Surround modulation of perceived contrast and the role of brightness induction

Cong Yu School of Optometry, University of California, Berkeley, CA, USA

Stanley A. Klein School of Optometry, University of California, Berkeley, CA, USA

Dennis M. Levi College of Optometry, University of Houston, Houston, TX, USA

We studied iso- and cross-orientation surround modulation of perceived contrast (contrast-contrast phenomenon) with a contrast-matching method. Our results indicate (1) iso-oriented surrounds at all contrasts suppress perceived contrast of the test pattern. Cross-orientation surrounds, however, tend to enhance the perceived contrast of the test, particularly for high-contrast test patterns. Iso-orientation modulation acts over larger distances than does cross-orientation modulation. Surround modulation of perceived contrast is not accompanied by a simultaneous change of discrimination threshold. (2) Iso-orientation surround suppression is phase insensitive when brightness induction due to local luminance contrast is eliminated by a small center-surround gap. (3) Perceived contrast is similarly affected when the surround spatial frequency is equal to or higher than the center spatial frequency, but lower spatial frequency surrounds markedly enhance perceived contrast as a result of brightness induction. These data indicate that the contrast-contrast phenomenon is often mixed with brightness induction when it is measured with sinusoidal grating stimuli, and we suggest that this may account for some of the individual differences. After excluding the role of brightness induction, surround modulation of perceived contrast appears to be a second-order process that is phase independent and not tuned or very broadly tuned to spatial frequency.

Keywords: contrast matching, contrast discrimination, surround modulation, brightness induction, second-order processing

Introduction

A visual pattern's perceived contrast, like its brightness, is influenced by surrounding stimuli (Ejima & Takahashi, 1985; Chubb, Sperling, & Solomon, 1989; Cannon & Fullenkamp, 1991, 1996a, 1996b; Solomon, Sperling, & Chubb, 1993; Ellemberg, Wilkinson, Wilson, & Arsenault, 1998; Snowden & Hammett, 1998; Olzak & Laurinen, 1999; Xing & Heeger, 2000). Surround modulation of perceived contrast, or the contrast-contrast phenomenon (Chubb et al, 1989), is most often studied with sinusoidal gratings and other luminance-defined stimuli, such as Gabor patches (Ejima & Takahashi, 1985; Cannon & Fullenkamp, 1991, 1996a, 1996b; Solomon et al, 1993; Ellemberg et al, 1998; Snowden & Hammett, 1998; Olzak & Laurinen, 1999; Xing & Heeger, 2000), and sometimes with texture-defined stimuli (Chubb et al, 1989; Solomon et al, 1993). For iso-oriented gratings (center and surround at the same orientation), surround modulation is mostly suppressive, regardless of the relative contrast (Cannon & Fullenkamp, 1991, 1996a; Solomon et al, 1993; Ellemberg et al, 1998; Olzak & Laurinen, 1999). However, robust individual differences are evident, and contrast enhancement may be seen in some observers, especially when the center grating has higher contrast than the surround grating (Ejima & Takahashi, 1985; Cannon & Fullenkamp, 1996b; Snowden & Hammett, 1998; Xing & Heeger, 2000).

Several models have been proposed which target iso-orientation surround suppression of perceived contrast (Cannon & Fullenkamp, 1996a; Snowden & Hammett, 1998; Olzak & Laurinen, 1999). Cannon and Fullenkamp (1996a) described surround suppression as lateral inhibitory interactions in which visual responses to center signals are divided by surround signals, similar to Foley's contrast-masking model (1994) except that divisive inhibition is now caused by surround stimuli. Snowden and Hammett (1998) further argued that surround effects on contrast detection, discrimination, and perception are variations of normal masking and are based on the same divisive inhibition mechanism. On the other hand, as an extension of Olzak and Thomas's (1999) 2-stage model of

DOI:10:1167/1.1.3 Received February 15, 2001; published June 20, 2001 ISSN 1534-7362

pattern perception, Olzak and Laurinen (1999) separated surround modulation of perceived contrast for simple sinusoidal gratings from that for more complex plaid gratings. They proposed that the former is based on lower-level phase-dependent visual processing and the latter on higher-level phase-independent visual processing. Our study examined some of the arguments related to these models.

Cross-oriented surround gratings (center and surround at perpendicular orientations), on one hand, reportedly produce much weaker or little suppression (Cannon & Fullenkamp, 1991; Solomon et al, 1993; Ellemberg et al, 1998; Xing & Heeger, 2000). On the other hand, modulation by contextual stimuli orthogonal to the preferred orientation of the receptive field has been reported in single-unit recordings (eg, Sillito, Grieve, Jones, Cudeiro, & Davis, 1995; Levitt & Lund, 1997). Cross-orientation surround modulation is also evident in high-level psychophysical tasks, such as the pop-out effect of a line segment embedded in orthogonally oriented line segments in visual search (Treisman, 1985). Recently, Yu and Levi (2000) demonstrated that cross-oriented surrounds could improve contrast discrimination. High-contrast cross-oriented surrounds can even completely eliminate masking produced by suprathreshold pedestal gratings. Significant facilitation of contrast detection and near-threshold discrimination (the dipper effect) by cross-oriented surrounds has also been observed (Yu, Klein, & Levi, 2001). These results suggest that cross-orientation surround modulation also occurs in low-level vision, which motivated us to investigate whether significant cross-orientation surround modulation on perceived contrast could be revealed under proper stimulus conditions.

During the course of this study, we also measured effects of spatial frequency, phase, and the size of center-surround gap on surround modulation of perceived contrast. Many of our measurements were replications of previous studies under similar stimulus conditions, but different results were often obtained. Moreover, we found that some of the results usually attributed to contrast-contrast phenomenon might actually be due to brightness induction. A preliminary report of our data was presented at the Association for Research in Vision and Ophthalmology annual conference in Fort Lauderdale, Florida, in May 2000.

Methods

Observers and Apparatus

Six adult observers with normal or corrected-to-normal vision served in part or all of the study. J.W., K.R., and M.L. were new to psychophysical observation and ran fewer experiments. Other observers were more experienced. Only Y.C. was aware of the purpose of the study.

Stimuli were generated by a Vision Works computer graphics system (Vision Research Graphics, Inc., Durham, NH) and presented on a U.S. Pixel Px19 monochrome monitor (1024 x 512 resolution, 0.28 mm [H] x 0.41 mm [V] pixel size, 117-Hz frame rate, 62-cd/m^2 mean luminance, and 3.8° x 3.0° screen size at the 5.64-meter viewing distance). Luminance of the monitor was made linear by means of a 15-bit look-up table. Experiments were run in a dimly lit room.

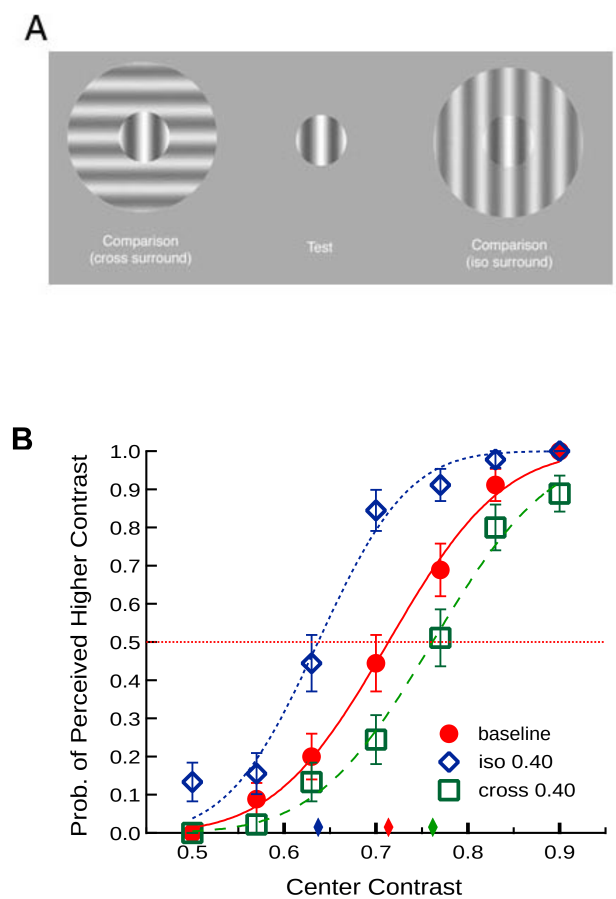

Figure 1. A. The stimuli. The middle stimulus is the test, those on the left and right are comparisons at iso- and cross-orientations. B. An example of experimental data and curve fitting. The 50% probability level in the psychometric function is the point of subjective equality. Perceived contrast for each function is indicated by a filled diamond on the x-axis.

Stimuli and Procedure

Surround modulation of perceived contrast was studied in foveal vision through contrast matching via the method of constant stimuli. The test (Figure 1A, center) was a sinusoidal grating disk. The comparison was the same grating disk (center disk) plus an annular grating surround (Figure 1A, iso-orientation at left and cross-orientation at right). The contrast, orientation, spatial frequency, and phase of the surround, as well as center-surround gap size, were varied in the experiments as independent variables. The size of the center disk was 18 arcmin in diameter, and the outer diameter of the annular surround was 61 arcmin when the surround abutted the center disk. The spatial frequency of the center disk was always 8 cpd. The test and comparison stimuli were presented separately in 2 successive stimulus intervals in a random order. The stimulus intervals lasted for 380 msec each and were separated by a 400-msec interstimulus interval. The test disk had 7 contrast levels, 3 above, 3 below, and 1 equal to the fixed contrast of the center comparison disk. Observers were asked to report which interval contained the higher-contrast grating disk. They received no feedback. Each trial was preceded by a 6.3' x 6.3' fixation cross in the center of the screen that disappeared 100 msec before the beginning of the trial. Each contrast level of the test was presented 15 times in a single session. Each measurement was repeated in 4 separate sessions, resulting in psychometric functions, each based on 420 (7 x 15 x 4) trials.

Results were plotted as a psychometric function showing the probability of the test disk being perceived as having higher contrast than the center comparison disk at each test contrast level. Each plot was fitted with a cumulative Gaussian function (unweighted). The perceived contrast of the center grating under each surround condition was equal to the test contrast corresponding to the 50% probability level of the psychometric function (the point of subjective equality [PSE]).

Discrimination threshold for the same center grating was also calculated from the same psychometric function and equal to the range of test contrast corresponding to one standard deviation of the Gaussian fit. Examples of the raw experimental data and curve fitting are presented in Figure 1B. They are one observer's (Y.C.) data from experiment 1. The solid curve in the middle represents the Gaussian fit for baseline measurement with no-surround (0.70 center contrast). The left fit (dotted curve) shows the perceived contrast of the center grating being suppressed (to 0.64) by an iso-oriented surround (0.40 contrast), and the right fit (dashed curve) shows the perceived contrast being enhanced (to 0.77) by a cross-oriented surround (0.40 contrast). The discrimination thresholds of the baseline, iso-orientation effect, and cross-orientation effect functions were 0.097, 0.078, and 0.099, respectively.

Results

Experiment 1: Iso- and cross-orientation surround modulation of perceived contrast and the effects of contrast and center-surround gap

Surround modulation of perceived contrast was measured with combinations of 4 center contrasts (0.10, 0.25, 0.40, and 0.70) and 4 surround contrasts at cross-orientation (0.10, 0.20, 0.40, and 0.80), as well as 1 surround contrast at iso-orientation (0.40). Four observers participated in this experiment (only three with the 0.40 center contrast condition). Perceived contrasts for each stimulus condition are presented in Figure 2A.

Iso-orientation. Iso-oriented surrounds suppressed the perceived contrast of center gratings in all observers (Figure 2A, the left "iso 0.40" section), regardless of whether the center contrast was higher or lower than the surround contrast. This suppression is consistent with many earlier studies (Cannon & Fullenkamp, 1991, 1996a; Ellemberg et al, 1998; Olzak & Laurinen, 1999), and our observers would all be categorized as "suppressors," according to Cannon & Fullenkamp (1996b). The average perceived contrast reduction was 0.037 (37%, the percentage ratio of contrast change versus center contrast), 0.055 (22%), 0.038 (9.5%), and 0.057 (8.1%), respectively, for center gratings at contrasts of 0.10, 0.25, 0.40, and 0.70. Contrast suppression was stronger for 2 observers (N.D. and Y.C.), and weaker for the other 2 (K.R. and J.P.).

Cross-orientation. In contrast to previous reports, cross-oriented surrounds typically produced enhancement of perceived center contrast (Figure 2A), especially at higher center contrasts (0.70 and 0.40). The average enhancement of perceived contrast was 0.05 (7.1%) at 0.70 center contrast. Enhancement appeared to be weaker at 0.40 center contrast, approximately 0.025 (6.3%) on the average. A "slight facilitation" at cross-orientation to a high contrast (0.80) central test was also reported by Xing and Heeger (2000), however, only at a low surround contrast (0.20). Surround effects were mixed at lower (0.25 and 0.10) center contrasts, generally very small at low surround contrasts, but strongly suppressive or enhancing for some observers at high surround contrasts. Despite large individual differences, these results demonstrate that cross-oriented surrounds are able to modulate the perceived contrast of center gratings, particularly at high center contrasts.

The cross-orientation data were replotted for each observer in the 4 panels of Figure 2B. Each panel presents the change of perceived contrast as a function of center contrast for each surround contrast condition. These plots suggest that higher contrast cross-oriented surrounds tend to induce stronger perceived contrast change (eg, J.P., N.D., and Y.C.), regardless of whether this change is enhancing or suppressive. Moreover, these plots indicate large quantitative and qualitative differences across individual observers in cross-orientation surround effects. For instance, J.P.'s data show significant enhancement at low center contrasts and less facilitation at high center contrasts, whereas Y.C. and N.D.'s data show suppression at low center contrasts that changes to enhancement at high center contrasts.

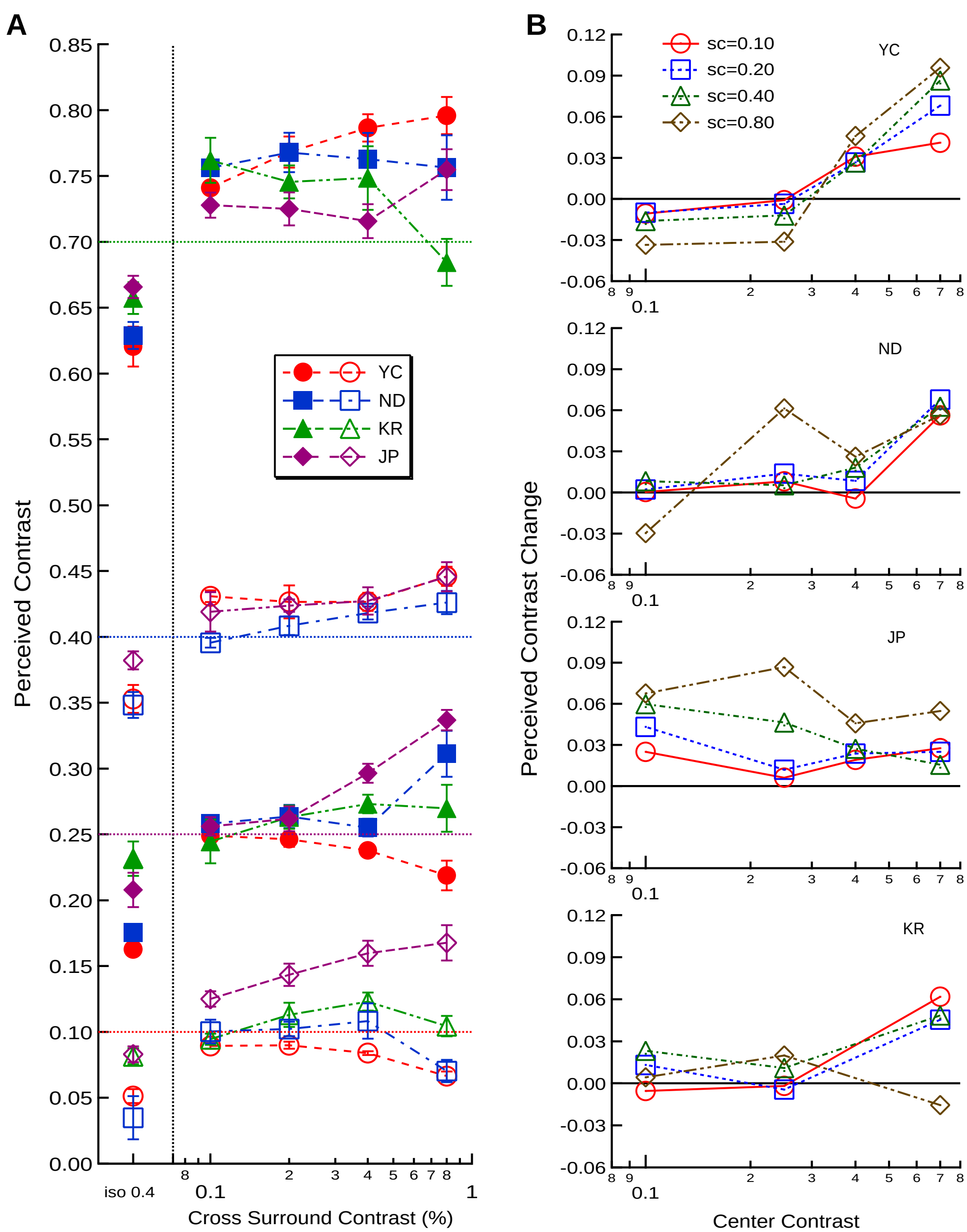

Figure 2. A. Iso- and cross-orientation surround modulation of perceived contrast for center gratings as a function of surround contrast. Results are grouped using filled or empty symbols around each center contrast (indicated by horizontal dotted lines). The small left section shows iso-orientation surround effects, and the large right section shows cross-orientation effects. B. The perceived contrast changes for the cross-orientation are plotted as a function of the center contrast for each surround contrast condition. Each panel shows one individual set of data. sc indicates surround contrast.

Snowden and Hammett (1998) reported that iso-orientation surround suppression of perceived contrast PSE does not come with a discrimination threshold (just noticeable difference [JND]) change, except for center gratings at low contrasts where discrimination thresholds are raised. We calculated the average contrast discrimination thresholds from the psychometric functions used to estimate the perceived contrasts shown in Figure 2 under 4 surround conditions: no surround, iso-surround at 0.40 contrast, and cross- surround at 0.40 and 0.80 contrasts, and plotted them against center contrast (Figure 3A). For comparison, the changes of perceived contrast under these surround conditions were also plotted as a function of the center contrast (Figure 3B and 3C [with the ordinate as Cref/Ccenter for comparison with other studies, such as Xing & Heeger, 2000]). These discrimination threshold data indeed indicate little change of discrimination thresholds at both iso- and cross-orientations, consistent with Snowden and Hammett's report. This decoupling of surround effects on perceived contrast and contrast discrimination will be considered in the Discussion section.

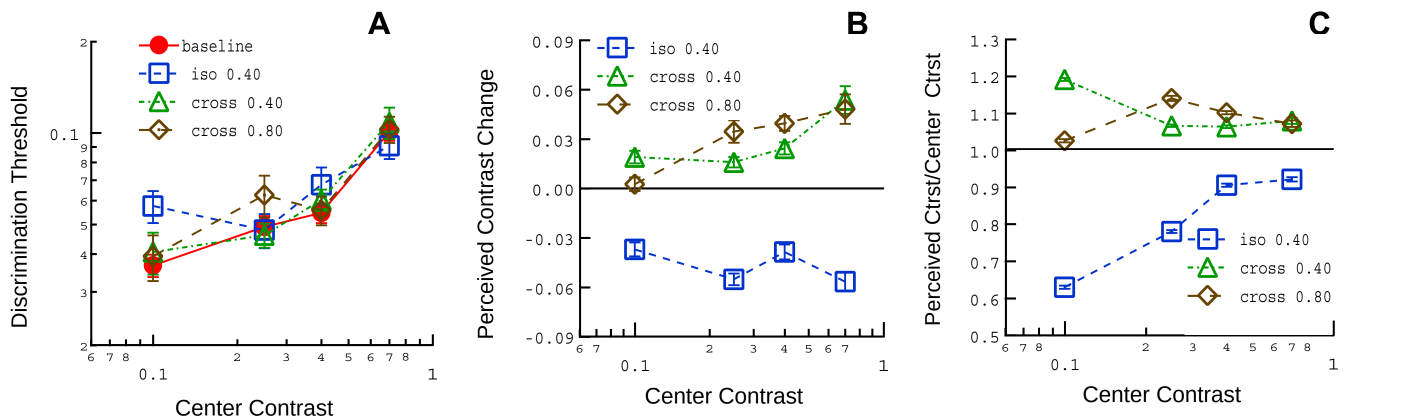

Figure. 3. A. Surround effects on contrast discrimination (JND) (averaged over the observers) presented as a function of center grating contrast under various surround conditions. B. Perceived contrast shifts (PSE) from Figure 2 (averaged over the same observers). C. A replot of panel B to ease the comparison to the results of earlier papers. In B, the ordinate is Cref - Ccenter. In C, the ordinate is Cref/Ccenter. The 2 ordinates provide different insights into the multiplicative and subtractive surround effects.

Cannon and Fullenkamp (1991) reported that iso-orientation surround suppression is still effective when the center and surround gratings are separated with a gap of up to 3 to 5 cycles. Here we compared the gap effects at both iso- and cross-orientations. The center and surround contrasts were 0.70 and 0.40, respectively. The area of the surround was kept constant when the center-surround gap was varied. The center and surround were at an equal spatial frequency of 8 cpd. When the surround was separated from the center, iso-orientation suppression (circles in Figure 4) reduced its strength very slowly and still retained some influence at the widest gap used (20 arcmin, or 3 cycles, between the outer edge of the center and inner edge of the surround), consistent with Cannon and Fullenkamp's (1991) data. However, cross-orientation enhancement (triangles in Figure 4) decreased more quickly and disappeared at a gap of about 7 to 11 arcmin (0.9-1.3 cycles). At larger gaps, the cross-orientation surround effects even became somewhat suppressive. This rapid reduction of surround enhancement might explain why only slight cross enhancement was sometimes observed by Xing and Heeger (2000). In their experiments, cross-orientation enhancement might have been weakened by the center-surround gap.

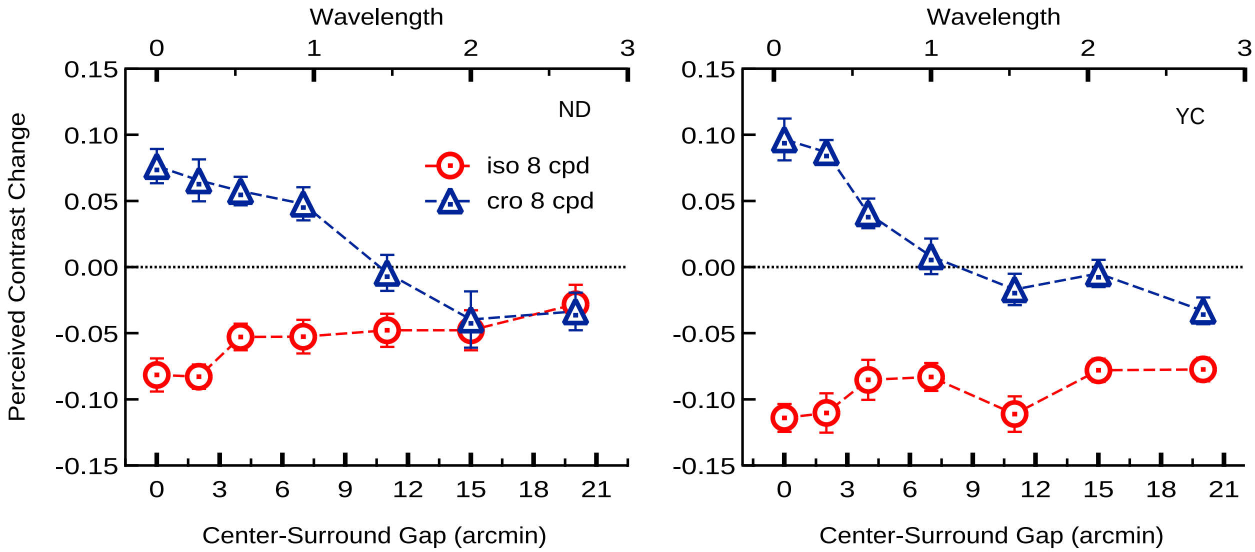

Figure 4. Contrast change as a function of center-surround gap size. The area of the surround is constant across gap sizes.

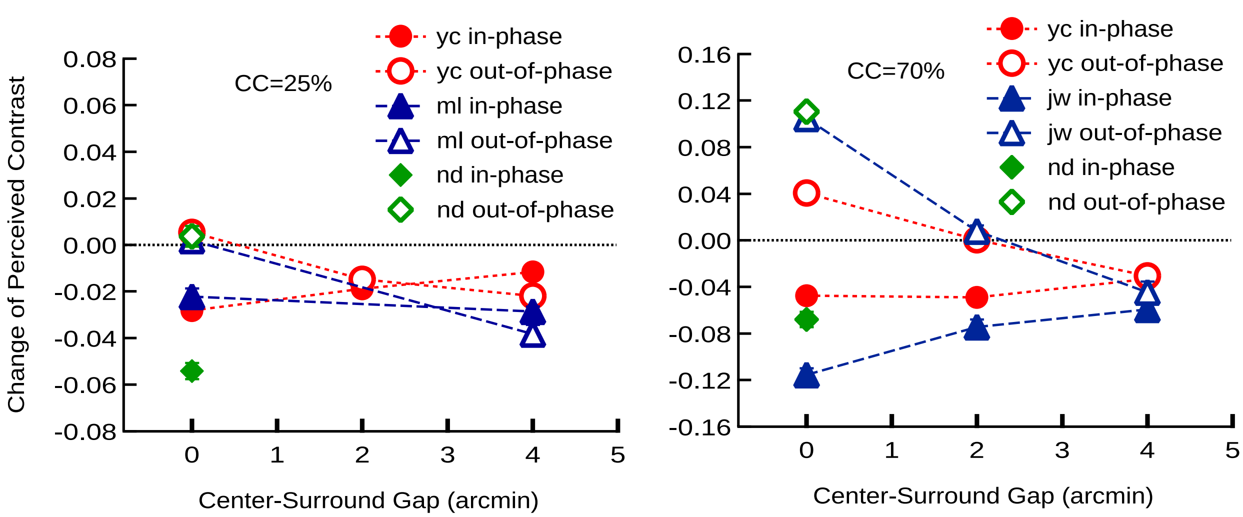

Figure 5. Perceived contrast change as a function of center-surround gap under in-phase and out-of-phase conditions. The surround contrast is 0.40. CC indicates center contrast.

Experiment 2: The effect of relative phase on surround modulation, and the role of brightness induction due to local contrast

This experiment was undertaken to clarify some conflicting explanations of phase effects on surround modulation of perceived contrast. Ejima and Takahashi (1985) first reported that iso-orientation contrast suppression diminishes and sometimes changes to enhancement when the center and surround gratings are 180° out of phase. They explained this phase effect as a result of brightness induction due to local luminance contrast. The darkness of the dark bars and the brightness of the light bars of the center grating are enhanced by abutting opposite-polarity bars of the out-of-phase surround grating and produce an overall contrast enhancement that offsets contrast suppression. On the other hand, Olzak and Laurinen (1999) reported that surround modulation of perceived contrast is affected by phase for sinusoidal gratings, but not for plaid gratings. They proposed a theory of multiple-stage gain-control processes in surround modulation of perceived contrast, in which surround modulation for simple sinusoidal gratings is a lower level phase-dependent process that "appears to operate only over spatially aligned pathways with similar phase or polarity tuning" and surround modulation for more complex plaid gratings is a higher level phase-independent process.

Xing and Heeger (2000) recently replicated a number of the previous experiments on surround modulation of perceived contrast using sinusoidal gratings as stimuli. To help their observers distinguish center and surround stimuli, they introduced a small center-surround gap, and surround modulation as they reported is unaffected by phase! These data appear to contradict Olzak and Laurinen's (1999) theory of phase-dependent first-order processing for sinusoidal gratings but favor Ejima and Takahashi's (1985) brightness induction explanation. The small center-surround gap diminishes local luminance (edge) contrast, which in turn diminishes brightness induction, but the contrast-suppression effect remains relatively unaffected.

We measured surround effects for iso-oriented sinusoidal gratings (8 cpd), in phase and out of phase, with the center-surround gap varying from 0 arcmin to 4 arcmin. The center and surround, when in phase, were clearly distinguishable at a gap of 4 arcmin. The center contrasts were 0.25 and 0.70, with the surround contrast constant at 0.40. The 0.25 center contrast was close to the 0.18 center contrast used by Olzak and Laurinen (1999), and the 0.40 surround contrast was about the same as their highest surround contrast (0.39). This stimulus configuration with abutting center and surround was similar to some of Olzak and Laurinen's (1999) conditions, and with a 4-arcmin gap it approximated some of Xing and Heeger's (2000) conditions. The use of a 0.70 center contrast would further increase the local luminance contrast between the abutting out-of-phase center and surround gratings. If local brightness induction is responsible for the phase effects, higher local luminance contrast would lead to more enhancement, which could eventually enhance the perceived contrast of the center grating. Our results (Figure 5) basically replicated all previous phase data and confirmed our predictions. At 0.25 center contrast, contrast suppression diminished when the abutting center and surround stimuli changed from in phase to out of phase. At 0.70 center contrast, suppression was reversed to enhancement. However, with a 4-arcmin gap, suppression was restored for out-of-phase stimuli regardless of the center contrast, and suppression for in-phase and out-of-phase stimuli was similar. These results clearly support Ejima and Takahashi's (1985) brightness induction explanation and argue against Olzak and Laurinen's (1999) first-order explanation of surround effects for sinusoidal grating stimuli. Surround effects on perceived contrast indeed are phase independent and appear to reflect second-stage visual processing.

Experiment 3: The effect of relative spatial frequency on surround modulation and the role of brightness induction in contrast enhancement by lower spatial frequency surrounds

The effects of relative spatial frequency on iso-orientation surround modulation of perceived contrast have been measured previously and the results reportedly indicate spatial frequency tuning except at low center spatial frequencies (Cannon & Fullenkamp, 1991). In this experiment, we measured the effects of relative spatial frequency at both iso- and cross-orientations. Experiments on iso-orientation effects were originally planned as controls because they would simply replicate previous measurements by Cannon and Fullenkamp, but we obtained different results. The center spatial frequency was 8 cpd, and the surround spatial frequency varied from 4 to 16 cpd (±1 octave). The center and surround gratings were always aligned with the middle points of their light center bars regardless of spatial frequency. Effects were measured at 3 center contrasts, 0.10, 0.25, and 0.70, with the surround contrast always being 0.40.

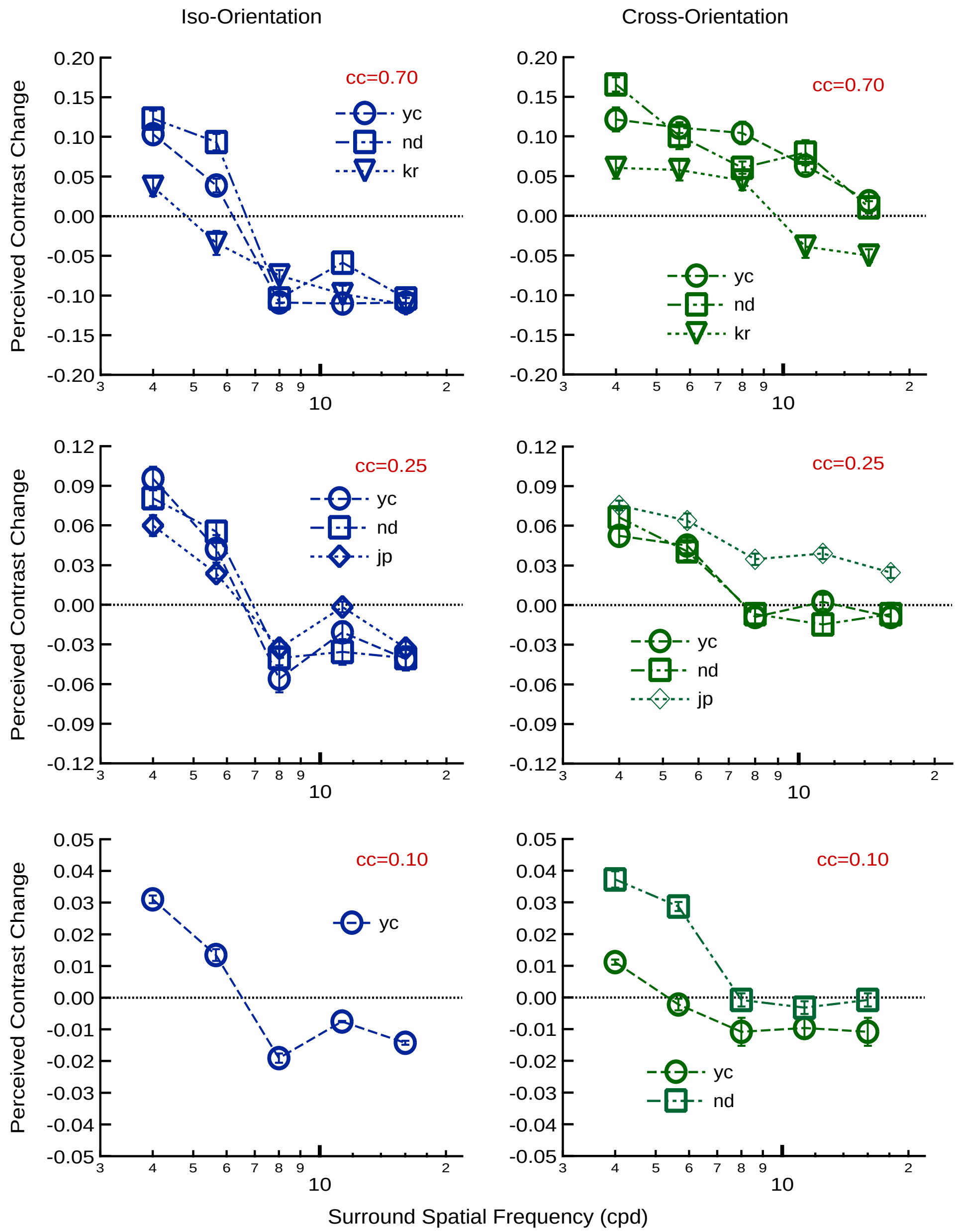

Figure 6. Iso- and cross-orientation surround effects at different center contrasts as a function of the surround spatial frequency. cc indicates center contrast.

Cannon and Fullenkamp's (1991) data suggest bandpass spatial frequency tuning of iso-orientation suppression (surround frequency matched to center frequency had greatest suppression). However, under very similar stimulus conditions (same 0.25 center contrast and 8 cpd spatial frequency, though our stimuli were smaller with fewer cycles), we obtained different data (Figure 6). When the surround spatial frequency was lower than the center frequency, we found marked enhancement of perceived contrast. However, when the surround spatial frequency was equal to or higher than the center spatial frequency, contrast suppression was nearly constant under each center contrast condition. The same trend can actually be seen in one of Cannon and Fullenkamp's observers (their Figure 10). Contrast enhancement at lower surround spatial frequency is consistent with Xing and Heeger's (2000) report, which also showed that a 0.5-cpd iso-oriented surround sometimes enhanced the perceived contrast of a 2 cpd-central grating. Xing and Heeger (2000) did not measure the effects of surrounds at higher spatial frequencies and used contrast enhancement at lower surround spatial frequency as evidence for spatial frequency specificity in surround modulation. Spatial frequency effects at cross-orientation (Figure 6) were generally similar to those at iso-orientation. Lower spatial frequency surrounds consistently enhanced perceived contrast.

Higher spatial frequency surrounds, in contrast, left the perceived contrast of lower contrast center gratings (0.10 and 0.25) largely unchanged, though enhancement for high contrast center gratings (0.70) decreased and was near the baseline at 16 cpd. Results at both orientations indicate no simple bandpass spatial frequency tuning of surround modulation. Unchanged surround effects at higher surround spatial frequencies suggest that surround modulation might not be tuned to spatial frequency at all. Moreover, the reversal of surround effects at lower surround spatial frequencies suggests that an additional low spatial frequency mechanism might have been involved. A simple bandpass spatial frequency tuning would predict only diminishing surround effects when the surround spatial frequency is distant from the center spatial frequency.

Interestingly, as Figure 6 suggests, the strength of contrast enhancement by surrounds at 4 cpd was about the same at iso- and cross-orientations, suggesting that this low spatial frequency mechanism is probably insensitive to orientation. Could this low surround spatial frequency enhancement, at least at iso-orientation, be a result of brightness induction due to increased local luminance contrast, as widened bars of a lower spatial frequency surround would produce? We ran a gap experiment to test this possibility. The effects of an iso-oriented 4 cpd, 0.40 contrast surround grating on an 8 cpd, 0.70 contrast center grating (one of the conditions in Figure 6) were measured as a function of the size of a center-surround gap. Figure 7 shows that contrast enhancement by a lower spatial frequency surround grating, though initially dropping quickly, was present at as far as a center-surround gap of 20 arcmin, suggesting that local brightness modulation is, at least, not the only cause for this effect.

To further explore this enhancement issue, we ran another experiment to measure surround effects at even lower spatial frequencies. The center spatial frequency was 8 cpd with a contrast of 0.25, and the spatial frequency of the iso-oriented surround was set at 8, 4, 2, 1, and 0 cpd, with a contrast of 0.40 and either in phase or out of phase. The 0-cpd surround was actually a bright ring when in phase and a dark ring when out of phase. Samples of the stimuli are presented in Figure 8A.

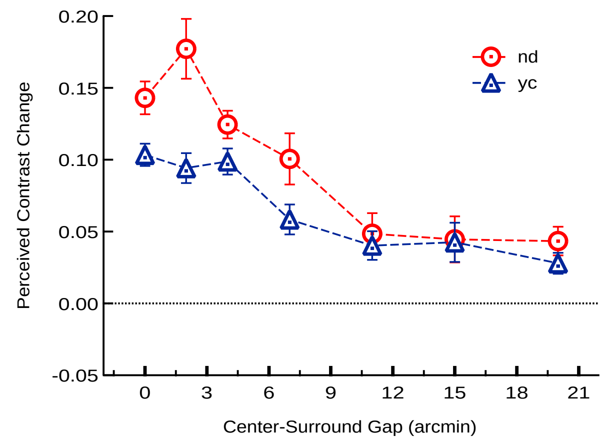

Figure 7. Iso-orientation contrast enhancement by lower spatial frequency surrounds as a function of center-surround gap. Surround SF = 4 cpd, contrast = 0.40; center SF = 8 cpd, contrast = 0.70.

The results (Figure 8A) show that contrast enhancement was always present when the surround spatial frequency was reduced from 4 cpd to 1 cpd, regardless of the phase. However, at 0 cpd, although the bright surround still produced enhancement, the dark surround actually reversed enhancement to suppression. Opposite results by bright and dark surrounds at 0 cpd show that low spatial frequency surround enhancement was not due to contrast modulation because the contrast-contrast between center and surround was similar under these conditions. More likely, the results reflect the effects of brightness modulation. We instructed the same 2 observers to match either only the darkness of the dark bars or only the brightness of the light bars under black and white surround conditions. The black surround reduced the darkness of the dark bars by 0.02 of the mean luminance for both observers. The white surround strongly enhanced the darkness of the dark bars by 0.08 for both observers. This darkness induction agreed with the change of perceived contrast for the same surround configurations. The induced brightness changes of the light bars, however, were less consistent across observers.

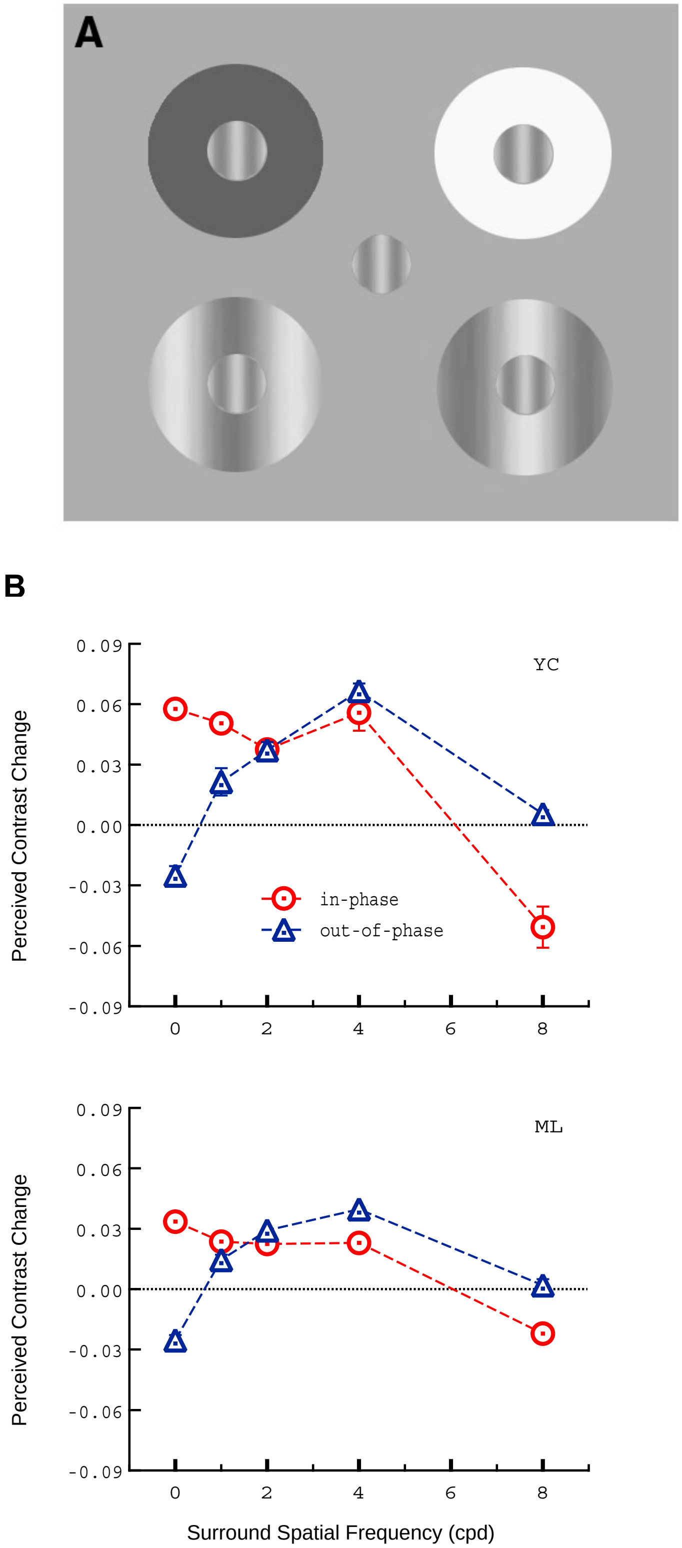

Figure 8. A. Samples of stimuli. B. Perceived contrast change as a function of surround spatial frequency under in-phase and out-of-phase conditions. Center contrast = 0.25; surround contrast = 0.40.

Brightness was suppressed for Y.C . (-0.03) and enhanced for M.L. (0.01) by the black surround, and it was unchanged for Y.C. and enhanced for M.L. (0.03) by the white surround. An additional observer (S.K.) repeated the same conditions and found the light bar judgments to be very difficult because there were multiple criteria that could be used. This did not present a problem for the dark bar judgments. The dark bars thus likely served as the cue for the observers to determine the perceived contrast. For frequencies from 1 to 4 cpd for both phase conditions, dominant darkness enhancement of dark center bars by light bars of the surround consistently enhanced perceived contrast. This enhancement is probably unaffected by phase and orientation as long as the surround is not totally black. Because contrast enhancement is present under in-phase and out-of-phase conditions, this low spatial frequency surround enhancement would show up when the center grating is larger with more cycles, as in Xing and Heeger's (2000) case.

Higher spatial frequency surround gratings, however, are not able to produce significant brightness induction. This could be because narrower light and dark bars of the surround have weaker but opposite effects on the same wider bars of the center, and the effects tend to cancel each other. After excluding the influences of brightness induction by lower spatial frequency surrounds, surround modulation of perceived contrast might not be tuned to spatial frequency, or would likely be very broadly tuned to spatial frequency.

Discussion

The main features of our data are (1) surround gratings at both iso- and cross-orientations affect the perceived contrast (PSE) of a center grating without a simultaneous change of contrast discrimination threshold (JND). (2) When surround spatial frequency is equal to or higher than the center spatial frequency, iso-oriented surrounds suppress PSE, but cross-oriented surrounds often enhance PSE. Lower spatial frequency surrounds at both orientations are consistently enhancing, probably as a result of brightness induction. (3) Iso-orientation surround effects are phase insensitive after excluding local brightness induction. (4) Iso-orientation surround modulation acts over larger distances than does cross-orientation surround modulation when center and surround spatial frequencies were matched. A summary of our hypotheses follows. We believe that there is a general inhibitory contrast-contrast gain control process that reduces perceived contrast similar to what Chubb et al (1989) and Cannon and Fullenkamp (1996a) discuss. This is a process that is independent of phase or polarity, fairly independent of gap size, and broadly tuned to spatial frequency. This gain control process could be divisive when the surround has higher contrast than the center, and subtractive when the surround has lower contrast. The subtractive effect could be caused by an obligatory effect wherein the observer involuntarily compares the center to the surround rather than to the reference. In addition, there are one or more brightness-induction processes associated with luminance-defined stimuli. The brightness induction tends to act on the salient features of the central patch, which are typically the dark bars. The presence of large (low frequency) light-surround regions makes the dark central bars darker, thereby increasing the perceived contrast.

Second-order processing of surround modulation of perceived contrast

Our experimental data suggest that surround modulation of perceived contrast is at a phase-independent second-order stage of visual processing after excluding brightness induction due to local luminance contrast. Moreover, again, after excluding the influences of brightness modulation, data from spatial frequency tuning experiments (Figures 5, 6,7) suggest that surround modulation of perceived contrast may have a very broad tuning to spatial frequency or no tuning at all. On the basis of these data, we conclude that center and surround signals may have been first pooled separately from filters tuned to a very broad range of spatial frequencies before the surround signals interact with center signals laterally to produce an inhibitory contrast-contrast gain control. This is consistent with previous evidence that perceived contrast is more likely mediated by response pooling from filters tuned to a wide range of spatial frequencies, rather than by a single maximally excited mechanism (Cannon & Fullenkamp, 1988). Contrast-matching can be independent of stimulus spatial frequency bandwidth up to 6 octaves (Tiippana & Nasanen, 1999). To effectively modulate the perceived contrast of center stimuli, a similar pooling of surround signals across filters tuned to a wide range of spatial frequencies must be activated. Because surround modulation of perceived contrast is tuned to orientation (Cannon & Fullenkamp, 1991; Solomon et al, 1993), wide-range spatial frequency pooling and limited orientation pooling in contrast modulation fits the description of the second-order "cigar" mechanism proposed by Olzak and Thomas (1999).

Perceived contrast, brightness induction, and individual differences

In experiments 2 and 3, we demonstrated how phase and spatial frequency effects on surround modulation of perceived contrast could be influenced by brightness induction. Ejima and Takahashi (1985) speculated that a form of brightness induction, the grating-induction effect (McCourt, 1982), might explain contrast enhancement by out-of-phase surround gratings. The grating-induction effect refers to the illusory perception of an out-of-phase grating on a narrow blank field that is a cut through a sinusoidal-inducing grating. However, we are uncertain how large a role grating induction has played in the brightness-induction effects shown in our study where the inducing gratings surround a suprathreshold center grating instead of a blank field. In the phase experiment (experiment 2), the surround had the same spatial frequency as the center at 8 cpd. At this relatively high spatial frequency, the grating-induction effect is reportedly weak for a blank field as big as our center field. Moreover, at a higher center contrast (0.70), the abutting surround produced stronger enhancement. This enhancement is easily accounted for by a summation of increased localized brightness induction (of abutting pairs of dark and bright bars), as described earlier. However, grating induction may or may not increase as a result of increased center-grating contrast. When the surround spatial frequency was lower than the center spatial frequency, for instance, at 4 cpd as in experiment 3, a grating-induction effect would be expected to induce the perception of a 4 cpd out-of-phase grating. The induced grating would sum with the 8 cpd center grating to produce a composite grating. However, no composite was seen in our experiments. Thus, we suggest that our effect is the result of a generic brightness induction and has little to do with the grating-induction effect, even though we used sinusoidal gratings as stimuli.

Brightness induction might also explain iso-orientation surround enhancement of perceived contrast for in-phase stimuli as occasionally seen in some observers (Cannon & Fullenkamp, 1996b; Snowden & Hammett, 1998; Xing & Heeger, 2000). When the center and surround are in phase, the local contrast between abutting gratings is relatively small compared to those under the out-of-phase condition, and the resulting contrast change is normally not strong enough to determine the final contrast perception (provided that the center field is big enough to be unaffected by the grating-induction effects [McCourt, 1982]). The exception is when the center contrast is much higher than the surround contrast, in which brightness and darkness of individual bars of the high contrast center grating could be more enhanced by low-contrast surround grating due to increased local contrast. For some observers, this enhancement could be strong enough to overcome contrast suppression and raise the perceived contrast. Indeed, in-phase iso-orientation surround enhancement is most often reported when the center contrast is much higher than the surround contrast (eg, Snowden & Hammett, 1998), though not shown in our study.

Although local brightness and darkness induction can be easily excluded by adding a small center-surround gap, surround modulation of perceived contrast of sinusoidal gratings is also affected by more general brightness modulation as revealed in experiment 3 (Figures 5,6,7) when the surround had a lower spatial frequency than the center. This brightness modulation appears to be unrelated to local luminance contrast, and is more effective on dark areas of the center stimuli. One way to lessen this problem is to use single-polarity stimuli, such as Gaussian blobs. These single-polarity stimuli have another advantage in that they could potentially reduce individual differences. Our informal observations suggest that different observers may use different strategies to determine the contrast. They may pay more attention to the brightness of the light bars, or to the darkness of the dark bars, or alternately, use these cues under different stimulus conditions. Another alternative is to use textural stimuli as center and surround stimuli (eg, Chubb et al, 1989). For textual stimuli, the brightness and contrast are nearly orthogonal and can be separately measured using a nulling method (Krauskopf, Zaidi, & Mandler, 1986). This method, however, cannot be easily applied to luminance-defined gratings because of the covariance of brightness and contrast in these stimuli.

Perceived contrast (PSE) and contrast discrimination (JND)

Snowden and Hammett (1998) argued that surround effects on perceived contrast (PSE) and contrast discrimination (JND) are variations of normal masking and based on the same divisive inhibition mechanism, though PSE and JND may have different effective contrast ranges, with JND changes only at low contrast. According to this view, the pool of divisive signals would be very extensive because iso-orientation effects occur across a large center-surround gap (3-5 cycles, Cannon & Fullenkamp, 1991; Figure 6). However, the effective area of normal masking, which suggests the area of divisive signal pooling, is only slightly larger than the target (Yu & Levi, 1997; Snowden & Hammett, 1998). This discrepancy rather indicates that surround modulation is more likely a visual process separate from normal masking. We suggest that the observers may be involuntarily comparing the center grating to the surround grating, rather than a direct comparison to the comparison stimulus (no surround). The referencing is a subtractive effect that would reduce the perceived contrast of the center. This effect would be expected to be strongest when the surround is similar in orientation and spatial frequency to the center, as can be seen by viewing the stimuli in Figure 1. This obligatory referencing to the surround seems to hold even if a gap is present (Figure 6), though it is slightly reduced in magnitude. For the case where the surround is of higher contrast, divisive inhibition may also be present.

We collected data for both PSE and JND in the same experiment. The data shown in Figure 3 indicate that there are significant shifts in PSE with minimal change in the JND under these same conditions. The dramatic changes of PSE as a function of spatial frequency shown in Figure 4 are accompanied by no changes in JND (not shown). A possible explanation of this decoupling is that the JND and PSE judgments take place at different stages of processing. For example, Klein, Stromeyer, and Ganz (1974) argued against a single processing stage for the shift of perceived spatial frequency following adaptation. They provided 2 arguments against a single stage. First, they produced a spatial frequency shift by using a simultaneous surround rather than by successive adaptation. A spatial frequency shift was found with no change in contrast detection. This effect of a surround on the PSE but not on detection is similar to the present experiments where the surround produces a PSE shift but no JND shift. Klein, et al (1974) also analyzed the spatial frequency tuning of the PSE shift and of the threshold elevation. They argue that the PSE shift was too broad by about a factor of 2 to be able to be explained by the 1.5-octave mechanisms responsible for threshold elevation, even when nonlinearities were allowed. A 2-stage model could account for this decoupling.

However, it is possible to decouple the perceptual (PSE) and discrimination (JND) judgments with a single-stage model. Suppose the surround contributes to the response in an additive or subtractive manner. That is $Resp(Cc, Cs) = Fc(Cc) + Fs(Cs)$, where Cc and Cs are the contrasts of the center and surround. The JND would depend on the derivative of Resp with respect to Cc. Given the additive nature of the 2 terms, the derivative (JND) would not depend on Cs. However, the PSE would depend on the surround contrast. For example, an increase in Cs would lead to an increase in Resp, with an expected increase in the PSE. Our data and that of Snowden and Hammett (1998) show that for low pedestal contrast, the surround does have an effect on the JND. That could be easily included into our single-stage model by having Fc depend on Cs and well as Cc.

Another possible reason that we and Snowden and Hammett (1998) failed to reveal real surround effects on contrast discrimination is related to the Westheimer effect. The reason for our argument is simple: For a visual target, maximal masking occurs when the pedestal is slightly larger than the target, but further enlarging the pedestal would reduce masking. These desensitization and sensitization effects were originally suggested by Westheimer (1965, 1967), and many variations using grating stimuli have been studied by Yu and Levi (1997, 2000). For the current stimulus configuration, the target and pedestal are the same center grating, so that the abutting surround grating actually covers both the desensitization and sensitization regions. The surround grating desensitizes and sensitizes contrast discrimination at the same time, but these actions cancel each other and produce the false impression that the surround is incapable of modulating contrast discrimination. An optimal way to study surround modulation of contrast discrimination has been applied by Yu and Levi (2000), which separates desensitization and sensitization effects, and robust surround effects are evident in that study.

Conclusions

Surround modulation of perceived contrast is likely a phase-independent, broadly spatial frequency tuned, second-order process. Surround effects on perceived contrast of sinusoidal gratings involve both contrast modulation and brightness induction. Better stimuli are recommended for the measurement of contrast-contrast phenomenon.

Acknowledgments

This research was supported by National Institutes of Health Grants R01EY01728 and R01EY04776. We thank David Heeger and Jing Xing for their helpful discussions relative to phase effects (experiment 2).
Commercial relationships: N.

References

Cannon, M. W., & Fullenkamp, S. C. (1988). Perceived contrast and stimulus size: Experiment and simulation. *Vision Research*, 28, 695-709. [PubMed]

Cannon, M. W., & Fullenkamp, S. C. (1991). Spatial interactions in apparent contrast: Inhibitory effects among grating patterns of different spatial frequencies, spatial positions and orientations. *Vision Research*, 31, 1985-1998. [PubMed]

Cannon, M. W., & Fullenkamp, S. C. (1996a). A model for inhibitory lateral interaction effects in perceived contrast. *Vision Research*, 36, 1115-1125. [PubMed]

Cannon, M. W., & Fullenkamp, S. C. (1996b). Spatial interactions in apparent contrast: Individual differences in enhancement and suppression effects. *Vision Research*, 33, 1685-1695. [PubMed]

Chubb, C., Sperling, G., & Solomon, J. A. (1989). Texture interactions determine perceived contrast. *Proceedings of the National Academy of Science*, 86, 9361-9365.

Ejima, Y., & Takahashi, S. (1985). Apparent contrast of a sinusoidal grating in the simultaneous presence of peripheral gratings. *Vision Research*, 25, 1223-1232. [PubMed]

Ellemberg, D., Wilkinson, F., Wilson, H. R., & Arsenault, A. S. (1998). Apparent contrast and spatial frequency of local texture elements. *Journal of the Optical Society of America* A, 15, 1733-1739. [PubMed]

Klein, S., Stromeyer, C. F. 3rd, & Ganz, L. (1974). The simultaneous spatial frequency shift: A dissociation between the detection and perception of gratings. *Vision Research*, 14, 1421-1432. [PubMed]

Krauskopf, J., Zaidi, Q., & Mandler, M. B. (1986). Mechanisms of simultaneous color induction. *Journal of the Optical Society of America* A, 10, 1752-1757. [PubMed]

Levitt, J. B., & Lund, J. S. (1997). Contrast dependence of contextual effects in primate visual cortex. *Nature*, 387, 73-76. [PubMed]

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

Olzak, L. A., & Laurinen, P. I. (1999). Multiple gain control processes in contrast-contrast phenomena. *Vision Research*, 39, 3983-3987. [PubMed]

Olzak, L. A., & Thomas, J. P. (1999). Neural recoding in human pattern vision: Model and mechanisms. *Vision Research*, 39, 231-256. [PubMed]

Sillito, A. M., Grieve, K. L., Jones, H. E., Cudeiro, J., & Davis, J. (1995). Visual cortical mechanisms detecting focal orientation discontinuities. *Nature*, 378, 492-496. [PubMed]

Snowden, R. J., & Hammett, S. T. (1998). The effects of surround contrast on contrast thresholds, perceived contrast and contrast discrimination. *Vision Research*, 38, 1935-1945. [PubMed]

Solomon, J. A., Sperling, G., & Chubb, C. (1993). The lateral inhibition of perceived contrast is indifferent to ON-center/OFF-center segregation, but specific to orientation. *Vision Research*, 33, 2671-2683. [PubMed]

Tiippana, K., & Nasanen, R. (1999). Spatial-frequency bandwidth of perceived contrast. *Vision Research*, 39, 3399-3403. [PubMed]

Treisman, A. (1985). Preattentive processing in vision. *Computer Vision and Image Processing*, 31, 156-177.

Westheimer, G. (1965). Spatial interaction in the human retina during scotopic vision. *Journal of Physiology*, 181, 881-894. [PubMed]

Westheimer, G. (1967). Spatial interaction in human cone vision. *Journal of Physiology*, 190, 139-154. [PubMed]

Xing, J., & Heeger, D. J. (2000). Center-surround interactions in foveal and peripheral vision. *Vision Research*, 40, 3065-3072. [PubMed]

Yu, C., & Levi, D. M. (1997). End stopping and length tuning in psychophysical spatial filters. *Journal of the Optical Society of America A*, 14, 2346-2354 [PubMed]

Yu, C., & Levi, D. M. (2000). Surround modulation in human vision unmasked by masking experiments. *Nature Neuroscience*, 3, 724-728. [PubMed]

Yu, C., Klein, S. A., & Levi, D. M. (2001). Iso and cross orientation surround modulation of contrast detection and discrimination. Presented at the Vision Sciences Society Annual Meeting, Sarasota, Florida, 2001