings at spatial frequencies of 1.0 and 4.0 c/deg.

Experimental results from two observers appear in Fig. 6. Unlike Fig. 3, discrimination functions for the real pedestal and inducing grating conditions are plotted in separate panels. Note that results for the inducing grating conditions are plotted in terms of inducing grating contrast rather than equivalent real pedestal contrast. Reasons for this include that:

1. Matching results could not be obtained from observer FK in the 1.0 c/deg condition, or from either observer in the 4.0 c/deg condition, making conversion into units of equivalent real pedestal contrast impossible; and
2. Even for observer MM the matching function for the

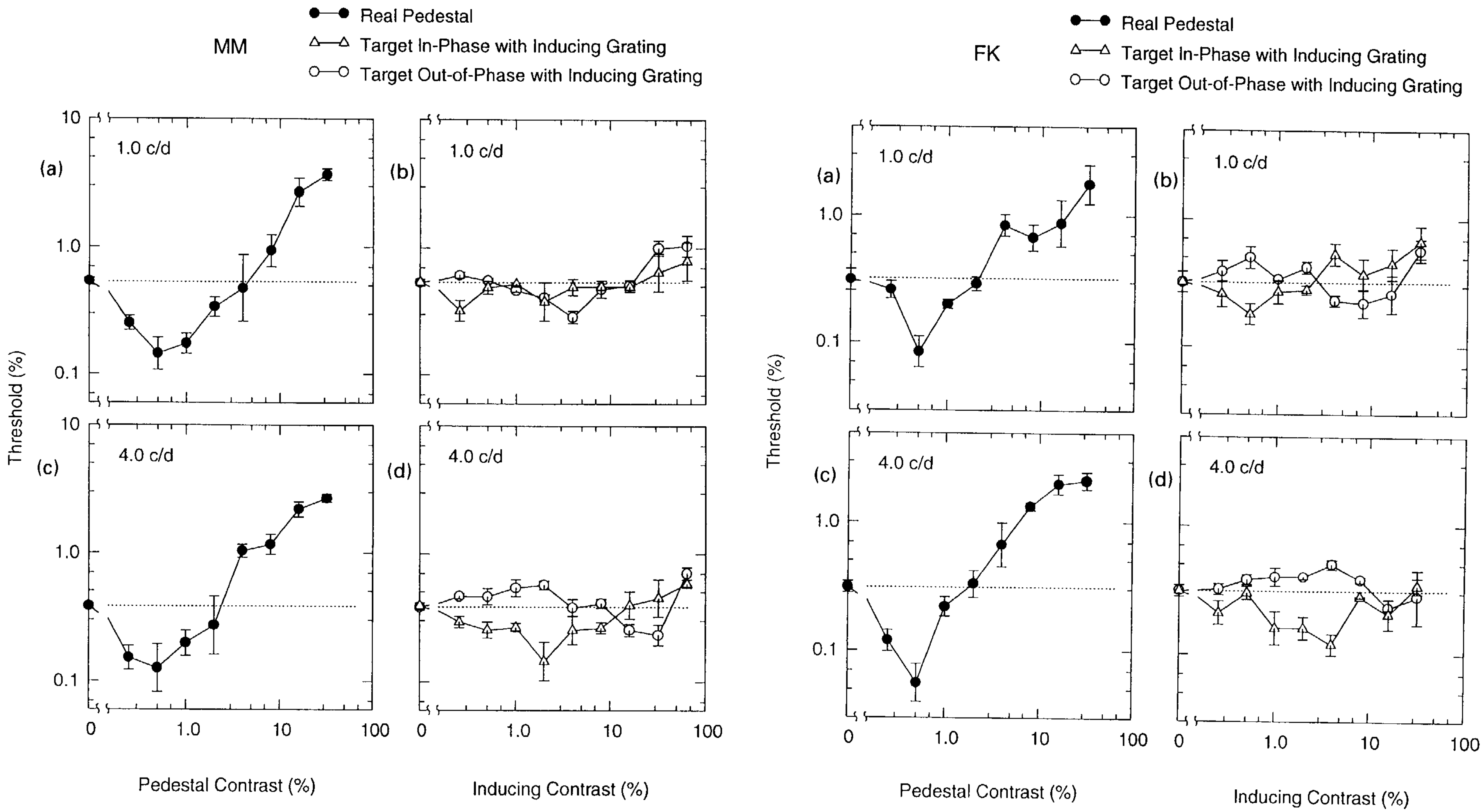

FIGURE 6. Target detection thresholds for both phase-aligned (△) and opposite phase inducing gratings (○,●) at 1.0 and 4.0 c/deg. Discrimination functions for real pedestal and inducing grating contrast conditions are plotted in separate panels. Results for the inducing grating conditions are plotted in terms of inducing grating contrast rather than equivalent real pedestal contrast. In the real pedestal conditions [●, (a) and (c)] the familiar dipper function is observed at both 1.0 c/deg [(a) and(b)] and 4.0 c/deg [(c) and (d)]. For the inducing grating condition [○, △ (b) and (d)] the results are somewhat more complex. For the 1.0 c/deg inducing grating condition [○, △ (b) and (d)] there is no consistent pattern of facilitation or masking across the two observers for target gratings presented either in-phase (△) or out-of-phase (○) with inducing gratings, although there is a hint of in-phase facilitation at the lowest inducing contrasts. A clear pattern emerges at 4.0 c/deg: target gratings presented *in-phase* with inducing gratings are facilitated, whereas they are masked when presented *out-of-phase*, up to inducing contrasts of *c.* 10%.

1.0 c/deg inducing frequency is so compressive (see Fig. 2) that such a transformation would virtually superimpose the data points, thus obscuring any pattern of threshold variation which might exist.

In the real pedestal conditions [●, Fig. 6 (a) and (c)] the familiar dipper function is observed at both 1.0 c/deg [Fig. 6(a) and (b)] and 4.0 c/deg [(c) and (d)]. For the inducing grating condition [○, △ Fig. 6(b) and (d)] the results are somewhat more complex. For the 1.0 c/deg inducing grating condition [○, △ Fig. 6(b) and (d)] there is no consistent pattern of facilitation or masking across the two observers for target gratings presented either in-phase (△) or out-of-phase (○,●) with inducing gratings, although there is a hint of in-phase facilitation at the lowest inducing contrasts. A clear pattern emerges at 4.0 c/deg: target gratings presented *in-phase* with inducing gratings are facilitated, whereas they are masked when presented *out-of-phase*, up to inducing contrasts of *c.* 10%. This pattern is precisely the opposite of that found for low spatial frequency target/inducing gratings, where robust facilitation is observed for targets presented out-of-phase with inducing gratings at low contrasts. The spatial frequency at which the phase change for facilitation occurs is *c.* 1.0 c/deg.

DISCUSSION

A brief summary of the results thus far concludes that "induced pedestal" gratings in a 1 deg high test field ("constant height" condition) facilitate the detection of real target gratings added in phase to them, for inducing and target grating spatial frequencies up to *c.* 0.5 c/deg. The amount of facilitation diminishes as inducing/target grating spatial frequency increases. "Induced pedestal" gratings facilitate the detection of real gratings across a wide range of inducing/target spatial frequencies (from 0.125 to 1.125 c/deg), when the product of test field height to inducing grating spatial frequency was held constant at 0.125. In this "constant product" condition the amount of facilitation is largely independent of spatial frequency. For inducing frequencies of 0.0625 and 0.125 c/deg in the constant height condition, and for all three constant product conditions, induced pedestals act nearly identically to their real pedestal counterparts (which were matched in perceived contrast) with regard to their facilitation and masking interactions with added target gratings. As inducing grating spatial frequency increases above 1.0 c/deg, facilitation of target gratings presented out-of-phase with inducing gratings gives way to facilitation of targets presented in-phase with inducing gratings.

Addressing rival hypotheses

Under a wide range of conditions induced gratings were observed to facilitate the detection of real gratings added in-phase to them. Prior to discussing the potential theoretical significance of these findings, however, it is proper to consider whether any other factors besides the existence of an induced pedestal within the test field might be responsible for target grating facilitation. One possibility is that as inducing grating contrast increases from zero, the test field (target) region simply becomes physically demarcated. Such demarcation will reduce positional uncertainty associated with the target and might itself facilitate its detection. Cole *et al.* (1990) found that demarcating a region with a black ring did in fact facilitate the detection of targets presented within it. A second possibility is that the inducing grating itself, and not the illusory grating it induces in the test field, might act directly as the pedestal stimulus, as if it simply extended across the test field.

To address both possibilities a control experiment was performed in which detection thresholds were measured for a 0.125 c/deg target grating presented in-phase with inducing gratings (the results of Fig. 3 are for targets presented out-of-phase with inducing gratings). Over the range of inducing grating contrast for which induced pedestals were subthreshold (and for which observers responded as usual by selecting the interval with the higher apparent contrast),* detection thresholds for target gratings presented in-phase with the inducing grating were always elevated relative to a no-pedestal control condition [i.e. displayed the "bumper" effect described by Kulikowski (1976); Bowen & Cotten (1993); and Yang & Makous (1995)]. Therefore, the phase specificity of the facilitation makes it very unlikely that the reduction of positional uncertainty associated with the physical demarcation of the test region underlies our results. Such phase specificity also rules out the second, inducing grating-as-pedestal hypothesis, at least for frequencies below 1.0 c/deg, since it erroneously predicts that facilitation should occur for targets presented in-phase with inducing gratings.

Common processing of real and induced gratings

It was earlier argued that the strongest test of the hypothesis that induced and real gratings were signaled by a common mechanisms would be to demonstrate that induced gratings facilitate the detection of real gratings. The results of this study therefore confirm this hypothesis and add to the mounting body of evidence which suggests that early, or low-level, visual mechanisms are responsible for grating induction. Insofar as real luminance gratings are signaled by activity in linear band-pass filters at an early stage of visual processing, the same can therefore be said of the mechanisms signaling induced gratings, as has been suggested elsewhere (Foley & McCourt, 1985; Moulden & Kingdom, 1991; McCourt & Blakeslee, 1994).

*When induced gratings are suprathreshold, target gratings added in-phase with the inducing gratings act as canceling stimuli. This has the paradoxical effect of making the interval containing the target grating appear to possess a lower contrast than the no-target interval.

Effect of inducing grating spatial frequency

We now consider why the pattern of target detection diverges for the induced and real pedestal conditions as spatial frequency increases in the "constant height" condition (Fig. 3), yet not in the "constant product" condition (Fig. 5). Grating induction magnitude does decrease with increasing spatial frequency in the former, but not the latter, case [see Foley & McCourt (1985)]. The divergence cannot, however, be a trivial consequence of any reduction in induced pedestal contrast in the "constant height" condition because target thresholds are already plotted in terms of equivalent real pedestal contrast. The only difference is that greater *inducing grating* contrast is required to produce a criterion amount of induction for the "constant height" vs the "constant ratio" condition.

A clue to the actual cause of the divergence comes from a consideration of the results with the 1.0 and 4.0 c/deg inducing grating conditions (Fig. 6). Here, the robust facilitation observed for targets presented out-of-phase with inducing gratings observed at low spatial frequencies is replaced at higher frequencies by facilitation for targets presented in-phase with inducing gratings. The results with the 4.0 c/deg inducing gratings confirm previous reports by Takahashi and Ejima (1985) and Cannon and Fullencamp (1993), and imply the existence of at least two distinct mechanisms. One produces facilitation for low frequency targets presented out-of-phase with inducing gratings, and another facilitates the detection of high frequency targets presented in-phase with inducing gratings. These mechanisms are presumed to act antagonistically, where their relative activation depends upon factors such as the ratio of inducing grating period and test field height. For a test field height of 1.0 deg the two mechanisms appear roughly equipotent at inducing frequencies of *c*. 1.0 c/deg. Interestingly, 1.0 c/deg is also the spatial frequency at which the relative magnitudes of grating induction and contrast-contrast (Chubb, Sperling & Solomon, 1989; Cannon & Fullencamp, 1991) become equipotent (McCourt, 1995).

At present we can only speculate as to what these mechanisms might be. One possibility is that at low inducing grating spatial frequencies and/or narrow test field heights, the mechanisms most responsive to target gratings are those whose receptive fields are spatially tuned to the scale of the test field itself rather than to the period of the inducing grating—these could either be concentric center–surround mechanisms whose centers were similar in scale to the test field, or elongated filters (like simple cells) whose spatial half-period and orientation matched that of the test field. Either mechanism will produce a counterphase output in the test field in response to the inducing grating [see Foley & McCourt (1985), Fig. 10, and Moulden & Kingdom (1991), Fig. 2]. At inducing grating spatial frequencies above 1.0 c/deg, however, and particularly in conjunction with large test fields, the mechanisms most sensitive to target gratings may be those actually tuned to the inducing/target grating frequency (i.e. whose centers or half-periods are similar in scale to the inducing grating half-period), and these will respond in-phase with the inducing grating. It is additionally possible that the in-phase facilitation observed at high inducing frequencies is related to the mechanisms responsible for the facilitation and masking interactions of collinear Gabor patches shown recently by Polat and Sagi (1993), although they report that facilitation is phase-indifferent, whereas for our extended gratings it is not. Future experiments measuring the spatial frequency and orientation tuning of the mechanisms producing the facilitation of target gratings by both real and induced pedestals will test this hypothesis.

Suprathreshold brightness and contrast threshold mechanisms

In their classic study Cornsweet and Teller (1965) measured increment thresholds for a small (24 min dia) circular target presented on a wide (8.5 deg dia) background. Whereas the brightness of the background could be substantially altered by variations in the luminance of a surrounding annulus (via simultaneous brightness contrast), induced background brightness variations produced no effect on target thresholds other than that predicted by light scatter from the annulus. On the other hand, changing the luminance of the background itself produced the expected Weber's Law relationship. Other studies employing similar techniques (Van Esen & Novak, 1974; Guth, 1973) or using the fading of stabilized images or Troxler fading to decouple the brightness and luminance of background fields have produced essentially similar results (Burkhardt, 1966; Sparrock, 1969; Buck *et al.*, 1983). The weak or nonexistent association between background brightness and target detection has sponsored the view that threshold sensitivity and suprathreshold brightness perception are governed by different mechanisms and are essentially independent. The present results suggest otherwise.

Similar to simultaneous brightness contrast, induced gratings decouple the luminance and brightness of the test field. In fact, grating induction has been suggested to represent a generalization of simultaneous brightness contrast (McCourt, 1982), such that the latter corresponds to a special case of grating induction in which the inducing grating possesses an effective spatial frequency of 0 c/deg. The current discovery that induced gratings profoundly affect grating detection thresholds and under certain conditions act as nearly perfect spatial metamers of the luminance variations they resemble clearly indicates that sensitivity and brightness are not independent. This calls into question prior conclusions regarding the relationship between simultaneous brightness contrast and threshold processes. Interestingly, investigations of other brightness phenomena such as Mach Bands (Fiorentini, 1972), the Ehrenstein figure (Spillmann, Fuld & Neumeyer, 1984; Jory, 1987) and square wave patterns resembling the grating induction display (Jory, 1987) also support the idea that brightness variations can influence detection thresholds. The general similarities between the grating induction and simultaneous brightness contrast phenomena and their distinctly different effects on target sensitivity may make them particularly well-suited to the further investigation of the conditions under which brightness and sensitivity are related.

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