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Comparing the spatial-frequency response of first-order and second-order lateral visual interactions: Grating induction and contrast – contrast

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Abstract. The magnitudes of two suprathreshold lateral spatial-interaction effects—grating induction and contrast – contrast—were compared with regard to their dependence upon inducing-grating spatial frequency. Both effects cause the contrast of target stimuli embedded in surrounding patterns to be matched nonveridically. The magnitudes of each effect were measured in a common unit that indexed the degree of nonveridical contrast matching across a large range of target-grating contrasts (± 0.80). Grating induction was a low-pass effect with respect to spatial frequency, whereas contrast – contrast was bandpass, peaking at approximately 4.0 cycles deg^{-1}. The magnitude of grating induction exceeded that of contrast – contrast, both overall and at their optimal frequencies (0.03125 and 4.0 cycles deg^{-1}, respectively); the two effects are equipotent at an inducing-grating spatial frequency of 1.0 cycle deg^{-1}. A significant negative correlation between the magnitudes of the two effects suggests a link whereby activation of second-order normalization mechanisms may inhibit first-order mechanisms.

1 Introduction

Grating induction is a first-order (ie luminance-based) suprathreshold lateral spatial interaction in which brightness variations are induced in a spatially homogeneous region of visual space which are counterphase replicas of the surrounding inducing gratings (McCourt 1982). Induced gratings produce distortions of both the contrast and phase of physical luminance gratings added to them (McCourt and Blakeslee 1994), and can act as pedestals to facilitate the detection of luminance gratings added to them (McCourt and Kingdom 1996). Contrast – contrast is a second-order (ie contrast-based) suprathreshold lateral interaction in which the perceived contrast of a patch of texture, or a grating, is changed when the patch is surrounded by a patch of higher or lower contrast (for textures see Chubb et al 1989; Solomon et al 1993; for gratings see Ejima and Takahashi 1985; Cannon and Fullencamp 1991, 1993, 1996). Conceptually uniting the two effects is the proposition that grating induction and contrast – contrast both reflect the operation of response-normalization processes that facilitate 'seeing' at suprathreshold intensity levels (Spehar and Zaidi 1997; Blakeslee and McCourt 1999, 2001, 2003, 2004; Xing and Heeger 2001).

The quantitative similarities and differences between contrast – contrast and simultaneous brightness contrast (a variant of grating induction, see Blakeslee and McCourt 1997) were described by De Bonet and Zaidi (1997). They found that the magnitude of contrast – contrast was weaker overall than brightness induction, and that the spatial integration region for contrast – contrast exceeded that for brightness induction. In the present paper, this comparative approach is extended by measuring the relative magnitudes of grating induction and contrast – contrast with respect to their dependence upon the spatial frequency of the inducing pattern.

2 Methods

2.1 *Subjects*

Subjects included the author, MEM, and five additional observers, DAB, MAS, SF, SM, and TK. All possessed normal or corrected-to-normal vision and were, except for observer MEM, naïve to the purposes of the experiment. All subjects except SM participated in all conditions of the experiment; subject SM was tested at spatial frequencies of 0.25 – 4.0 cycles deg^{-1}. The research protocol was approved by the Institutional Review Board of North Dakota State University and all subjects provided informed consent. All subjects were well-practiced as psychophysical observers.

2.2 *Instrumentation and calibration*

Stimuli were generated and presented by computer and were displayed on an RGB monitor at a frame rate of 60 Hz. Images appeared in square aspect ratio at a resolution of 512×512 pixels; pixels possessed 2^8 linearized luminance levels. Luminance and contrast calibrations were made with a Spectra Brightness Spotmeter (model UB 1/2°). Mean display luminance was 66 cd m^{-2}.

2.3 *Stimuli*

To facilitate the comparison of the two suprathreshold effects, all stimuli were presented in a common format consisting of two variations of grating induction-type displays, which have been described in detail elsewhere (McCourt and Blakeslee 1994). Figure 1 illustrates several displays used in the experiment, and perceptually demonstrates several of the empirical results. 'Target'-grating stimuli were centered in the upper half of the display, and consisted of rectangular strips of vertically oriented sine-wave luminance gratings. Matching gratings were centered in the lower half of the display, and were viewed against a homogeneous field set to the mean luminance of the display. Target gratings possessed eleven levels of Michelson contrast: ± 0.80, ± 0.60, ± 0.40, ± 0.20, 0.0, 0.50, and 0.70. Vertically flanking the target gratings were inducing gratings whose contrast was constant at 0.75. In experiments assessing the magnitude of grating induction, the upper and lower inducing gratings were aligned in phase. Figures 1a, 1b, 1c, and 1d illustrate target gratings in the test-field region of grating induction-type displays (McCourt 1982). Here, the sign associated with target-grating contrast indexed the spatial phase of the target grating relative to the inducing grating. Specifically, a negative sign signifies that the two gratings are 180° out of phase, and a positive sign signifies that they are in phase. In conditions designed to measure the magnitude of contrast – contrast, the upper and lower inducing gratings had a phase offset of 180°, and target gratings were presented at 90° spatial phase to both. Figures 1e and 1f illustrate target gratings in the test fields of contrast – contrast displays. Here, the sign associated with target-grating contrast refers to either $+90°$ or $-90°$ phase with respect to the upper inducing grating. Inducing and target gratings possessed ten spatial frequencies, in octave intervals ranging from 0.03125 to 16.0 cycles deg^{-1}. Inducing-grating and target-grating frequencies were always identical. Depending upon the spatial frequency of the inducing grating (in parentheses), four viewing distances were used: 26.5 cm (0.03125 cycle deg^{-1}), 53 cm (0.0625 – 4.0 cycles deg^{-1}), 106 cm (8.0 cycles deg^{-1}), and 212 cm (16.0 cycles deg^{-1}). At the viewing distance of 53 cm, for example, the entire display subtended 32 deg in height and width. Display height and width scaled with viewing distance. Target-grating height, however, was constant at 0.5 deg across all viewing distances. A matching stimulus, consisting of a luminance grating of identical spatial frequency as that of the inducing and target gratings, was centered in the lower half of the display. Matching gratings, like target gratings, always subtended 0.5 deg in height.

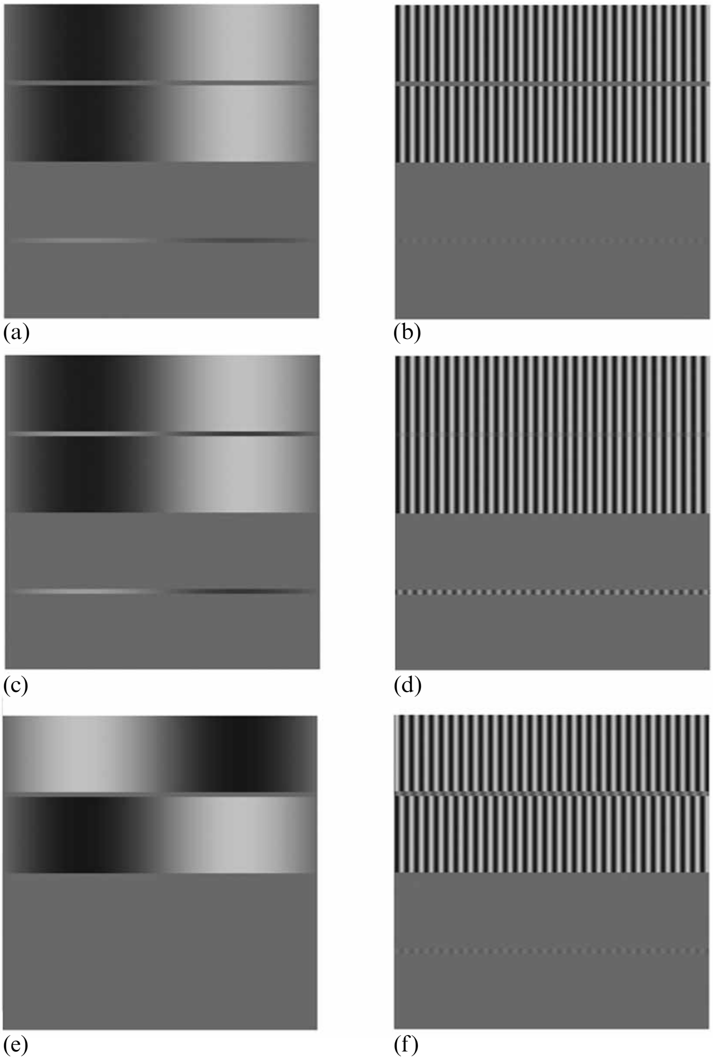

Figure 1. Facsimiles of grating-induction and contrast–contrast displays demonstrating the principal methods and findings. (a) A grating-induction display in which the upper and lower inducing gratings are phase aligned. Overall display size is 32 deg by 32 deg. Inducing-grating frequency is 0.03125 cycle $\deg^{-1}$; inducing contrast is 0.75. Target-grating contrast (C_T) is 0.0 (eg the test field is physically homogeneous). The contrast of the matching grating (C_M), centered in the lower half of the display, is -0.26. It appeared equal in contrast to the target grating to observer DAB (see figure 2b). Target and matching gratings are 0.5 deg in height. (c) As in (a), except that $C_T = -0.40$, and $C_M = -0.46$. These contrast values produced perceptual equivalence for observer DAB. (e) A contrast–contrast display, in which the upper and lower inducing gratings are phase-shifted by 180°; no grating is induced within homogeneous test fields under these conditions. (b) Same as (a) for a 1.0 cycle $\deg^{-1}$ inducing grating. At this spatial frequency, grating induction in a homogeneous field ($C_T = 0.0$) is very weak, $C_M = -0.05$. (d) $C_T = 0.60$; $C_M = 0.38$. (f) Contrast–contrast condition which illustrates undermatching, $C_T = 0.20$; $C_M = 0.10$.

2.4 *Procedures*

The magnitude of grating induction was assessed with a contrast-matching technique as described previously (McCourt and Blakeslee 1994). Inducing gratings with a common spatial phase were presented above and below the test field, while a variety of target gratings of varying contrast were added to the test field, either in phase (+), or 180° out of phase (−) with the surrounding inducing gratings. Observers adjusted the contrast (and phase, via contrast reversal) of the matching grating until it appeared to possess a contrast and phase identical to that of the target grating. Grating-induction magnitude decreases as the upper and lower inducing gratings become misaligned (Zaidi 1989; McCourt and Blakeslee 1994; Blakeslee and McCourt 1997). As illustrated in figure 1e, grating-induction magnitude is zero when the upper and lower inducing gratings are misaligned by 180°.(1) Thus, the magnitude of contrast–contrast was assessed by shifting the relative spatial phase of the upper and lower inducing gratings by 180° (the upper and lower inducing gratings were offset by +90° and −90°, respectively), which eliminates a coherent induced-grating percept, while target gratings were added to the test field in an intermediate (ie 0°) spatial phase.(2)

Each adjustment trial began with matching-grating contrast being randomly assigned a value between 0 and 1.0. To minimize long-term contrast-adaptation effects, stimuli were presented in each trial for a duration of 2 s, during which time subject responses were polled by computer. During this interval, subjects increased or decreased the contrast (and/or phase, via contrast reversal) of the matching grating by pressing appropriate response buttons. Each button press was echoed by a brief tone pip and resulted in a change of 0.8% in matching-grating contrast. Stimulus contrast was zeroed for 2 s between presentations. This sequence continued until subjects indicated a successful match by pressing a 'done' button. All adjustment settings were recorded by computer, which also sequenced and initiated each block of adjustment trials. Ten matching settings were obtained from each subject in each experimental condition. Trials assessing grating induction and contrast–contrast were presented in separate blocks, as were trials assessing different levels of inducing-grating spatial frequency. The values of target-grating contrast were quasirandomly interleaved within blocks.

Natural eye movements do not produce or otherwise affect the magnitude of grating induction (Foley and McCourt 1985). Stimuli were viewed binocularly through natural pupils in an otherwise moderately illuminated room, such that the state of light adaptation was constant.

3 Results and discussion

3.1 *Analysis of contrast-matching data*

Figure 2 presents examples of contrast-matching functions, from subject DAB, which serve to illustrate the pattern of original data and the method by which the magnitudes of contrast–contrast and grating induction were computed. Open symbols refer to mean contrast matches in grating-induction conditions (ie for phase-aligned inducing gratings), and filled symbols refer to mean contrast matches made in the contrast–contrast conditions (ie with 180° phase offset inducing gratings). The variability of match settings was small; standard errors are approximately equivalent to the size of the symbols used to graph the mean values.

Both matching-grating and target-grating contrast are signed quantities where, for grating induction (open symbols), the sign denotes either the perceived spatial phase (for matching-grating contrast, plotted on the ordinate) or the physical spatial phase (for target-grating contrast, plotted on the abscissa) of each type of grating, with respect to

(1) Bright and dark meniscuses are observed at the borders of the test fields and the inducing fields when the upper and lower inducing gratings are misaligned by 180° in spatial phase. While these brightness variations arise through the same process as grating induction (Blakeslee and McCourt 1997), they do not complete across the test field to form a coherent grating percept, and subjects match such stimuli with zero-contrast sine-wave gratings.

(2) Figure 1f illustrates that in the contrast–contrast displays the target grating may possess a pronounced induced tilt away from vertical. This effect is interesting in its own right, and has been reported previously (Haig 1989). It does not influence contrast matches, however, and further discussion of this illusory orientation shift is beyond the scope of this brief report.

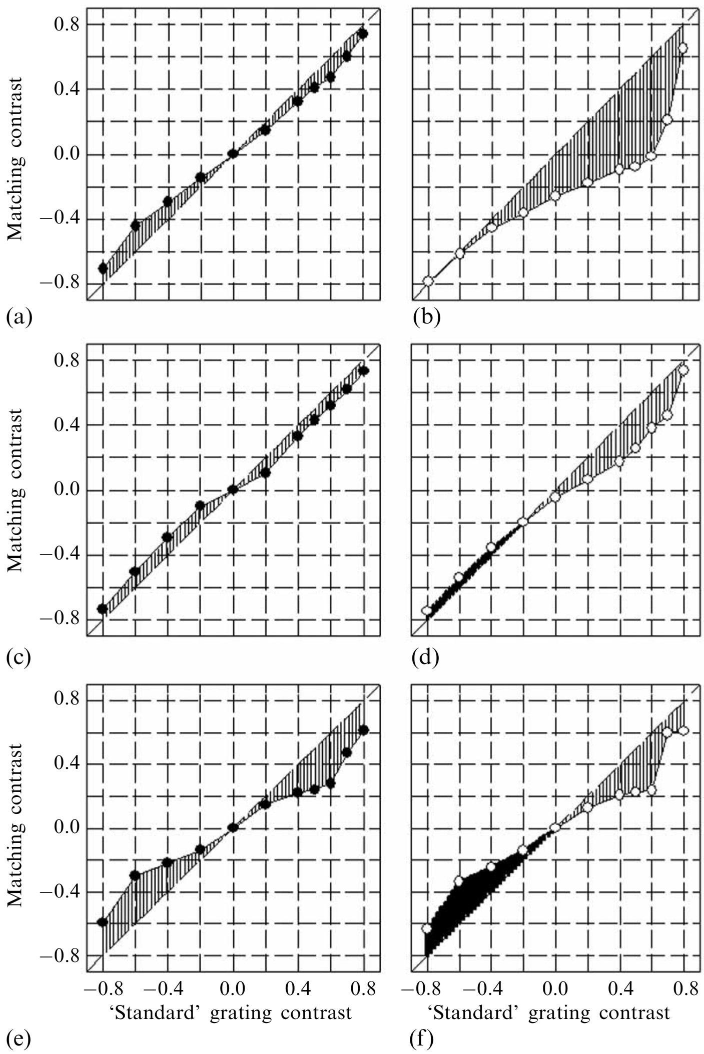

Figure 2. Examples of contrast-matching functions for observer DAB that illustrate the method used to compute contrast – contrast and grating-induction magnitude. (a), (c), (e) Contrast – contrast (phase-offset) conditions; mean contrast matches ($n = 10$) to eleven target-grating contrasts at inducing-grating frequencies of 0.03125, 1.0, and 16.0 cycles deg^{-1}, respectively. The locus of veridical contrast matching is indicated by the dashed diagonal lines. The hatched regions, bounded by the interpolated matching function and the diagonal line which denotes veridical matching, are numerically integrated to provide a comprehensive index of the magnitude of contrast – contrast at each inducing-grating spatial frequency. (b), (d), (f) Grating-induction (phase-aligned) conditions; mean contrast matches ($n = 10$) to eleven target-grating contrasts at inducing-grating frequencies of 0.03125, 1.0, and 16.0 cycles deg^{-1}, respectively. Grating-induction magnitude was computed at each inducing-grating spatial frequency by numerically integrating the area between the matching function and the diagonal line denoting veridical matching. Hatched areas are assigned a positive weight; filled areas are weighted negatively in the integration. See text for details.

inducing-grating spatial phase. Here, a negative sign signifies that the target or matching gratings are (or are perceived to be) out of phase, whereas a plus sign signifies that the target or matching gratings are (or are perceived to be) in phase with the surrounding inducing grating. For contrast – contrast conditions (filled symbols), the sign associated with target-grating contrast again refers to the physical spatial phase of the target grating, where it is in either $+90^{\circ}$ or -90° phase with respect to the upper inducing grating.

Figures 2a, 2c, and 2e illustrate mean matching-grating contrast, in a contrast–contrast condition, plotted as a function of target-grating contrast, at three widely separated inducing-grating frequencies: 0.03125, 1.0, and 16.0 cycles deg^{-1}. Note that in contrast–contrast conditions the spatial phase of target gratings is never misperceived. Accordingly, the sign associated with target-grating and matching-grating contrast is never discrepant, and all matches lie in the lower-left and upper-right quadrants of the graphs. By comparison, in grating-induction conditions, shown in figures 2b, 2d, and 2f, it is common (particularly in the low spatial-frequency conditions) for induction to cause even relatively high-contrast target gratings (eg $+0.50$) to appear to be (and hence to be matched by) gratings of opposite spatial phase (ie negative matching contrast). Such matches are plotted in the lower right quadrants of these diagrams, eg figure 2b.

Note in figure 2, that veridical contrast matches will lie along the dashed diagonal lines of unit slope. To the extent that a contrast–contrast effect from the inducing grating reduces the perceived contrast of the target grating, contrast matching will be nonveridical. Matching in contrast–contrast conditions is indeed observed to systematically depart from veridicality, such that the matching contrast is invariably less than target-grating contrast. This undermatching which generally occurs for high-contrast surrounding gratings, is consistent with previous reports, and is in fact a defining characteristic of the contrast–contrast effect (Chubb et al 1989; Cannon and Fullencamp 1991, 1993).

An index of the magnitude of contrast–contrast as a function of spatial frequency was obtained from these matching data by numerically integrating the area, across the entire range of target-grating contrast, between the interpolated matching functions and the diagonal lines that denote match veridicality. These areas are indicated by vertically hatched regions in figures 2a, 2c, and 2e.

Grating-induction magnitude was likewise computed by numerically integrating the area between the matching functions and the diagonal line denoting match veridicality. These areas are indicated by both hatched and solid filled regions in figures 2b, 2d, and 2f. Unlike contrast–contrast, grating induction produces a brightness modulation in a homogeneous test field which is invariably opposite in phase to the surrounding inducing grating. Hence, integrated grating-induction magnitude was evaluated as positive where maching contrast was less than target contrast for target gratings added in phase with the inducing grating (indicated by hatched regions). On the other hand, grating-induction magnitude must be evaluated as negative when matching contrast is less than target-grating contrast for target gratings added out of phase with the inducing grating (indicated by solid regions in figures 2d and 2f). By numerically integrating these areas, a comprehensive assessment of the overall magnitude of both the grating induction and contrast–contrast effects was obtained which allows them to be compared by using a common unit: (contrast)^2.

3.2 *Effect of inducing-grating spatial frequency*

The magnitudes of contrast–contrast (filled symbols) and grating induction (open symbols) for the six observers, expressed in units of total integrated contrast area, are plotted as a function of inducing-grating spatial frequency in figure 3. Lines connect the aggregate mean values.

A two-way ANOVA was conducted on these data with display type (grating induction versus contrast–contrast) and inducing-grating spatial frequency as within-subjects factors. There is a significant main effect of display type ($F_{1,5} = 6.94$, $p = 0.046$); collapsed across spatial frequency, the average magnitude of grating induction (0.210) exceeds that for contrast–contrast (0.137). There is also a significant main effect of inducing-grating spatial frequency ($F_{9,45} = 16.34$, $p < 0.001$); effect magnitude collapsed

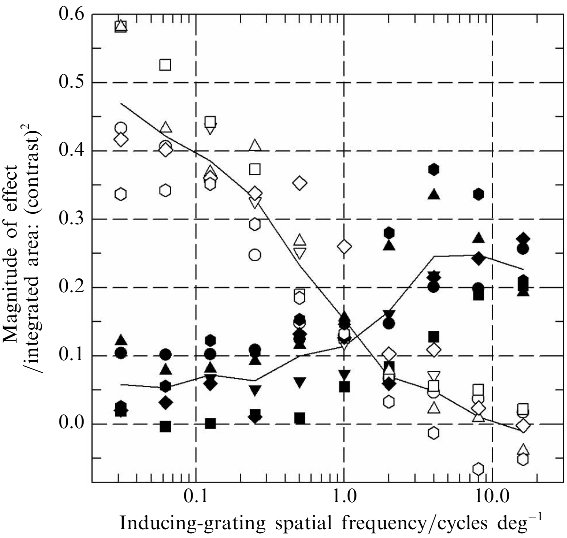

Figure 3. The magnitudes of contrast–contrast (filled symbols) and grating induction (open symbols) for the six observers, expressed in units of total integrated contrast area, plotted as a function of inducing-grating spatial frequency. Solid lines smoothly interpolate the aggregate mean values. Grating induction is a low-pass effect whereas contrast–contrast is high-pass or bandpass; the effects are equipotent at approximately 1.0 cycle deg^{-1}. There is considerable between-subject variability in both suprathreshold effects.

across the two display types diminishes with increasing spatial frequency. The chief result, however, is a significant display-type by spatial-frequency interaction ($F_{9,45} = 130.39$, $p < 0.001$).

Consistent with previous reports (McCourt 1982; Foley and McCourt 1985) grating induction is a low-pass effect that single-sample t-tests reveal becomes nonsignificantly different from zero at inducing-grating frequencies above 4 cycles deg^{-1} (8 cycles deg^{-1}: $t_5 = 0.66$, $p = 0.54$; 16 cycles deg^{-1}: $t_5 = -0.89$, $p = 0.42$). As measured by using the stimulus configuration in this experiment, contrast–contrast possesses a bandpass frequency response and is very weak (indeed, absent for some observers) at inducing-grating frequencies below 0.5 cycle deg^{-1}. The two effects are equipotent at an inducing frequency of 1.0 cycle deg^{-1}, the only inducing frequency at which the effect magnitudes of grating induction and contrast–contrast do not significantly differ (when using a posteriori paired-sample t-tests). In addition to being significantly larger overall, mean grating-induction magnitude (0.475) significantly exceeds ($t_5 = 3.48$, $p = 0.018$) that of contrast–contrast (0.250)[(3)] at their optimal spatial frequencies of 0.03125 and 4.0 cycles deg^{-1}, respectively. This finding is in agreement with that of De Bonet and Zaidi (1997). The relative magnitudes of the two effects can be directly compared by using phase-aligned and phase-offset grating-induction display types, because current evidence supports the view that the suppressive component of contrast–contrast is independent of the spatial phase of the surrounding gratings (Xing and Heeger 2001; Yu et al 2001; but see Olzak and Laurinen 1999). The results of the present experiment also support this view. We compared the contrast-matching functions in the phase-aligned (grating-induction) and phase-offset (contrast–contrast) display type conditions at inducing-grating spatial frequencies above 2 cycles deg^{-1} (where the contribution of grating induction to matching errors becomes negligible), and found no systematic differences. The spatial frequency at which the two effects become comparable in strength, 1.0 cycle deg^{-1}, represents a watershed for spatial vision since, at this spatial scale, response normalization mechanisms operating primarily on first-order stimulus variables (eg luminance) segue to those which operate primarily on second-order stimulus properties (eg contrast).

[(3)] A magnitude comparison in terms of the mean contrast-matching nonveridicality that each effect produces is obtained by taking the square root of the peak values of figure 3.

3.3 *Individual differences and linkages between first-order and second-order mechanisms*

The ANOVA conducted on the matching data of figure 3 revealed a significant between-subjects variability in the magnitude of both grating-induction and contrast–contrast ($F_{1,5} = 900.20$, $p < 0.001$). Observer MEM, for example, evinces the weakest overall contrast–contrast, displaying virtually no effect at spatial frequencies below 1.0 cycle deg^{-1} (square symbols in figure 3). This replicates a result reported in an earlier study (McCourt and Blakeslee 1994), in which observers MEM and BB both produced veridical contrast matches for low-frequency gratings in a similar phase-offset display configuration. Since each data point in figure 3 reflects the integrated influence of 50–100 match settings across a wide range of test-grating contrasts, it is highly unlikely that these large and consistent individual differences are due to random sampling variations. Similar large between-subjects variations in the strength of contrast–contrast have been reported in numerous previous investigations of this effect (Cannon and Fullencamp 1991, 1993; Xing and Heeger 2001; Yu et al 2001).

In an effort to better understand the origin and significance of these individual differences, a correlation analysis was performed. Correlograms were constructed by plotting the magnitudes of grating induction versus contrast–contrast at each of the ten spatial frequencies tested. Since the absolute magnitudes of both effects vary greatly across inducing-grating spatial frequency, to assess the possible correlation between the relative magnitudes of these effects, and to plot these scores on common axes, the magnitudes of each effect were z-transformed for each spatial frequency. The aggregate correlogram of z-transformed values is presented in figure 4. Data obtained at the ten spatial frequencies are indicated by symbol type (see figure legend). The solid line represents the optimal linear regression as determined by the method of least squares, and the dashed lines indicate the 95% confidence intervals for the regression equation. There is a significant negative correlation between the magnitudes of grating induction and contrast–contrast ($r_{55} = -0.30$, $p = 0.025$). This means that strong grating induction is associated with weak contrast–contrast, and vice versa. While this correlation accounts for only 10% of the total variance in the matching data, its existence suggests

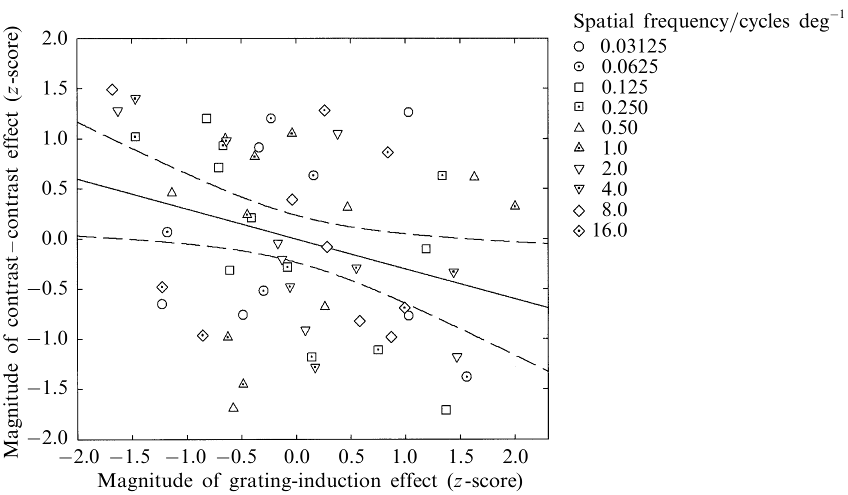

Figure 4. A correlogram of the z-transformed effect magnitudes of grating induction and contrast–contrast for the six observers, aggregated across inducing-grating spatial frequency. Spatial frequency is indicated by symbol type; the solid line represents the optimal linear regression as determined by the method of least squares. There is a significant negative correlation between the magnitudes of grating induction and contrast–contrast ($r_{55} = -0.30$, $p = 0.025$), suggesting a functional link between the response-normalization processes responsible for these two effects.

the possibility of a functional linkage between the mechanisms producing these two effects. Specifically, perhaps elevated activity in mechanisms that code second-order (contrast) information, which are generally tuned to high spatial frequencies, reduces activity in mechanisms that code first-order (luminance) information, which are generally tuned to low spatial frequencies. This idea is consistent with several previous unexplained results: square-wave inducing gratings produce significantly weaker grating induction than sine-waves (McCourt 1982); the addition of high-frequency (interfering) gratings to low-frequency sine-wave inducing gratings significantly reduces the magnitude of grating induction (McCourt and Foley 1985); and attenuating the high-frequency content (ie blurring) of the edges separating test and inducing fields in grating induction or simultaneous-contrast displays increases the magnitude of induction (McCourt and Blakeslee 1993; Kingdom 2003). Bindman and Chubb (2004) likewise suggest that interactions between mechanisms which code contrast and luminance might explain seemingly paradoxical brightness assimilation effects in bulls-eye displays. Thus, although by no means conclusive, these results suggest that a complete understanding of both brightness and contrast perception may ultimately depend upon an enhanced appreciation of the relationship between the mechanisms which encode first-order and second-order stimulus features.

4 Summary and conclusions

Both grating induction and contrast – contrast cause the contrast of target gratings to be perceived and matched nonveridically. When the magnitude of each effect is measured in a common unit [$(\text{contrast})^2$] that indexes the extent of nonveridicality in contrast matching across a large range ($\pm 80\%$) of target-grating contrasts, grating induction is found to operate primarily at low spatial frequencies, whereas contrast – contrast is a relatively high-frequency effect, peaking at 4.0 cycles deg^{-1}. At their optimal spatial frequencies, the magnitude of grating induction exceeds that of contrast – contrast, but the two effects are equipotent at inducing-grating frequencies of approximately 1.0 cycle deg^{-1}. This intermediate frequency represents a watershed for spatial vision, since at this spatial scale response-normalization mechanisms operating primarily on first-order stimulus variables (eg luminance) are supplanted by those which operate primarily on second-order stimulus properties (eg contrast). The significant negative correlation between the magnitudes of grating induction and contrast may reflect a functional link between first-order and second-order response-normalization mechanisms. Understanding the relationship between these processes will be important for theories of both contrast and brightness perception.

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