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LETTER TO THE EDITORS

THE MECHANISMS INVOLVED IN BRIGHTNESS INDUCTION EFFECTS: A REPLY TO ZAIDI

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McCourt (1982) described what he called the "grating induction effect": an illusory grating is induced in a physically homogeneous grey stripe superimposed upon and orthogonal to a sine-wave grating. The induced grating is 180 deg out of phase with, and (at least in the case described above) has the same spatial frequency and orientation as, the inducing grating.

Zaidi (1989) has recently described some demonstrations of grating induction effects from which he concluded that Foley and McCourt's (1985) explanation of the effect in terms of elongated receptive fields is incorrect. Since Foley and McCourt had extended their argument to apply also to White's effect (1979; see below) it might seem not only that there is a variety of effects but also that there is no general explanation for any of them. The intention of this communication is to try to unravel the apparent confusion.

We wish to argue firstly that Zaidi's demonstrations show only that models based on elongated filters are insufficient, not that they are wrong, and secondly that the two mechanisms of brightness induction that we (Moulden & Kingdom, 1989a) have recently revealed can account for both Foley and McCourt's findings and Zaidi's findings, as well as for White's effect, which provided the original stimulus for our investigations.

White (1979) described a remarkable phenomenon in which grey bars replacing segments of the white phase of a square-wave grating appeared darker than identical grey bars replacing segments of the black phase of the grating. The effect is counter-intuitive because the grey bars on the white phase are bounded on their long vertical edges by black and on their short horizontal edges by white. To be consistent with classical demonstrations of brightness contrast one would expect the lightening effect of the long black boundary to be greater than the darkening effect of the short white boundary, so that the grey patch as a whole would appear lighter than normal: it actually appears darker, and is thus a challenge to conventional theory. Where brightness effects are in the opposite direction to brightness contrast, "assimilation" is sometimes invoked as an explanation. But not only is there no generally-accepted account of the mechanism underlying "assimilation" effects, White's effect occurs for stimuli having much lower spatial frequencies than those for which it has been possible to demonstrate "assimilation". This is why we (Moulden & Kingdom, 1989a) chose to investigate it in some detail.

White (1981) attempted to account for his phenomenon in terms of what he called "pattern specific inhibition". The suggestion was that elongated cortical filters having similar preferred orientations and spatial frequencies, and which receive their input from adjacent retinal locations, might tend to inhibit each other. This would reduce the amplitude of the signal generated by the mutually inhibiting filters and thereby reduce the apparent contrast of a grating so that, presumably, the dark bars of a grating would look lighter and the light bars would look darker than similar bars viewed in isolation, although the notion has never been tested in this way. If this did happen, then the grey "victim" bars in his stimulus would also suffer the effects of the contrast reduction. Grey bars positioned on the white phase would have their contrast with the adjacent dark bars reduced: they would look darker than they would if viewed in isolation. By the same mechanism the grey bars on the black phase would be made to seem lighter than they would in isolation.

Both White and White (1985) and Foley and McCourt (1985) were agreed that White's effect and McCourt's grating induction effect are related and mediated by the same mechanism, but they disagreed about what that mechanism was. Foley and McCourt (1985) proposed an alternative to White's "pattern specific inhibition". The model that they put forward to account for the two effects was couched in terms of cortical filters having small centres and elongated surrounds; the elongated surrounds were necessary to account for the fact (Foley & McCourt, 1985) that the contrast of the induced grating increases with the length of the inducing grating at least up to between 2 and 5 deg.

Both of these theoretical approaches were adequate to give at least a qualitative account for the two phenomena given the empirical data then available. More recently, however, we have made a detailed quantitative study of induction effects using stimuli that, we argued, were the crucial elements of White's figure (Moulden & Kingdom, 1989a). The basic form of the stimulus we employed was one that we referred to as the 'H-figure", and this is illustrated in Fig. 1. This figure is formally identical in its essential features to Zaidi's figures in the accompanying communication, particularly his Fig. 1.

This stimulus consisted of a central grey square bounded on its left and right vertical margins by "flanking" bars and on its upper and lower horizontal margins by "coaxial" bars. Flanking and coaxial bars were mutually opposite in luminance polarity with respect to the victim square, and could be either black or white according to the condition. In one experiment, for example, we varied the height of the flanking bars from zero (the stimulus was then just a grey square with two vertical coaxial bars) to a maximum when the flanking bars extended 1.6 deg above and below the victim square. In another experiment we varied the height of the coaxial bars with the height of the flanking bars held constant. (Another of our experiments was identical to an experiment that had previously been carried out by Morgan and Ward, who were the first to suggest the importance of corners in such figures; their "corner effect" is part of the model we described in Moulden & Kingdom, 1989a, and which we outline below.) Our data (which in the case of the experiment that was similar to that of Morgan and Ward replicated their data almost exactly) revealed a number of interesting features, two of which are of particular relevance here.

1. THE EFFECT OF FLANKING BAR HEIGHT

The first major feature was that as the height of the flanking bars in our stimulus was increased, their modulatory effect on the brightness of the grey square also increased but, significantly, showed a marked asymptote when they reached a height just a little (6–12 min arc) greater than that of the grey patch. Following Morgan and Ward, we attributed this, the "corner effect", to the operation of a purely local mechanism which we modelled in terms of the responses of circularly-symmetric opponent-surround receptive fields. Although of course these filters will operate at all points adjacent to the border of the grey square, they are especially sensitive to corners such as those created as soon as the flanking bar height exceeds that of the grey patch. Once this corner-creating height has been reached (its optimal value being related to the size of the inhibitory surrounds of the circular filters), further increases in the height of the flanking bars has no additional effect. We have subsequently (Kingdom & Moulden, 1990) extended these observations into the chromatic domain, where precisely analogous effects may be observed.

Figure 2 shows the post-convolution image that results from operating upon a stimulus like that shown in Fig. 1 with a Difference-of-Gaussians (DOG) approximation to the receptive field of a ganglion cell. The figure is reproduced from Moulden and Kingdom (1989a), where details of space-constants and so on are given. The critical feature, we argued, is the *difference* in the outputs of filters whose centres are (a) just inside and (b) just outside the grey patch in the regions of the corners. The ouput of the individual filters is modulated, crucially, by the luminances falling in their inhibitory surrounds. (In some cases, and particularly in the kinds of stimuli described here, contrast signals at different points on the boundary of a figure may have not merely different magnitudes but also different polarities. In such cases the brightness of the bounded region is a function of the joint effects of the different signals. Using one restricted set of stimuli—grey squares bounded on their right and left by white squares and above and below by black squares, for example—we, Moulden & Kingdom, 1989b, have shown that the resultant

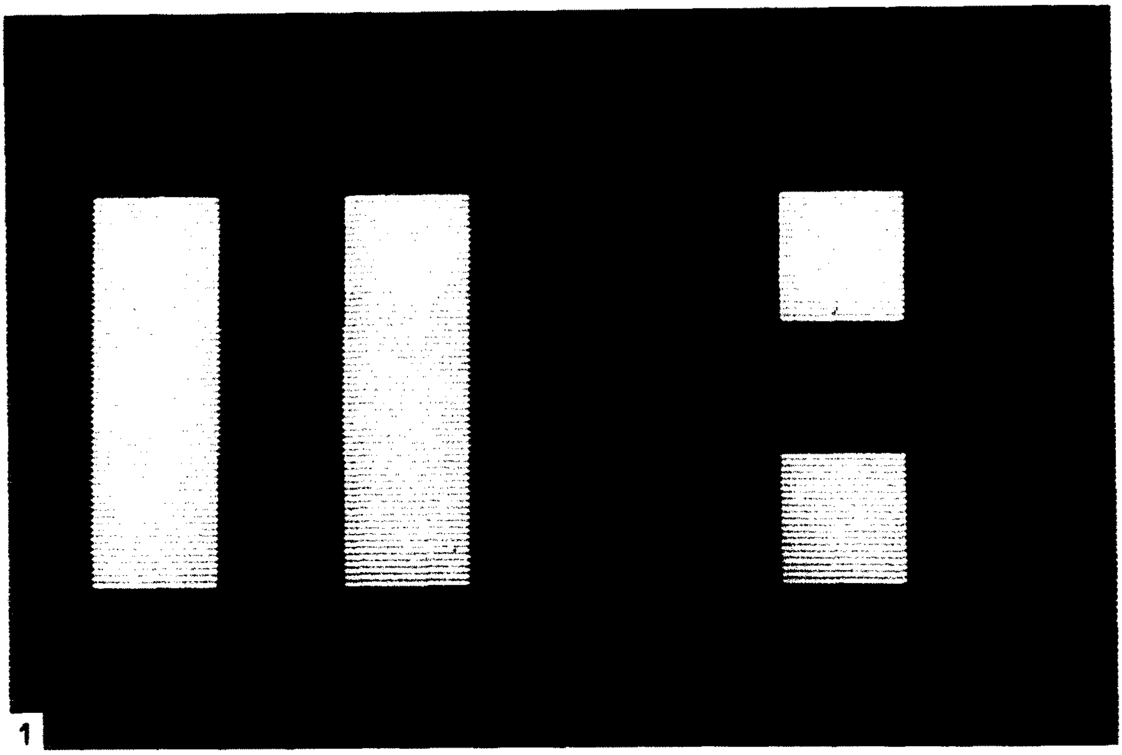

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Fig. 1. Examples of the "H-figures" used in Moulden and Kingdom (1989a). The stimulus on the left has white flanking bars and a black coaxial bar; the stimulus on the right has the reverse polarity. Particularly when viewed from a distance the same direction of brightness induction is seen as in White's effect: the grey square on the left looks lighter than the one on the right.

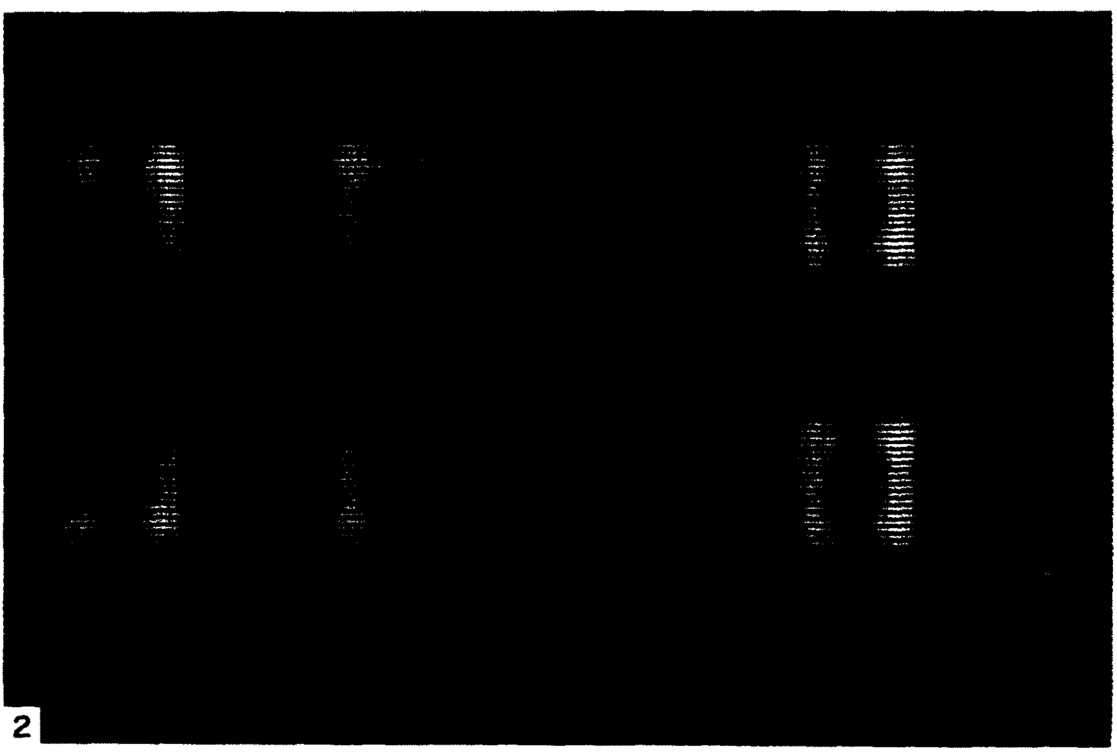

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Fig. 2. The post-convolution image that results from convolving the images in Fig. 1 with a DOG filter. The presence of "hot-spots" in the region of the corners is evident.

brightness can be described by a simple mathematical function.)

In the original paper from which Fig. 2 is taken we used the "hot spots" in that image as a qualitative demonstration of the operation of the corner effect, arguing that it was the exaggerated local contrast signals at the corner of the victim square that accounted for the brightness differences. We suggest that the operation of a purely local border effect, even in the absence of the corners to which the underlying mechanism is especially sensitive, can give an account of Zaidi's demonstrations (see below). Indeed, with hindsight we discover that we (Morgan & Moulden, 1986) have previously published convolution images based on local differencing operators that demonstrate the operation of such a mechanism in an unintentional homologue of grating induction stimuli. We were investigating a version of the Munsterberg figure known as the "cafe wall" illusion in which thin grey "mortar" lines are intermediate in luminance between alternating black and white "bricks". The way in which illusory light and dark regions (the essence of our explanation of the illusion) might be induced into the grey stripes is clearly shown in Figs 1b and 3b of that paper. (in a paper published since the first version of this communication was written, Haig, 1989 has described a very similar argument; see particularly his Figs 1b and 8b.)

We are thus suggesting that Zaidi's demonstrations can be explained in terms of the same mechanism as one (the local border effect) of the two we have suggested to underlie other brightness induction effects. The remaining mechanism is the one we have referred to as the "spatially extensive" mechanism.

2. THE EFFECT OF COAXIAL BAR LENGTH

Like Foley and McCourt (1985) and Zaidi (1989) we also found that more distal part of a stimulus could exert a powerful modulatory effect. Again using the "H-figure", we found that when we varied the length of the coaxial bars (holding the height of the flanking bars constant) their modulatory influence increased with their length at least up to 1.6 deg, the largest value we used. We attributed this to the operation of a spatially-extensive mechanism involving filters with elongated opponent end-regions, similar to but less complex and more physiologically-plausible than those proposed by Foley and McCourt (1985). We suggested that this mechanism might play a part both in White's effect and in McCourt's effect.

Very recently, Zaidi (1989) has produced some interesting and informative variants of the grating induction effect. In particular, some of his displays involved inducing gratings whose orientation was at an oblique angle to the superimposed grey induction region, rather than the two being orthogonal as in McCourt's original demonstration. He showed convincingly that the induced grating produced by these oblique gratings has neither the same spatial frequency nor the same orientation as the inducing gratings. He convolved his oblique-grating stimuli with elongated filters such as those proposed by Foley and McCourt and found that the post-convolution images contained no cohesive grating features. He concluded that "such elongated features are probably not the correct mechanism for grating induction"; that "local edge effects are the factors primarily responsible for visual grating induction"; and that "parts of the inducing stimuli that are distal to the test field influence only the amplitude of the induced modulation"; but he did not speculate upon the nature of the filters that might be involved in the mediation of either the distal or the local effects.

At first sight the position appears to be one of confusion and conflict; it need not be.

We have one essential objection to Zaidi's line of reasoning, which is simply this: it is not safe to argue that since elongated filters cannot account for one version (his own) of the grating induction effect then they are not involved in any such effects.

Our proposed resolution of the apparent confusion is as follows: we have demonstrated brightness induction effects which require for their explanation the operation of two distinct mechanisms; one is the purely local effect (which we model in terms of circularly-symmetrical filters) and one is the spatially extensive effect (which we model in terms of filters with elongated opponent surrounds). Both of these mechanisms are in operation in White's effect, of which our H-stimuli were elemental fragments. The local mechanism underlying the corner effect (circularly-symmetric opponent filters) would also operate along the local border between and inducing grating and the grey induction stripe to produce just the sort of local effects isolated by Zaidi. Finally, in the original McCourt induction effect both the local effect and the spatially extensive effect will operate; their effects will be consistent and will reinforce each other, leading to the additive influence of increased height observed for vertical induction gratings by both Zaidi and Foley and McCourt.

The dual mechanisms revealed by Moulden and Kingdom (1989a) can thus account for the observed phenomena; this may offer a resolution of both the apparent inconsistency in data and the conflict in theory.

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