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Letters to the Editor

In Defence of "Lateral Inhibition" as the Underlying Cause of Induced Brightness Phenomena: a Reply to Spehar, Gilchrist and Arend

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Illusory, or induced, brightness phenomena have for many years interested vision scientists because they offer the potential to reveal fundamental truths concerning the mechanisms of brightness and contrast processing. The traditional idea that such phenomena reflect the operation of "lateral inhibition", a term which predates and is cognate to the modern usage of "bandpass filtering", has recently come under attack from a number of quarters. It has been shown for instance, in the classic demonstration of simultaneous contrast in which two identical grey patches appear markedly different in brightness depending on the luminance of their backgrounds, that the magnitude of the brightness difference between the grey patches depends on whether the viewer perceives the backgrounds to be of different reflectance and thus identically illuminated, or of identical reflectance and thus differently illuminated (Gilchrist, 1977, 1979; see also Knill & Kersten, 1991; Arend & Spehar, 1993a,b; Adelson, 1993). Such important demonstrations reveal that low-level brightness percepts are susceptible to modification or reinterpretation by secondary (presumably higher order, but poorly understood) visual processes which, for example, are invoked to establish whether intensity variations within scenes are based on reflectance or illumination changes. These demonstrations do not, however, discredit the substantial body of evidence which links induced brightness phenomena to early visual filtering operations.

One of the strongest such links concerns the induced brightness effect known as grating induction (McCourt, 1982). This effect refers to the illusory, "induced", grating observed in a uniform test stripe that runs orthogonal to the orientation of the bars of a real, "inducer", grating. We have recently shown that the detection of real gratings can be facilitated by induced gratings, under some circumstances to a degree identical to that found for a real grating with the same spatial characteristics and perceived contrast (Kingdom & McCourt, 1993; McCourt & Kingdom, 1996). The fact that the induced brightness variations can act as almost perfect metamers of real luminance variations is most parsimoniously accounted for by the idea that the same mechanisms which transduce real luminance variations (i.e., contrast) are transducing the illusory luminance variations as well. These mechanisms are generally understood to be retinal and cortical neurons, whose receptive fields perform bandpass spatial filtering operations on the distribution of luminance in scenes.

It is therefore of particular interest when new evidence is brought forward and interpreted to challenge this traditional view. The recent study by Spehar, Gilchrist and Arend (Spehar *et al.*, 1995) is such a case in point. Spehar *et al.* measured the magnitude of brightness induction in two previously quite well-studied effects: White's effect (White, 1979) and grating induction. The simplest and arguably best understood of these two varieties of induced brightness is grating induction, and we will, therefore, concentrate our response on Spehar and colleagues' claims concerning this phenomenon, although our analysis may apply to White's effect as well. Spehar *et al.* reported that the perceived contrast of induced gratings depended on the luminance of the test stripe relative to that of the mean of the inducer grating. When test stripe luminance was either higher or lower than the mean of the inducer grating, the perceived contrast of the induced grating was reduced compared with the situation when the test stripe was at the mean luminance of the inducer (see their Fig. 3). Spehar *et al.* regard as critical, however, their finding that when the luminance of the test stripe exceeds the peak of the inducer, or falls below that of the trough, no induced grating was observed. Spehar *et al.* concluded that "..........we have demonstrated the importance of qualita-

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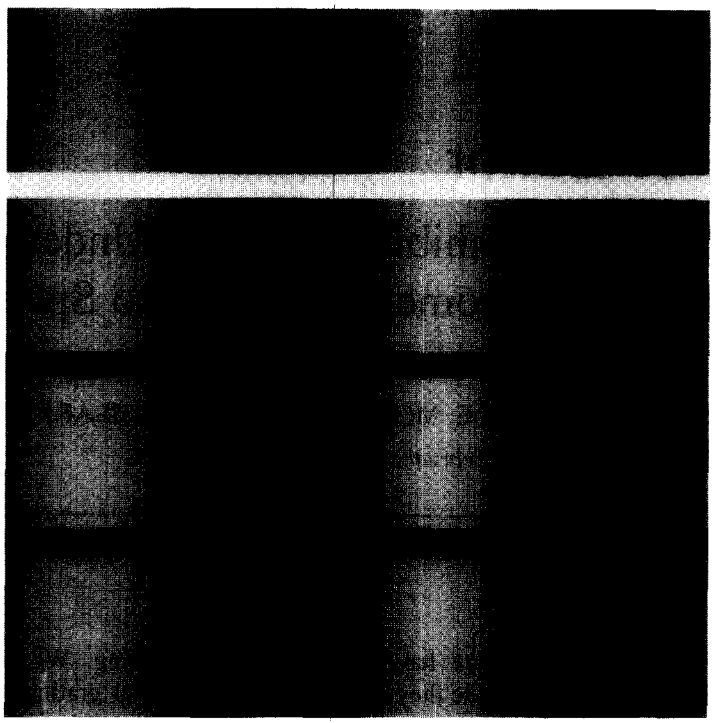

FIGURE 1. Grating induction with a low spatial frequency sine-wave inducer. The luminances of the three uniform test stripes are from top to bottom: A greater than the peak, B at the mean, and C less than the trough of the inducer. The contrast of the inducer on the monitor surface was 60%, making its peak 80% and trough 20% of maximum luminance. A, B and C were 7%, 50% and 97% of maximum luminance, respectively. Note that due to the limitations of photographic reproduction these values may be slightly inaccurate in the actual figure.

tive boundaries in the luminance relationships that support the appearance of both White's effect and Foley and McCourt's grating induction: the luminance of the test patches must lie within the range of luminances of the grating stripes........... when this constraint is violated the effects are not observed. None of the existing models can readily accommodate these findings" (p. 2163). Because previous models of grating induction have emphasised the role of early bandpass filters to account for grating induction (Foley & McCourt, 1985; Moulden & Kingdom, 1991) Spehar *et al.* clearly regard their results as constituting an important challenge to such an approach.

In this communication we show that the findings of Spehar *et al.* are in fact precisely what one would expect from the operation of bandpass filters normally associated with signalling real luminance contrast. We begin with a simple demonstration (see also Fig. 6 in McCourt, 1982) to refute Spehar and colleagues' assertion that when test stripe luminance is greater than the peak, or less than the trough, luminance of the grating, no grating induction is ever found. Figure 1 shows that this is not the case when the inducer grating is of a low spatial frequency. An induced grating is observed in all three test stripes in Fig. 1, yet only the luminance of the middle stripe, B (set to the mean luminance of the inducing grating) lies within the luminance range of the grating. The apparent contrast of induced gratings in test fields A and C (43% above and below mean luminance, respectively), are reduced relative to that seen in B, and especially in C, but are visible nonetheless.

The results of previous quantitative studies of the effect of test field luminance on grating induction magnitude also indicate that the amplitude of grating induction diminishes as the luminance of the test stripe departs from the mean luminance of the inducer. It is important to note, however, that no categorical boundaries are observed and grating induction is clearly visible at test field luminances well above and below the peak and trough of the inducer grating (Foley & McCourt, 1985; McCourt, 1994).

The obvious question is: Why was this induction not observed by Spehar *et al.*? As explanation we begin by noting that they used sub-optimal stimuli and hence produced only weak grating induction in the first place. For instance, they employed square-wave rather than sinewave inducing gratings. The former are known to produce much (up to 40%) weaker levels of induction than sinewaves of identical spatial frequency (McCourt, 1982; McCourt & Foley, 1985). In addition, their inducer possessed a relatively high spatial frequency, and their test fields were rather large. The exact values of these parameters were not reported. Inspection of their Fig. 3, however, suggests that they might have been approximately 0.25 c/d, and 2 deg, respectively. Grating induction magnitude is a lowpass function of spatial frequency and is inversely related to test field height, falling, for example, to half-maximum amplitude for a 2 deg test field at a spatial frequency of 0.15 c/d (McCourt, 1982). Because the magnitude of grating induction in the stimulus displays of Spehar *et al.* was initially so low, we do not regard it as particularly surprising or significant that the effect of setting test stripe luminance to lie

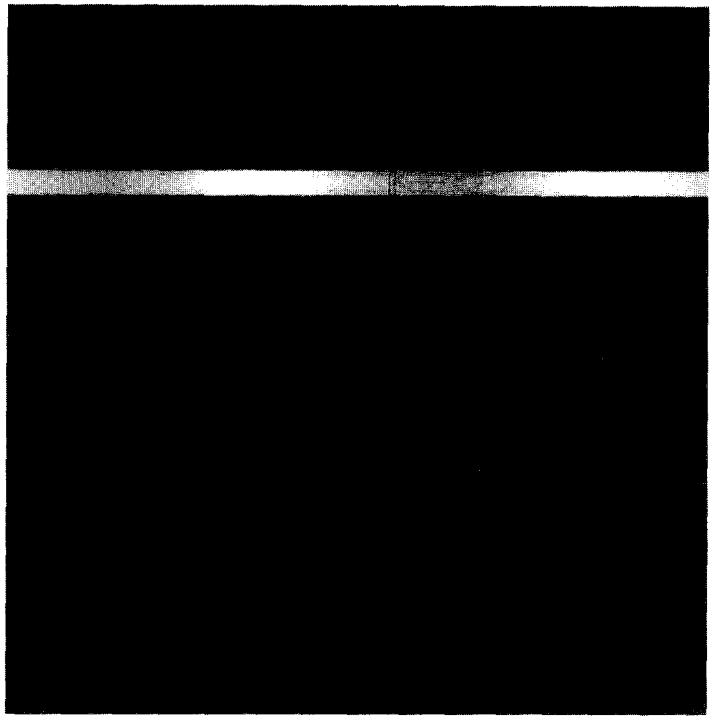

FIGURE 2. The effect of test stripe luminance with real gratings. A sine-wave with an amplitude of 14% of maximum luminance has been added to each of the three test stripes, whose luminances are the same as in Fig. 1. The background is uniform and of the same mean luminance as in Fig. 1.

outside the luminance range of the inducer grating was to render the induced brightness variations invisible to their observers in that particular stimulus condition. In other words, we believe Spehar *et al.* have overinterpreted their negative results, mistaking what is essentially a basement effect for a real effect of test field luminance. The amplitude of grating induction does diminish as the luminance of the test stripe departs from the mean luminance of the inducer, but not in the categorical way suggested by Spehar *et al.*

Why then does the magnitude of grating induction diminish as the test stripe luminance increasingly departs from that of the mean of the inducer? A strong clue to the answer to this question is given by inspection of Fig. 2, which shows the analogous situation for real grating stimuli. Instead of an induced grating, each test stripe in Fig. 2 contains a real grating of the same amplitude (14% of maximum luminance), and the three test stripes are now shown on a uniform background rather than on one containing an inducer grating. The amplitude of the real gratings in Fig. 2 was chosen because it produced the same resultant apparent contrasts as those of the induced gratings in Fig. 1. The pattern of apparent contrasts of the real gratings in Fig. 2 is virtually identical to that of the induced gratings in Fig. 1, suggesting that the reduced visibility of the outer test stripes in both figures has a similar underlying cause. A simple explanation now immediately lends itself. It is widely believed from studies of contrast discrimination (Legge & Foley, 1980; Wilson, 1980; Greenlee & Heitger, 1988; Kingdom & Whittle, 1996), contrast magnitude estimation (Gottesman *et al.*, 1981), contrast or brightness scaling (Whittle, 1993) and contrast matching (Swanson *et al.*, 1984) that contrast transduction involves a compressive nonlinearity which depends on contrast, at least over much of the suprathreshold range.* Such a contrast-dependent compressive nonlinearity can explain the reduced visibility of the gratings in the outer test stripes of Fig. 2. In the outer test stripes the grating is effectively sitting on a "pedestal" contrast produced by the luminance difference between the test stripe and the background. This pedestal serves to push the response of the mechanisms sensitive to the luminance variations of the grating into the compressed part of the response range, thus reducing the apparent contrast of the grating compared to that in the middle stripe where no pedestal is present.

If this is accepted as the explanation of the reduced visibility of the real gratings in the outer test stripes of

*There are alternative explanations for the results of contrast discrimination studies to that of a compressive contrast transducer function. For example, Legge *et al.* (1987) have shown that contrast discrimination thresholds can be modelled in terms of a linear, rather than compressive contrast transducer function with multiplicative, rather than additive internal noise, and Foley (1994) has modelled contrast discrimination thresholds using the notion of divisive inhibition. Two points are worth mentioning in the light of these alternatives. First, our demonstrations involve suprathreshold levels of "ΔC" with respect to "pedestal" contrast C, if C is considered to be the contrast of the test stripe and ΔC the modulation of the grating within it. Thus our findings are not necessarily cognate with those from contrast discrimination experiments, which by definition involve threshold levels of ΔC. Second, even if they are, a compressive nonlinearity is still an adequate mathematical model for our purpose even if not necessarily correct physiologically.

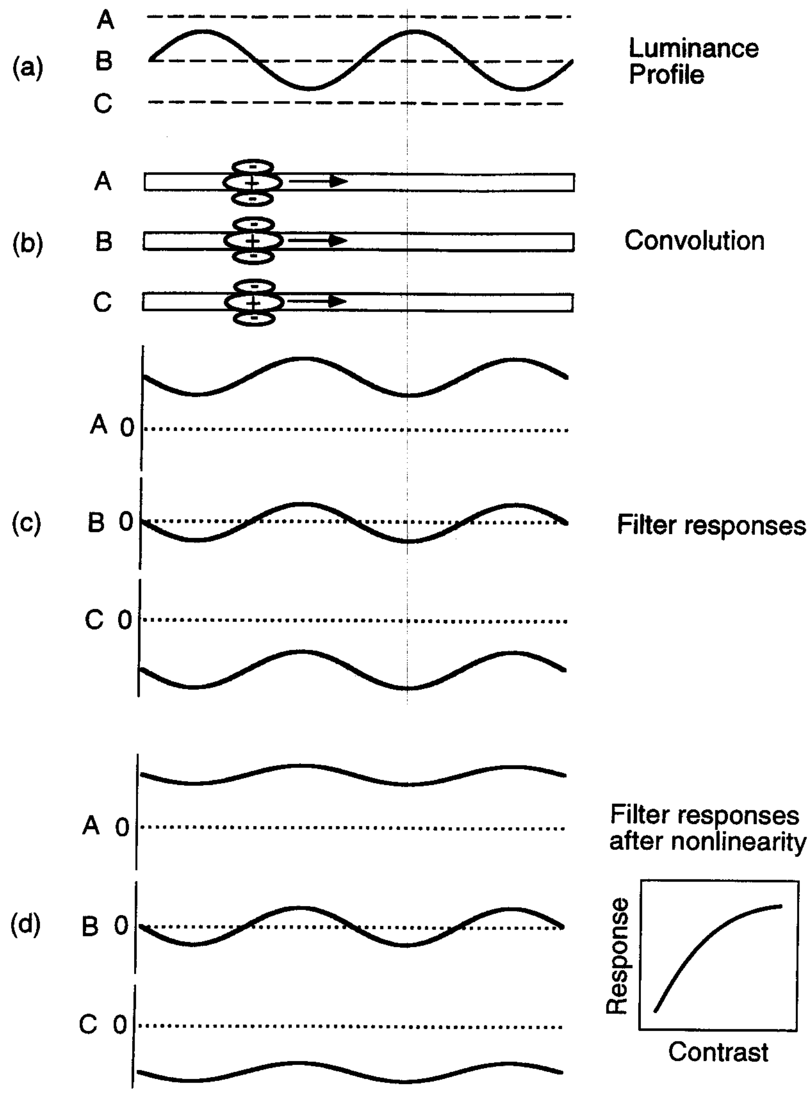

FIGURE 3. Schematic representation of a simple model for the appearance of the gratings in the test stripes in Figs 1 and 2. For explanation see text.

Fig. 2, then a simple filtering model incorporating the compressive nonlinearity will account for the appearance of the induced gratings in Fig. 1, as well as the real gratings in Fig. 2. The model is illustrated schematically in Fig. 3. The essential idea is that both the induced and real gratings in the test stripes are signalled by a bandpass filter with a conventional centre–surround receptive field organization, whose receptive field centre fits just within the width of the test stripe, and whose surround falls outside the stripe. Such a filter is optimal for signalling, within the test stripe, the presence of either an inducer outside the test stripe, or a real grating within it, provided that the gratings have a cycle width significantly larger than the height of the test stripe. The filter shown in Fig. 3 is oriented, though a circularly symmetric filter would suffice just as well, as we have shown previously (Foley & McCourt, 1985; Moulden & Kingdom, 1991).

Figure 3 shows the model as applied to the illusory gratings of Fig. 1, but it is essentially identical in its predictions for the real gratings in Fig. 2, except that the luminance profile in Fig. 3(a) needs to be phase-reversed. In the Figure, A, B and C refer respectively to the test stripes greater than, equal to and less than the luminance of the background. Figure 3(a) shows the luminance profile of the inducer in Fig. 1 (phase reversed for the real gratings in Fig. 2) with the dashed lines representing the luminance of the three test stripes. Figure 2(b) shows an oriented filter sitting within each test stripe, the arrows indicating that the filter is being convolved with the stimulus along the length of the test stripe. Assuming linear spatial summation, the resulting convolution outputs are shown in Fig. 3(c), with the dotted lines showing the zero response levels. Notice that the responses are 180 deg out of phase with the inducer grating [Fig. 3(a)] in accordance with the percept, because it is the inhibitory surround of the filter that is stimulated directly by the inducer grating. If applied to the stimulus in Fig. 2, the excitatory centre of the filters would be stimulated directly, producing in-phase modulation. Notice also that whereas in the case of B the response modulation is about zero, in A it is modulated about a positive dc response level, and in C around a negative dc response level. These dc levels can be thought of as "pedestal" levels of response. In Fig. 3(d) we simply assume there is a compressive nonlinearity on the *absolute* response, while preserving its sign, and as shown this has the effect of reducing the amplitude of the response modulations in A and C compared with B. It is this reduction in response amplitude which we argue is the cause of the reduced visibility of the gratings in the outer stripes in Figs 1 and 2. The model incidentally also accounts for the rapid fall-off in the magnitude of grating induction with inducer spatial frequency for a constant test height, as has been previously demonstrated by Moulden & Kingdom (1991), at least for circularly symmetric filters.

Although we have illustrated only the operation of an ON-centre oriented filter in Fig. 3, it is of course widely believed that the below-zero components of the convolution responses shown in the figure would probably be carried by other filters, such as OFF-centre filters, with the outputs of all classes of filter being half-wave rectified. If modelled in such a way it would not have been necessary to apply the compressive nonlinearity to the absolute responses, while at the same time preserving the sign of the response. We have used the single class of filter, however, for simplicity of exposition. We also wish to emphasize that we are not asserting or implying that only one receptive field size or filter is involved in grating induction. Doubtless filters not optimally tuned to the test stripe height will contribute to some degree or other to grating induction, and some may serve to reduce it (e.g. see Moulden & Kingdom, 1991). Figure 3 is meant to illustrate how *in principle* the appearance of the gratings within the test stripes in Figs 1 and 2 can be simply explained using well-established notions about the mechanisms involved in signalling periodic luminance variations. We are also well aware that higher level processes will undoubtedly modify the magnitude of the induced gratings produced by the early filtering mechanisms that we have postulated. In particular, the mechanisms which are believed to be involved in integrating local contrast information across luminance boundaries to establish, generally, a more veridical representation of the reflectance of surfaces (Arend *et al.*, 1971; Arend, 1973, 1994; Arend & Goldstein, 1987; Gilchrist, 1979, 1994; Kingdom & Moulden, 1988, 1992; Whittle, 1994), undoubtedly act in some circumstances to reduce the magnitude of grating induction. McCourt and Blakeslee's (McCourt & Blakeslee, 1993) finding that removing the high spatial frequencies from grating induction figures enhances the effect is pertinent to this issue, since it is likely that such integrative mechanisms principally employ the high spatial frequency information at the sharp edge boundaries of the test stripes.

In conclusion we have shown how a simple model consisting of a bandpass filter with a contrast-dependent compressive nonlinearity can account for the decrease in the amplitude of grating induction that occurs as the luminance of the test stripe departs from the mean luminance of the inducer. In so far as bandpass filters can be said to exhibit what is traditionally referred to as "lateral inhibition", we assert that lateral inhibition is the simplest and still most plausible explanation of grating induction. Furthermore, to the extent that White's effect (Moulden & Kingdom, 1990) or classical brightness contrast (Blakeslee & McCourt, 1996) have properties in common with grating induction, we suggest that such an explanation may be applicable to these phenomena as well.

REFERENCES

Adelson, E. H. (1993). Perceptual organization and the judgement of brightness. *Science, 262*, 2042–2044.

Arend, L. E. (1973). Spatial differential and integral operations in human vision: implications of stabilized retinal image fading. *Psychological Review, 80*, 374–395.

Arend, L. E. (1994). Surface colors, illumination, and surface geometry: intrinsic-image models of human color perception. In Gilchrist, A. L. (Ed.), *Lightness, brightness, and transparency* (pp. 159–213). Hillsdale, NJ: Lawrence Erlbaum.

Arend, L. E., Buehler, J. N. & Lockhead, G. R. (1971). Difference information in brightness perception. *Perception and Psychophysics, 9*, 367–370.

Arend, L. E. & Goldstein, R. (1987). Lightness models, gradient illusions, and curl. *Perception and Psychophysics, 42*, 65–80.

Arend, L. R. & Spehar, B. (1993a) Lightness, brightness and brightness contrast: 1. Illuminance variation. *Perception and Psychophysics, 54*, 446–456.

Arend, L. R. & Spehar, B. (1993b) Lightness, brightness and brightness contrast: 2. Reflectance variation. *Perception and Psychophysics, 54*, 457–468.

Blakeslee, B. & McCourt, M. E. (1996). Does a single mechanism underlie simultaneous brightness contrast and grating induction? *Investigative Ophthalmology and Visual Science*, (Suppl.), *37*, S520.

Foley, J. M. (1994). Human luminance pattern-vision mechanisms: masking experiments require a new model. *Journal of the Optical Society of America A, 11*, 1710–1719.

Foley, J. M. & McCourt, M. E. (1985). Visual grating induction. *Journal of the Optical Society of America A, 2*, 1220–1230.

Gilchrist, A. L. (1977). Perceived lightness depends on perceived spatial arrangement. *Science, 195*, 185–187.

Gilchrist, A. L. (1979). The perception of surface blacks and whites. *Scientific American, 240*, 112–123.

Gilchrist, A. L. (1994). Absolute versus relative theories of lightness perception. In Gilchrist, A. L. (Ed.), *Lightness, brightness, and transparency* (pp. 1–33). Hillsdale, NJ: Lawrence Erlbaum.

Gottesman, J., Rubin, G. S. & Legge, G. E. (1981). A power law for perceived contrast in human vision. *Vision Research, 21*, 791–799.

Greenlee, M. W. & Heitger, F. (1988). The functional role of contrast adaptation. *Vision Research, 28*, 791–797.

Kingdom, F. A. A. & McCourt, M. E. (1993). Do illusory gratings behave like real gratings? Perception, 22, A5.

Kingdom, F. & Moulden, B. (1988). Border effects on brightness: a review of findings, models and issues. *Spatial Vision, 3*, 225–262.

Kingdom, F. & Moulden, B. (1992). A multi-channel approach to brightness coding. *Vision Research, 32*, 1565–1582.

Kingdom, F. A. A. & Whittle, P. (1996). Contrast discrimination at high contrasts reveals the influence of local light adaptation on contrast processing. *Vision Research*, *36*, 817–829.

Knill, D. C. & Kersten, D. (1991). Apparent surface curvature affects lightness perception. *Nature, 351*, 228–230.

Legge, G. E. & Foley, J. M. (1980). Contrast masking in human vision. *Journal of the Optical Society of America, 70*, 1458–1471.

Legge, G. E., Kersten, D. & Burgess, A. E. (1987). Contrast discrimination in noise. *Journal of the Optical Society of America A, 4*, 391–404.

McCourt, M. E. (1982). A spatial frequency dependent grating-induction effect. *Vision Research, 22*, 119–134.

McCourt, M. E. (1994). Grating induction: a new explanation for stationary visual phantoms. *Vision Research, 34*, 1609–1618.
McCourt, M. E. & Blakeslee, B. (1993). The effect of edge blur on grating induction magnitude. *Vision Research, 33*, 2499–2508.
McCourt, M. E. & Foley, J. M. (1985). Spatial frequency interference on grating-induction. *Vision Research, 25*, 1507–1518.
McCourt, M. E. & Kingdom, F. A. A. (1996). Facilitation of luminance grating detection by illusory gratings. *Vision Research, 36*, 2563–2573.
Moulden, B. & Kingdom, F. (1990). The mechanisms involved in brightness induction effects: a reply to Zaidi. *Vision Research, 30*, 1247–1252.
Moulden, B. & Kingdom, F. (1991). The local border mechanism in grating induction. *Vision Research, 31*, 1999–2008.
Spehar, B., Gilchrist, A. & Arend, L. (1995). The critical role of relative luminance relations in White's effect and grating induction. *Vision Research, 35*, 2603–2614.
Swanson, W. H., Wilson, H. R. & Giese, S. C. (1984). Contrast matching data predicted from increment thresholds. *Vision Research, 24*, 457–459.
White, M. (1979). A new effect of pattern on perceived lightness. *Perception, 8*, 413–416.
Whittle, P. (1992). Brightness, discriminability and the "crispening effect". *Vision Research, 32*, 1493–1507.
Whittle, P. (1994). Contrast brightness and ordinary seeing. In Gilchrist, A. L. (Ed.), *Lightness, brightness, and transparency* (pp. 111–157). Hillsdale, NJ: Lawrence Erlbaum.
Wilson, H. R. (1980). A transducer function for threshold and suprathreshold human vision. *Biological Cybernetics, 38*, 171–178.

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Qualitative Boundaries Critical in White's Effect and Square-wave Brightness Induction: A Reply to Kingdom *et al.* (1997)

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The experiments reported by Spehar *et al.* (1995) show that both White's effect and square-wave version of grating induction occur only when the luminance of the test regions lies between minimum and maximum luminance values of the inducing stripes. For the purpose of brevity we will refer to this effect as "the luminance constraint".

Kingdom *et al.* (1997) make several claims regarding our paper: (1) that the luminance constraint in grating induction is an artifact of the stimulus conditions we chose and therefore is not a real constraint of the phenomenon; (2) that the luminance constraint in White's effect is likely to be similarly artifactual.

In this reply we claim: (1) even though square-wave inducing gratings produce weaker levels of induction (McCourt, 1982) the spatial frequency characteristics of stimuli in Spehar *et al.* (1995) were appropriately chosen to study grating induction and the reported observations constitute a real constraint for square-wave gratings with parameters similar to White's effect; (2) Kingdom *et al.* (1997) offer no explicit treatment of White's effect, and no evidence was presented as justification for their claims regarding White's effect.

Spehar *et al.* (1995) did not vary the spatial frequency of the inducing gratings, but it can be demonstrated that the luminance constraint holds over a wide range of spatial frequencies of the inducing grating. Figure 1 consists of two White's effect patterns of different spatial frequency. Both panels (top and the bottom) show typical White's effect: the test patches intersecting lighter stripes of the inducing square-wave pattern appear darker than the test patches intersecting darker stripes of the inducing grating. Figure 2 shows the opposite effect. In both panels the test patches intersecting lighter stripes of the inducing grating appear lighter than patches intersecting darker stripes of the inducing square-wave pattern. In both figures the inducing square-wave gratings are

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