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THE LOCAL BORDER MECHANISM IN GRATING INDUCTION

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Abstract—Both White's effect and the grating induction effect are examples of brightness contrast phenomena. Models to account for these effects have either explicitly rejected local border mechanisms (such as retinal ganglion cells) in favour of cortical mechanisms, or explicitly rejected elongated cortical filters in favour of local mechanisms. We have argued that any viable model must include both classes of mechanism. In this paper we present some novel versions of induction effects, and describe the explanatory power of a model couched solely in terms of the operation of local spatial filters. The model employs filters at different spatial scales whose outputs are then averaged. Using this approach it is possible to give a good account not only for the novel demonstrations we present, but also for the pattern of results reported by others concerning various manipulations of the spatial parameters of induction displays.

INTRODUCTION

McCourt (1982) first demonstrated that an illusory sinusoidal grating can be induced into a homogenous stripe running orthogonally through a sinusoidal grating. The effect is an example of simultaneous brightness contrast. If the homogenous stripe is of the same mean luminance as the inducing grating, the induced grating is 180 deg out of phase with the inducing grating, and for this reason the phenomenon has been termed "counterphase brightness induction" (Foley & McCourt, 1985).

In this communication we describe some novel and compelling examples of grating induction whose explanation is not immediately obvious. We make the general case that these phenomena can be explained in terms of the patterns of response of conventional local edge-detecting mechanisms like retinal ganglion cells. In some cases a good explanation can be given solely in terms of filters at a single spatial scale. However, it appears that other phenomena can only be explained in terms of a model that involves pooling the outputs of filters at different spatial scales, within the framework of a multi-channel model of the kind we have previously applied to the Craik–Cornsweet–O'Brien illusion (Moulden & Kingdom, 1990b).

All the stimuli we have examined with the model consist of horizontally modulated inducing gratings, or "inducers", and homogenous "test" stripes which run through the inducing gratings horizontally.

An extraordinary example of grating induction

We begin with a particularly powerful example of grating induction. The background in Fig. 1 is a single period of a spatially extensive low-frequency sinusoid. The thin horizontal stripe is of homogeneous luminance throughout. The remarkable thing is that the magnitude of the induced, illusory, modulation in the stripe is actually greater than the apparent contrast of the inducing grating.

Figure 2 shows the convolution output of a single DOG filter for both a vertical (A) and two horizontal (B and C) tracks through Fig. 1, at the positions indicated. The narrow homogenous test stripe spatially gates that receptive field so that a large part of its inhibitory surround is covered by the inducer region. The absolute magnitude of the output of any DOG filter to a sinusoid is maximal when that filter is exactly centred upon either a peak or trough of the sinusoid. Track A represents this location. The filter response at this position (see function A) illustrates the peak response of the filter to both the inducing sinusoid and the homogenous stripe. The peak response thus represents the amplitude of modulation of filter response along horizontal tracks like those marked B and C.

It is this response amplitude which we argue is the correlate of perceived contrast, whether real or illusory. Because the filter output is modulated to a much greater extent as it passes along the test stripe (curve C) than along the background (curve B) it produces the greatest perceived contrast in this region.

Interlaced ramp inducers

An inducer grating consisting of a linear luminance ramp may be regarded as approaching the limiting case as the spatial frequency of the inducing grating is reduced towards zero. Foley and McCourt (1985) showed, with sinusoidal gratings, that the lower the spatial frequency of the inducing grating the higher is the apparent contrast of the induced grating. We would therefore expect a relatively large degree of brightness induction from this stimulus.

In Fig. 3(a) a linear inducing ramp is interlaced with homogenous stripes, the heights of the homogenous and inducing stripes being the same. The remarkable thing is that only under close inspection is it possible to distinguish the ramp stripes from the homogenous stripes (apart from the difference in the polarity of their perceived gradient), such is the magnitude of brightness induction produced by the former in the latter.

Figure 3(b) illustrates the two-dimensional convolution response of a single DOG filter whose space constant is chosen to approximate that of the point spread function of human vision (about 3–4 arc min according to Wilson, 1978) when the figure is viewed from a distance of about a third of a metre. The amplitude of the output of the DOG is coded by luminance in Fig. 3(b).

Crucially, the computed response amplitudes of the filter to the two types of stripe are identical with the exception that their phases are reversed, in keeping with the percept.

Interlaced sinusoidal inducers

The important difference between a sinusoid and a ramp is that the response of a DOG filter is not everywhere zero in a sinusoid. Unlike the case of the ramp, therefore, a DOG filter does have the potential to discriminate between sinusoidal modulation and homogeneous patches.

Figure 4(a) and (b) are patterns in which homogenous stripes alternate with a single period of a sinusoidal grating. The contrast of the inducing grating in Fig. 4(a) is of low contrast compared with that of Fig. 4(b). As can be seen, it is difficult to distinguish between the inducer and induced stripes in Fig. 4(a), but comparatively easy in Fig. 4(b).

Figure 4(c) shows the convolution of a stripe pattern like those in Fig. 4(a) and (b) with the same DOG filter employed earlier. As with the ramp pattern of Fig. 3(a) [whose convolution output is shown in Fig. 3(b)], there is no signifi-

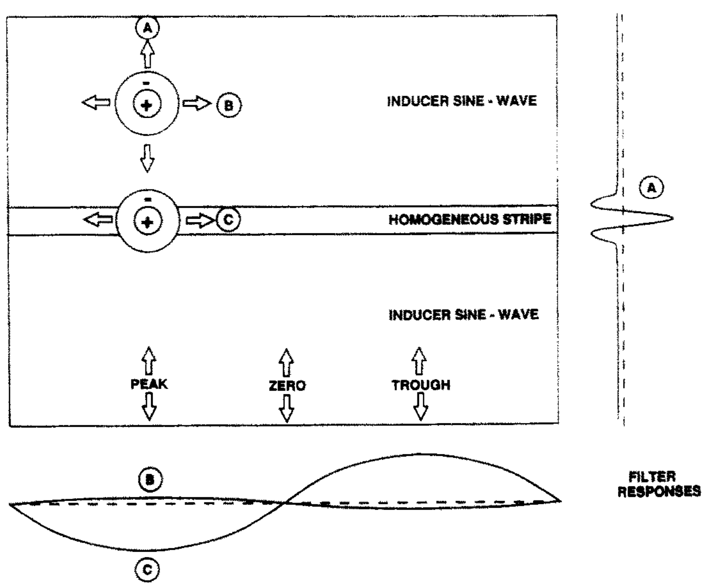

Fig. 2. Schematic representation of Fig. 1 showing DOG receptive fields at two notional locations. The outputs of the DOG as it is passed through the stimulus along tracks A, B and C are shown as the corresponding functions A, B and C. The difference in the modulation amplitude of B and C may be the explanation for the subjective appearance of Fig. 1.

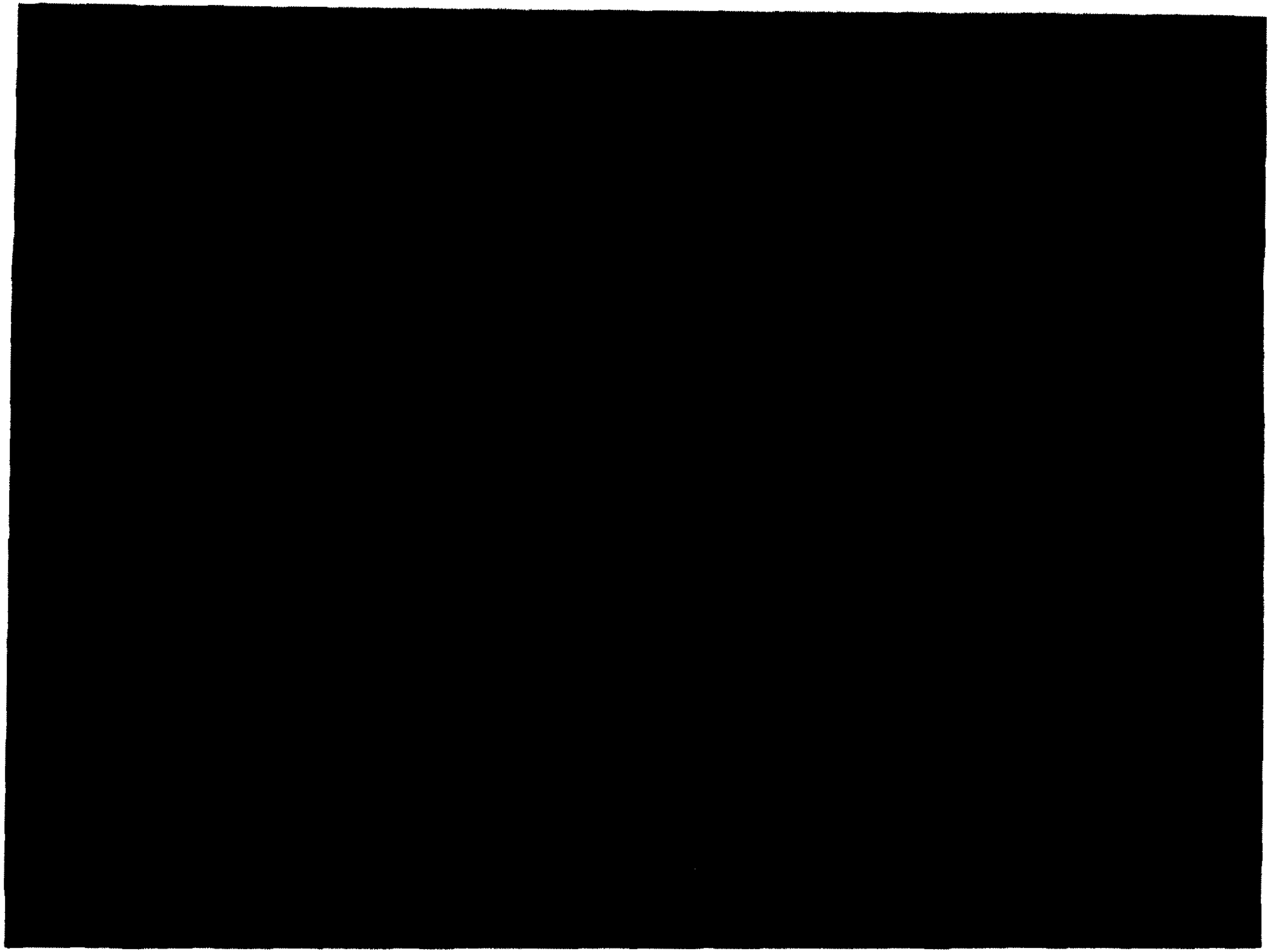

Fig. 1. The narrow stripe is homogeneous in luminance throughout its extent. The background is sinusoidally modulated in luminance. The illusory induced brightness modulation of the stripe is greater than the apparent modulation of the background.

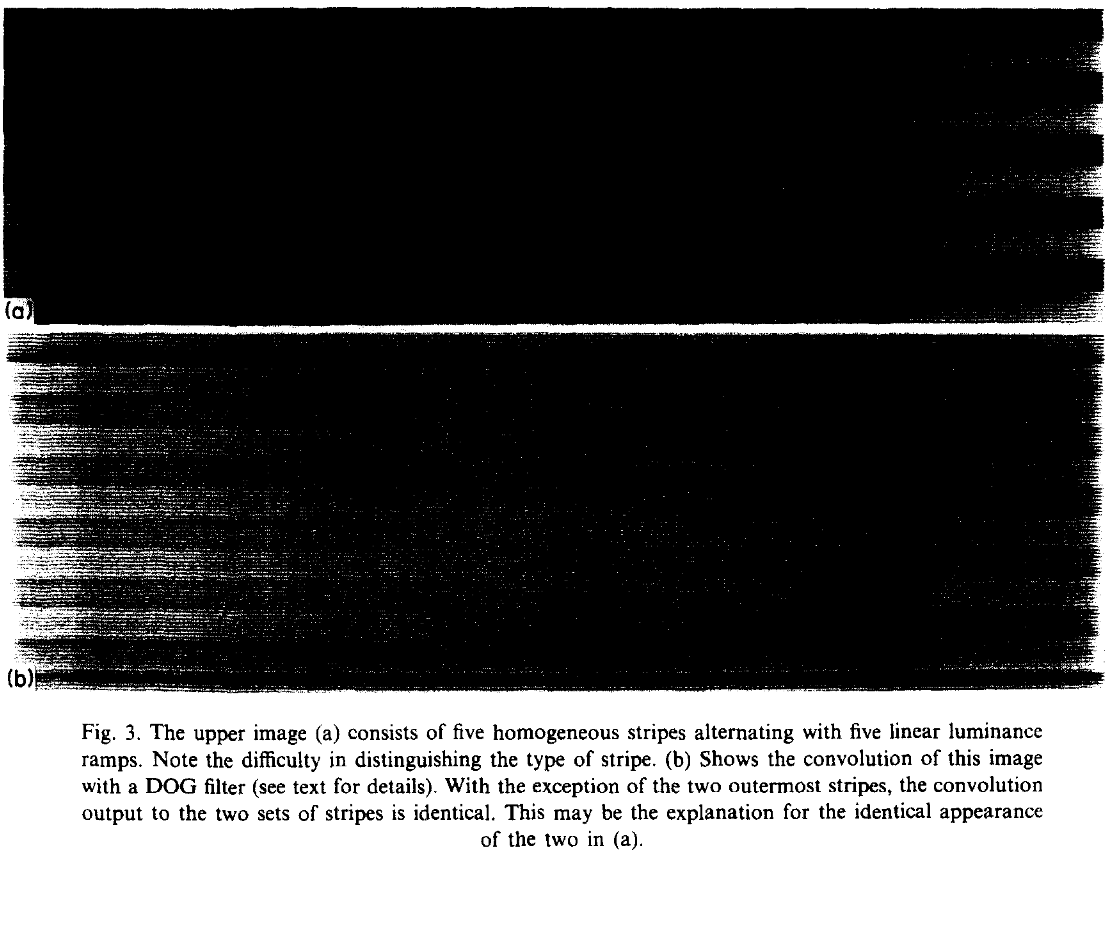

Fig. 3. The upper image (a) consists of five homogeneous stripes alternating with five linear luminance ramps. Note the difficulty in distinguishing the type of stripe. (b) Shows the convolution of this image with a DOG filter (see text for details). With the exception of the two outermost stripes, the convolution output to the two sets of stripes is identical. This may be the explanation for the identical appearance of the two in (a).

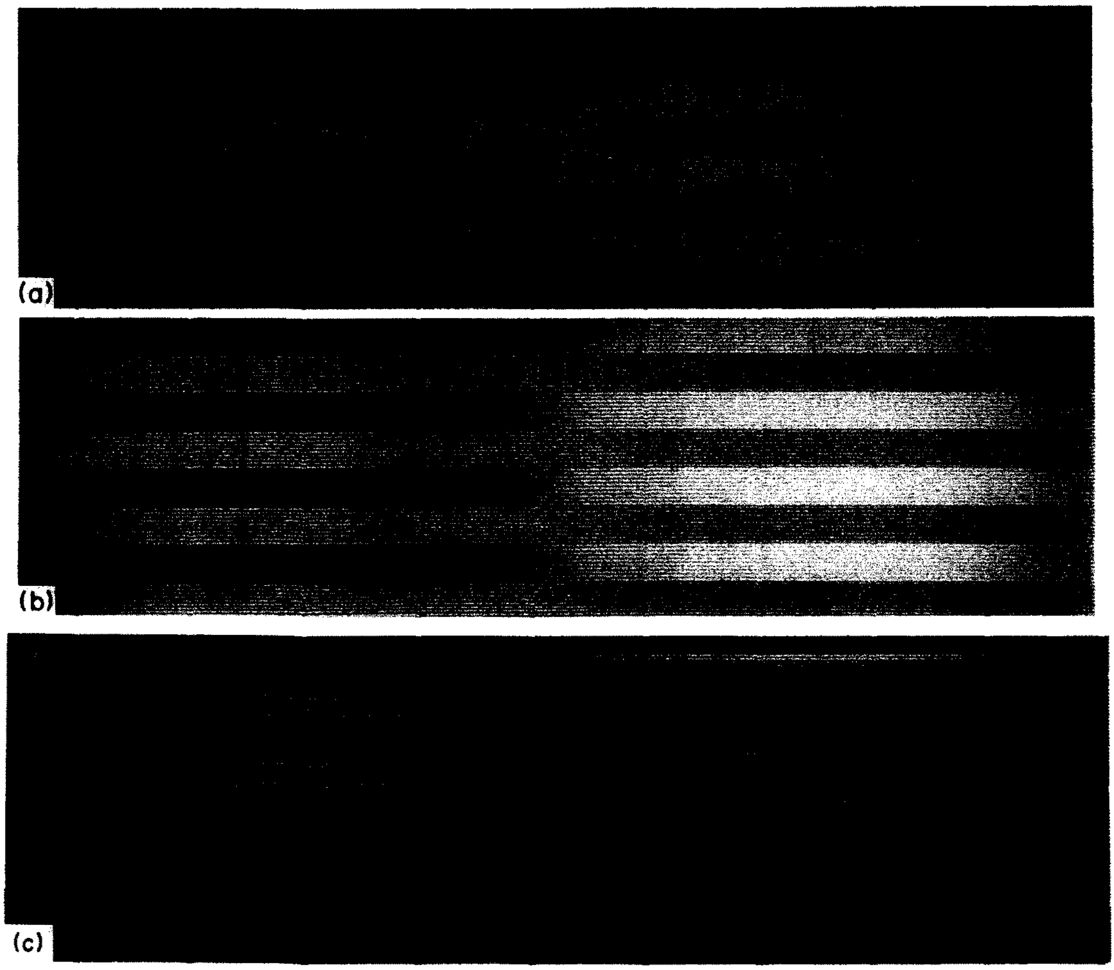

Fig. 4. Homogeneous stripes alternative with inducing stripes modulated by a single period of a sinusoid. In (a) the modulation of the inducing stripes is of low amplitude; in (b) the modulation is of high amplitude. It is difficult to discriminate induced and inducing modulation in (a), while the discrimination is relatively easy in (b). (c) Shows the result of convolving a stimulus like (a) and (b) with a DOG filter.

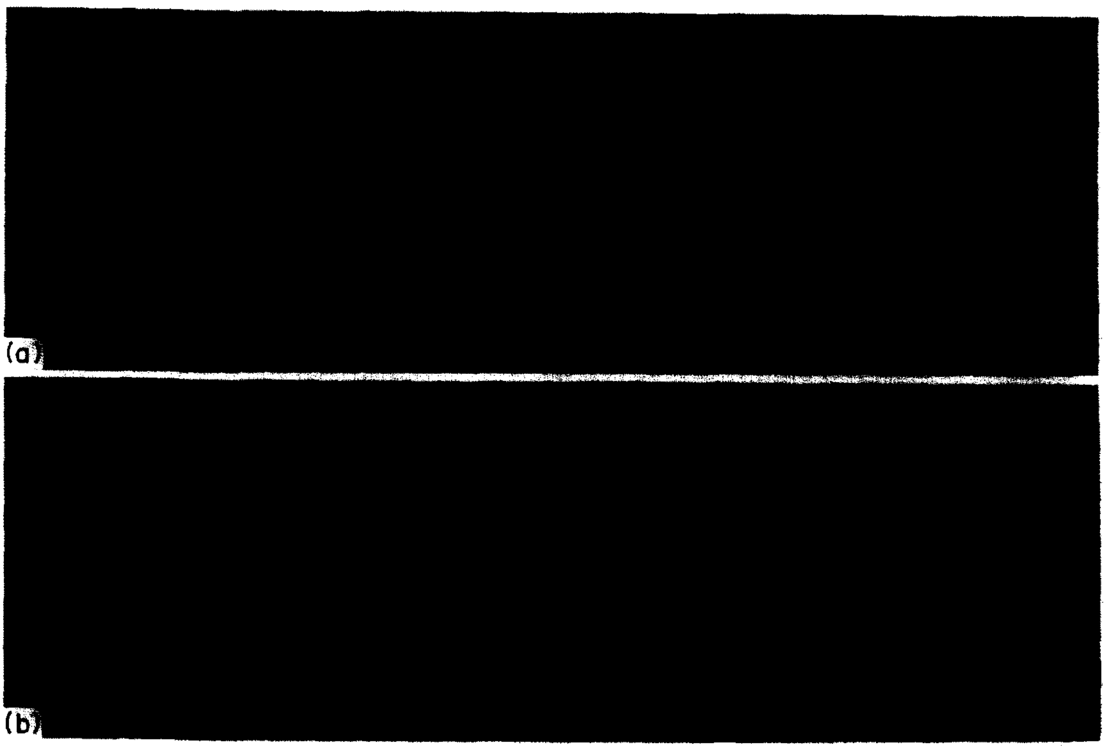

Fig. 6. In (a) homogeneous stripes alternate with sinusoidally-modulated inducing stripes of relatively high spatial frequency. The apparent contrast of the induced grating is very low. However, as (b) shows, the convolution of (a) with a single DOG filter shows a strong response in the homogeneous stripes, which does not accord with the percept.

cant information in the DOG filter output which would allow the distinction to be made between the induced and inducing stripes. While the results of the convolution shown in Fig. 4(c) accord with the perceptual experience of the low contrast stripe pattern Fig. 4(a), in which identification of the stripes is difficult, they differ markedly from that of the high contrast stripe pattern Fig. 4(b), in which the discrimination is easy.

The convolution output for Fig. 3(a) does not distinguish between the contrast of the induced and inducing stripes because the response of the filter to a ramp is zero, just as it is to homogeneous illumination. Unlike linear ramps, though, sinusoidal profiles can be detected by DOG filters. However, the filters will only respond strongly to such modulation within a certain spatial frequency range because of their band-pass characteristic. In Fig. 4(a) and (b), the spatial frequency of the grating is too low, we suppose, to create an above threshold response in the single DOG filter employed in the convolution, so this filter will not distinguish induced stripe from inducing stripe.

The most parsimonious explanation for the fact that with the high contrast in Fig. 4(b) the stripes are readily distinguishable is that the visual system has available larger-scale filters than the one employed in the convolution, and that the response is only above threshold in the presence of the high amplitude stimulus of Fig. 4(a).

To develop this notion, we employed four concentric two-dimensional "on-centre" DOG filters with space constants at octave intervals. The one dimensional spatial weighting function of each filter was given by

$$\mathrm{DOG}(r) = G\left\{\frac{1}{\sigma^2}\exp\frac{-r^2}{2\sigma^2} - G_s\cdot\frac{1}{R^2\sigma^2}\cdot\exp\frac{-r^2}{2R^2\sigma^2}\right\}$$

where r was the radial distance from the centre of the filter, σ the space constant of the centre, R the ratio of space constants of the surround and centre, set to 1.6 throughout. G_s and G were scaling parameters which scaled the surround of the filter and the overall filter response respectively. Normally G_s is set to unity to achieve a balanced filter, but because the filter was digitized, it had to be set to be greater than unity to produce approximately balanced filters in each instance. Table 1 gives the values of the space constants of the four filters we employed together with their respective values of G_s and G.

Table 1. Parameters of filters employed (arc min)

	1	2	3	4
σ	1.95	3.9	7.8	15.7
G_s	0.64	0.84	0.92	0.96
G	8.0	4.0	2.0	1.0

The filter which is able to discriminate the homogenous from the inducing stripes is actually rather larger than those which are normally employed to model contrast thresholds for sinusoidal gratings, where the range of space constants are, for example 1.68–7.5 arc min (Wilson & Bergen, 1979) or 0.35–2.8 arc min (Watt & Morgan, 1985). However, it is not implausible that such large filters exist.

We have assumed first that the growth of perceived contrast with the output of the filters is linear, and second the rate of growth is independent of the spatial scale of the filters. While both of these assumptions are matters of contention, they are not critical for the essentially qualitative explanations of the demonstrations described here.

The implementation of the model for grating induction is particularly simple and can be completely described by the following two rules.

(1) Grating induction occurs when one or more of the filters produces a response in the centre of the test stripe.

(2) The overall magnitude of grating induction is given by the average response amplitude of the four filters in this position.

Figure 5 illustrates the convolution response to Fig. 4(a) [or (b)] of the four filters employed in the multi-channel model as they track vertically downward at the location of the peak in the inducer, as shown by Track A in Fig. 2. Consider the response of the largest filter (curve IV in Fig. 5). The amplitude of its response is relatively small here, despite its spatial scale being well-matched to that of the inducing stripe, because of the gating effect of the narrow stripe width. But as can be seen by careful inspection, it is only this filter that shows any difference in the (absolute) amplitude of its output when positioned within a homogenous stripe rather than within an inducing stripe. We suggest that it is this asymmetry of the response in large-scale filters that provides the basis for the discrimination between the inducer and the induced regions in Fig. 4(b). For the low-contrast pattern in Fig. 4(a) we suppose that the response of these large filters is simply below threshold.

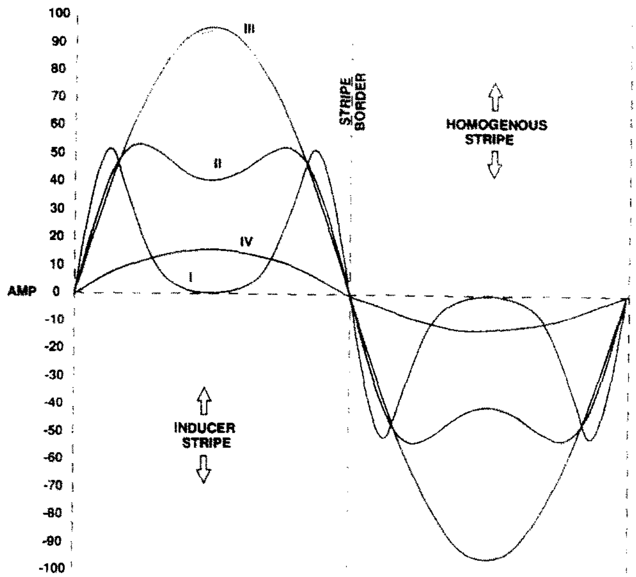

Fig. 5. DOG filters were passed vertically (orthogonal to the stripe axis) through inducing and homogeneous stripes like those in Fig. 4. The filters tracked vertically downward at the location of the sine peak as illustrated by track A in Fig. 2. Response amplitude (in arbitrary units) as a function of location is shown for four filters of different spatial scale. The response profile marked I is that of the smallest filter; the profile marked IV is that of the largest filter. The latter filter is the only one whose response amplitude to the homogeneous stripe is different (it is smaller) from that to the inducing stripe.

Thus small scale filters are needed to explain the detection and induction demonstrated in Fig. 4(a), and large-scale filters are needed to explain the stripe discriminability in Fig. 4(b). This is a good illustration of the need to consider the combined effects of filters at different spatial scales.

Spatial frequency effect

We now consider the effect of inducers of relatively high spatial frequency; McCourt (1982) showed that the magnitude of grating induction declined quite rapidly with increasing spatial frequency. In fact, the response of the single filter described above produces an induction effect which declines with increasing spatial frequency, but the slope of the high-cut part of its characteristic is much shallower than would be expected from what is observed. Figure 6 illustrates this. In Fig. 6(a) there is very little induction apparent, but as Fig. 6(b) shows, the corresponding DOG convolution output would lead one to expect a high amplitude of induction. The psychophysically observed rapid decline, according to our model, occurs because of the contribution of the larger filters to the brightness signal.

The decline in induction magnitude with increasing spatial frequencies occurs, we argue, for two reasons. The first reason is that as spatial frequency increases there will be fewer and fewer filters that are "relatively small" compared to the spatial scale of the stimulus. It is these relatively small filters that generate the in-phase induction signal. The result is that the absolute magnitude of the induction signal declines.

The second reason is that as the spatial frequency of the inducing grating increases, so more and more (smaller and smaller) filters become "relatively large" compared with the spatial scale of the stimulus, and begin to generate an asymmetric, discriminatory, signal in response to the inducing and induced regions. The relative magnitude of brightness induction compared to the contrast of the inducing stripe will therefore decrease with increased spatial frequency.

Figure 7(a) and (b) illustrate the response amplitudes of the four filters for the inducer and test stripes respectively as a function of spatial frequency.

Consider first the responses of the various filters when they are centred in the middle of the homogeneous stripe [Fig. 7(a)]. The very smallest filter gives zero output at all spatial frequencies, since its receptive field is so small that it is entirely contained within the homogeneous stripe. The medium-sized filters do respond, however, generating counterphase induction for low and medium spatial frequencies; the point at which their response changes

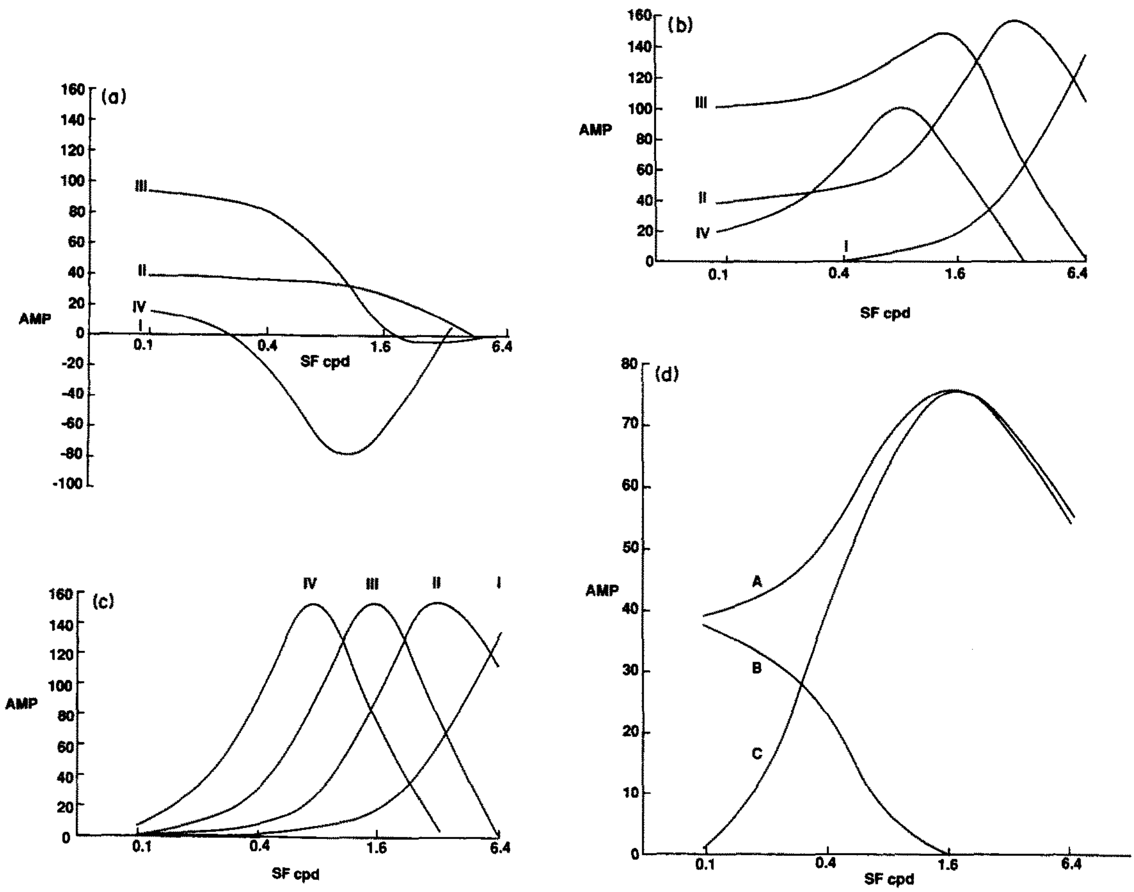

Fig. 7. The peak amplitude response of each of the four DOG filters used in the model when tracking horizontally along the centre of the stripes, as a function of the spatial frequency of the inducer. (a) Homogenous stripes, (b) inducer stripes. (c) Shows the magnitude of the difference in the amplitude of response to the homogeneous and the inducing stripe. (d) Shows the average output of the filters in each of the three cases shown in (a), (b) and (c) (A, B, C respectively).

to signalling in-phase induction depends upon their spatial scale. The largest filter begins to generate in-phase induction signals at a relatively low spatial frequency.

Foley and McCourt (1985) correctly pointed out that a single-filter model would predict in-phase grating induction at any but relatively low spatial frequencies. While the largest filter taken alone does indeed produce an in-phase induced grating with relatively high spatial frequency inducing stimuli, the amplitude of its response is more than balanced by the smaller filters which produce opposite-phase induction, as described below. Since according to our argument the overall brightness percept is the average value of those produced by each filter, the overall result is opposite-phase induced gratings. This is how the multiple-filter model avoids the problem raised by Foley and McCourt.

The responses of these filters when centred within the sinusoidal inducing stimuli are, as expected, quite different. The smallest filter responds best to high frequencies, with a marked low frequency cut. The large filter shows the characteristic band-pass response to sinusoids, peaking at low spatial frequency, while the two intermediate filters also show the expected band-pass characteristics, peaking in the middle range of spatial frequencies.

The functions shown in Fig. 7(a) represent the magnitude of the induction signal, while those in Fig. 7(b) represent the apparent contrast of the inducer, according to the outputs of each individual filter. We argue that if we now take the difference between the functions in Fig. 7(a) and (b) for each filter, this difference function will give an indication of the size of the signal that discriminates between the induced and the inducing grating, as a function of spatial frequency. This is illustrated in Fig. 7(c).

Figure 7(d) shows the responses averaged across filters. Curve C is the difference (A − B) between the two response functions.

This difference function is our prediction of the discriminability of the inducing and induced stripes. At low spatial frequencies it falls to zero: see Figs 3(a) and 4(a) above. As can be seen from curve B our model predicts a rapid fall off in induced grating amplitude with increase in spatial frequency of inducer. This predicted rapid decline with increased spatial frequency is very similar to what McCourt (1982) showed to occur with human observers.

Effect of stripe height

So far we have considered some aspects of the effects of spatial frequency and amplitude of the inducing grating; but what of the effects of the heights of the inducing grating and the homogeneous stripe? If the homogeneous stripe is wide then running along its centre there will be a set of filters whose surrounds do not impinge upon the adjacent induction region.

These null-responding filters could signal the fact that this stripe is not physically modulated. The wider the stripe, the greater will be the number of such filters at any one scale of which this is true. Moreover, widening the stripe will mean that more and more of the larger filters will be recruited to deliver this null signal.

The quantitative predictions of our model for the case of single stripe in an extended grating are shown in Fig. 8 for four stripe heights and five spatial frequencies of inducer. The overall pattern is qualitatively similar to that found empirically by McCourt (1982), though a direct comparison with McCourt's data is impossible since he employed a nulling technique to estimate the magnitude of brightness induction, whereas the model here provides a direct estimate.

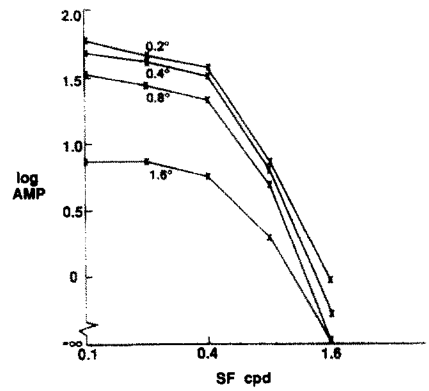

Fig. 8. This shows the averaged output of the four filters for four different stripe widths and five spatial frequencies. Response magnitude is in arbitrary units. The predicted magnitude of brightness induction is inversely proportional to stripe width.

SUMMARY

As we (Moulden & Kingdom, 1989, 1990a) and Foley and McCourt (1985) have argued, circularly symmetrical filters cannot provide the whole answer to the question of brightness induction: more spatially-extensive mechanisms are also necessary. But, as we have demonstrated in this paper, a model that involves the pooling of the outputs of circularly-symmetric filters at different spatial scales has considerable explanatory power in accounting for many of the features of brightness induction.

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