Contrast Energy and Contour Interaction

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Significance

Contour interaction describes an impairment of visual acuity produced by nearby flanking features, which exerts a significant impact in many clinical tests of visual acuity. Our results indicate that the magnitude of interaction depends either on the flanker contrast energy (i.e., the product of flanker contrast and width) or the flanker contrast alone, depending on the contrast energy of the flankers.

Abstract

Purpose: The discrimination of acuity targets is impaired by the presence of nearby flanking contours, a phenomenon known as contour interaction. Methods: In this study, we measured percent correct identification for threshold-size, high contrast Sloan letters at the fovea and at 5 deg in the inferior visual field for different combinations of flanking-bar width and Weber contrast corresponding to specific, fixed values of contrast energy (width x contrast, in %-min arc). Results: For flanking bars with low contrast energy, contour interaction exhibited no systematic dependence on the flanking-bar width. However, when the flanking bars had higher contrast energy, narrower high-contrast bars produced significantly greater contour interaction than wider bars of lower contrast. Conclusion: The results are consistent with the interpretation that contour interaction depends primarily on the *contrast energy* of flanking contours when their contrast energy is low. As the contrast energy of the flanking contours increases, the magnitude of contour interaction depends on the flanker *contrast.* For high-contrast flanking contours, the magnitude of contour interaction saturates when the width of the flanking contours is approximately 20% of letter size.

Key Words: Contour interaction, contrast, fovea, peripheral vision, crowding

The ability to make fine spatial discriminations, such as identifying small optotypes or reporting the direction of offset in a Vernier target, is degraded by the presence of nearby flanking targets (for reviews, see[1-4]). When the impairment of discrimination results from "simple" adjacent flanking contours, such as lines or bars, this phenomenon is referred to as contour interaction.[1, 5, 6] When more complex flanking stimuli, such as alphabet letters are employed, or when a series of neighboring targets are discriminated sequentially, as when reading the letters on one or several rows of an acuity chart, the interaction often is referred to as crowding.[1] According to Flom[1] (see also[7-9]), crowding includes a degradation of performance attributable to nearby flanking contours as well as the spatial discrimination errors that result from inaccurate eye movements and/or the imprecise deployment of attention. In this communication, we address only the theoretically simpler form of interaction that occurs during contour interaction.

Contour interaction can be characterized by its magnitude and extent. The *magnitude* of contour interaction refers to the maximum reduction in performance that occurs in the presence of flanking bars, compared to the condition when no flanking bars are present. The *extent* of contour interaction is the maximum target-to-flanking bar separation at which performance is affected adversely.

Numerous studies provided evidence that contour interaction represents primarily a neural rather than a physical interaction between nearby targets.[6, 10-12] Substantial evidence exists also that contour interaction differs fundamentally from spatial-frequency or pattern masking. For example, nearby bars impair discrimination, but not the detection of a small acuity target, and the lateral extent of contour interaction does not scale with the size the flanked target.[10, 13, 14] In her seminal study of contour interaction on two-line resolution, Takahashi[6] reported that varying the width of a pair of flanking bars from 1.4 to 4.3 min arc has little effect on either the extent or magnitude of measured foveal interaction. More recently, we observed a near independence of contour interaction in a foveal letter-acuity task when the width of the flanking bars varied from 0.9 to 10.7 min arc.[14] Similar results were obtained also at 2.5 and 5 deg in peripheral vision.[15]

Takahashi[6] interpreted her results to indicate that contour-interaction is produced primarily by the contrast of the flanking-bar edges that are nearest to the central resolution target. Alternatively, if contour interaction depends on the contrast energy (contrast x area) of the flanking bars, then increasing the bar width should have resulted in more substantial interaction. However, the visual system summates contrast over only a limited spatial extent, called Ricco's diameter. Estimates of the width of Ricco's diameter in the fovea are on the order of 2 – 7 min arc and become systematically larger at peripheral retinal locations.[16-22] It is clear that the wider flanking bar used by Takahashi[6] as well as some of the flanking bar widths used in the studies by Siderov and colleagues[15, 23] likely exceeded the limits of Ricco's diameter.

Although extant evidence is consistent with Takahashi's interpretation that contour interaction results primarily from the contrast of the flanking-bar edges that are nearest the target, it is not yet possible to rule out an explanation based on contrast energy, which we define as the product of the flanking bar's contrast and its width.[1*] In particular, it is possible that the magnitude of contour interaction depends on contrast energy when the width of the flanking bars is relatively narrow, but saturates when the flanking bars achieve a certain critical value. If so, then, a further increase in bar width would generate no additional contour interaction. The goal of the present study was to examine the influence of flanking-bar contrast energy directly, by assessing contour interaction for high-contrast letter targets at the fovea and at 5 deg in the peripheral visual field in the presence of flanking bars with different combinations of width and contrast.

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[*] The magnitude of contour interaction in a foveal letter identification task does not depend on the length of the flanking bars, as long as the length is at least 40% of the target-letter size (Norgett,[24] and subsequent unpublished observations).

Methods

Observers

Five observers (3 males and 2 females, 3 naïve, age range 30-68 years old) participated in the experiment. Observers were free from ocular pathology and had normal or corrected-to-normal visual acuity in each eye. Approval for this research was obtained from the Anglia Ruskin Ethics committee and the study was conducted in accordance with the tenets of the Declaration of Helsinki. Each observer voluntarily provided written informed consent before participating.

Stimuli

Dark Sloan letters (C D H K N O R S V Z; Weber contrast = -90%) were presented one at a time on a white background, either in isolation or surrounded symmetrically on 4 sides by flanking bars. The length of each flanking bar was the same as the height or width of the central Sloan letter. As elaborated below, the Weber contrast and width of the flanking bars were adjusted in the principal conditions to produce equal values of contrast energy, i.e., flanking-bar contrast x flanking-bar width. The stimuli were generated using custom software written by author FP and displayed on a flat-screen display. This display measured 22 inches diagonally, with 1680 x 1050 pixel resolution and provided a background luminance of 182 cd/m^2. Ambient illumination in the experimental room was dim. The exposure duration of each stimulus presentation was unlimited for author HEB and restricted to 250 ms for the other 4 observers.

Procedures

Testing was performed monocularly using the natural pupil, in conjunction with each observer's appropriate spectacle (range: -3.13 D to +2.38 D spherical equivalent) or contact-lens (-10.13 D spherical equivalent) correction. The untested eye was covered with an opaque occluder. The observer identified each presented letter by typing his or her response on the computer keyboard. In different blocks of trials, the stimuli were presented at the fovea and at 5 deg in the inferior visual field. Foveal testing was performed at a viewing distance of 15 m, after reflection from a front surface mirror. The software reversed each presented Sloan letter so that it appeared in the correct orientation after reflection. Peripheral testing was conducted at a viewing distance of 1.75 m.

At each testing location, preliminary trials determined for each observer the letter size required to achieve approximately 80% correct identification responses, when the letters were presented without any flanking bars. Averaged across the 5 observers, the average letter sizes presented at the fovea and at 5 deg inferior field were 4.0 ± 0.36 (SE) min arc and 17.6 ± 1.5 min arc, respectively. Percent correct letter identification was then determined in the absence of flanking bars and for either 6 (foveally) or 8 (at 5 deg inferior field) edge-to-edge separations between the letter and the surrounding flanking bars. The principal foveal and peripheral data were obtained using 5 combinations of flanking-bar width and Weber contrast: (1) width = 10% of letter size (i.e., 0.5 stroke width), contrast = -90%; (2) width = 20% of letter size, contrast = -45%; (3) width = 30% of letter size, contrast = -30%; (4) width = 20% of letter size, contrast = -90%; (5) width = 40% of letter size, contrast = -45%. Because of the difference in acuity between the fovea and 5 deg inferior field, one letter-stroke width corresponded to 0.81 and 3.52 min arc (averaged across observers), respectively, during foveal and peripheral testing. At each location tested, the first three and the second two combinations of flanking-bar width and contrast produced the same values of contrast energy. Specifically, at the fovea the first three and second two sets of flanking-bar combinations produced contrast energies of 36 and 72%-min arc, respectively. At 5 deg inferior field, the corresponding values of contrast energy for the first three and second two combinations of bar width and contrast were 158 and 317%-min arc, respectively.

Additional data were obtained both foveally and at 5 deg in the inferior field for one or two flanking bar widths greater than 20% of letter size and a fixed contrast of -90%. The two additional flanking-bar widths tested at the fovea were 30% and 40% of the letter size corresponding, on average, to 1.22 and 1.62 min arc. At an eccentricity of 5 deg, the additional flanking-bar width was 30% of letter size, representing an average size of 5.28 min arc. Because all of these flanking bars had a Weber contrast of -90%, their contrast energy increased in proportion to their widths.

Data Analyses

Separate repeated-measures ANOVAs were performed on the results of the 5 observers for the combinations of flanking-bar width and contrast at each eccentricity that generated the same contrast energy. Analyses were performed using SuperANOVA software (Abacus Concepts, Berkeley, CA, USA). When necessary, Huynh-Feldt corrections were applied for significant departures from sphericity, as indicated when fractional values of degrees of freedom are reported in the Results section, below.

Additional repeated-measures ANOVAs were performed on the data obtained at each eccentricity using flanking bars of -90% contrast and different widths. Again, Huynh-Feldt corrections were applied when necessary for significant departures from sphericity.

Results

The 2 panels in Figure 1 present percent correct letter identification at the fovea as a function of the target-to-flanker separation for 5 combinations of flanking-bar width and Weber contrast. Performance in the absence of flanking bars (the rightmost data points in each of the two panels) is similar in all of the conditions. This outcome is anticipated as, in the absence of flanking bars, the targets presented in these conditions are identical.

Figure 1A compares letter identification for 2 flanking-bar widths with the same contrast energy, i.e., 72%-min arc. Contour interaction is shown by the reduction in percent correct letter identification for target-to-flanker separations smaller than approximately 3 min arc and is confirmed by a main effect of target-to-flanker separation ($F_{3.74,14.98} = 19.58$, $P < 0.0001$). Letter identification is systematically better in the presence of the wider (40% letter width) flanking bars with lower contrast, compared to the narrower (20% letter width) high-contrast flanking bars (main effect of flanker width, $F_{1,4} = 15.18$, $P = 0.018$). This reduction in the magnitude of contour interaction for the condition with the wider, lower-contrast flanking bars was apparent in the results of each individual observer.

Figure 1B presents results for 3 combinations of flanking-bar width and contrast corresponding to a contrast energy of 36%-min arc. For each of these flanking-bar conditions, the magnitude of foveal contour interaction is reduced in comparison to the results shown in Figure 1A. Nevertheless, a significant contour-interaction effect exists (main effect of target-to-flanker separation, $F_{6, 24} = 5.85$, $P = 0.0007$). ANOVA indicated a marginally significant effect of flanking-bar width ($F_{1.99,7.94} = 4.51$, $P = 0.049$), which is accounted for by a higher percentage of correct letter identification in the presence of flanking bars of 10% vs. 30% width ($F_{0.99,7.94} = 8.97$, $P = 0.017$). However, a clear difference in performance between the conditions with flanking bars of 10% and 30% width was seen in the results of only 3 of the 5 observers. None of the other comparisons between the different conditions of flanking-bar width achieved significance (all $P > 0.13$).

Results obtained for targets presented at 5 deg in the inferior field are presented in Figure 2. Contour interaction, exhibited as a reduction in percent correct letter identification compared to the no-flanking-bar condition, is apparent for target-to-flanker separations up to at least 35 min arc (main effects of target-to-flanker separation, seen in Figure 2A: $F_{2.55,10.21} = 26.02$, $P < 0.0001$; right panel: $F_{3.78,14.91} = 12.50$, $P < 0.0001$). Figure 2A also shows the magnitude of contour interaction is greater for narrower (20% letter width) flanking bars of high contrast than for wider (40% letter width) flanking bars with lower contrast (main effect of target-to-flanker separation, $F_{1,4} = 11.49$, $P = 0.028$). This bar-width dependence is apparent in the individual results of 4 of the 5 observers. The results in Figure 2B also indicate that, on average, the magnitude of contour interaction is greater for narrow (10% letter width), high contrast flanking bars than for wider (20% and 30% letter width) flanking bars with lower contrast. However, this difference is apparent only in the results of 3 of the 5 observers and ANOVA reveals no significant differences in the magnitude of contour interaction for the 3 different flanking-bar widths (main effect of flanker width, $F_{1.64, 6.57} = 3.01$, $P = 0.12$).

Figure 3A shows that flanking bars of -90% contrast and a width equal to 10% letter size produce a smaller magnitude of foveal contour interaction than wider flanking bars with the same high Weber contrast (main effect of flanker width, $F_{3,12} = 13.66$, $P = 0.0004$; flanker width x target-to-flanker separation interaction, $F_{18,72} = 10.80$, $P = 0.0001$). However, flanking bars of -90% contrast and widths equal to 20%, 30% and 40% of the letter size result in foveal contour-interaction functions that are indistinguishable statistically (main effect of flanker width, $F_{2,8} = 1.28$, $P = 0.33$). Similarly, at 5 deg in the inferior field (Figure 3B), flanking bars of -90% contrast and a width of 10% letter size generate significantly less contour interaction than flanking bars of 20% and 30% letter size (main effect of flanker width, $F_{1.30,5.18} = 25.45$, $P = 0.0029$; flanker width x target-to-flanker-separation interaction, $F_{16,64} = 12.19$, $P < 0.0001$). However, the contour-interaction functions for flanking bar widths equal to 20% and 30% of the letter size do not differ statistically (main effect of flanker width, $F_{1,4} = 0.93$, $P = 0.39$; flanker width x target-to-flanker separation interaction, $F_{5.64,22.56} = 1.70$, $P = 0.17$).[∞] The difference in exposure duration for one of the observers (HEB) did not result in noticeable differences in the respective contour interaction functions either foveally or in the periphery.

Comparison of Figures 1A and 1B suggests that the extent of foveal contour interaction decreases from ~4 min arc to between 2.5 and 3 min arc when the contrast energy of the flanking bars is reduced from -72%-min to -36%-min. When testing at an eccentricity of 5 deg

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[∞] Additional data obtained from 3 of the 5 observers at 5 deg in the inferior field for a flanking-bar width of 50% letter size and a contrast of -90% did not differ from the results shown in Figure 3 for flanking-bar widths of 20% and 30% of letter size.

(Figure 2), the range of target-to-flanker separations that we presented was not sufficient to allow an accurate assessment of the extent of contour interaction. However, Figure 2A suggests that the extent of contour interaction is substantially greater than 50 min arc when the flanking bars have a contrast energy of -317%-min, but not necessarily when the contrast energy was reduced to -158%-min. In addition, the results shown in Figure 2B suggest that the extent of peripheral contour interaction may be greater for narrow, high (-90%) contrast flanking bars, compared to wider flanking bars with lower (-45% and -30%) contrast. However, no similar difference in extent is seen in Figure 1B for flanking bars of different width and the same contrast energy.

Discussion

Few previous studies addressed the dependence of either foveal or peripheral contour interaction on flanking-bar contrast. Takahashi[6] reported that the magnitude of foveal contour interaction decreases systematically as the *luminance* of the flanking bars is reduced in comparison to a central 2-line resolution target. Although we are aware of no studies that examined the influence of flanking-bar contrast on peripheral contour interaction, a few investigators assessed the impact of flanker contrast on peripheral *crowding*. Using spatially-filtered letters at an eccentricity of 5 deg, Chung, Levi and Legge[25] found that the magnitude of crowding, specified as the increase in contrast required to identify a central target letter, varies according to the contrast ratio between the central letter and the surrounding flankers. These authors reported that crowding occurs only when the contrast of the flanking stimuli is equal to or greater than the central target. Pelli, Palomares & Majaj[26] also defined crowding as the elevation of the contrast threshold for identifying a target letter between two flanking letters, at an eccentricity of 4 deg. For small flanker-to-target separations, crowding occurred when the contrast of the flanking letters was lower than that of the target and saturated when the contrast of the flankers reached only 25%. Kooi, Toet, Tripathy and Levi[27] as well as Rashal &

Yeshurun[28] reported that peripheral crowding varies according to the relative contrast of the target letter and the surrounding flanking letters. Both the magnitude and extent of crowding were larger when the contrast of the target letter was less than the flanking stimuli, but these studies also reported significant crowding at small flanker-to-target separations when the contrast of the target was greater than the flanking stimuli, by ratios of 3:1 and 2:1, respectively.

Only one of the studies cited above explicitly examined the influence of flanking-stimulus contrast energy on crowding. Pelli et al.[26] measured crowding for 0.32 deg letter targets that were surrounded by high-contrast flankers ranging in size from 0.32 to 3.2 deg. The authors observed no systemic effect of flanker size (and, hence, contrast energy) on either the magnitude or the extent of crowding. This outcome is consistent with the absence of a significant flanker-size effect on contour interaction, as reported by Takahashi[6] for a foveal two-line resolution task, by Siderov et al.[15, 23] for foveally and peripherally presented letter targets, and as shown in Figure 3, above.

However, the results shown in Figures 1A and 2A indicate that flanking bars with moderate amounts of contrast energy (72%-min arc at the fovea and 317%-min arc at 5 deg in the inferior field) produce dissimilar magnitudes of contour interaction, depending upon their width. Specifically, significantly greater contour interaction is generated at each eccentricity by narrower flanking bars of higher contrast, compared to wider flanking bars of lower contrast. These results are consistent with Takahashi's[6] conclusion that the magnitude of contour interaction depends primarily on the position and contrast of the flanking-bar edges, rather than on their contrast energy.

On the other hand, the magnitude of contour interaction produced by flanking bars with lower contrast energy (36%-min arc at the fovea and 158%-min arc at 5 deg inferior field) does not depend strongly on the bar width. This outcome does not appear to be consistent with

Takahashi's conclusion.[6] The widths of the two high-contrast flanking bars used in Takahashi's experiment[6] were 1.4 and 4.3 min arc, the second of which is considerably wider than the flanking bars in our foveal higher-contrast-energy condition (Figure 1B). The average widths of the flanking bars in our principal experiment ranged from 0.4 to 1.6 min arc at the fovea, which are less than the reported widths of foveal Ricco's diameter.[16-22] At an eccentricity of 5 deg, the average widths of the flanking bars ranged from 1.76 to 7.04 min arc. Estimates of Ricco's diameter at an eccentricity of 5 deg range from 5.3[20] to approximately 20 min arc,[19, 22] with a median value of 14 min arc.

The possibility therefore exists that the widest flanking bars (40% letter size) we tested at 5 deg in the inferior field exceed Ricco's diameter.[20] If so, then the *summated* contrast energy of flanking bars with a contrast of -45% and a width of 40% letter size would have been less than the narrower flanking bars (20% of letter size) with -90% contrast. Hence, if Ricco's diameter at an eccentricity of 5 deg is smaller than 7.2 min arc, then the significant difference between the two contour-interaction functions shown in Figure 2A could reflect unequal magnitudes of summated contrast energy. However, we consider this possibility to be unlikely, as Levi and Klein[20] (p. 1982) suggested that differences between their estimates of Ricco's diameter and those of previous reports could be attributed to the low-pass temporal windowing that they imposed on their stimuli. Temporal windowing was not applied in the other studies of peripheral Ricco's diameter that we cite here,[19, 22, 29] or in our own experiments.

Although Figure 3 indicates that high-contrast flanking bars with a width equal to 20% of the letter size or larger produce essentially the same magnitude of contour interaction (see also Siderov et al.,[15, 23]), flanking bars with a width equal to 10% of the letter size generate a substantially reduced magnitude of contour interaction, both in the fovea and at 5 deg in the inferior field. We interpret this result to indicate that the magnitude of contour interaction produced by narrow flanking bars depends primarily on their contrast energy. However, for flanking bars that exceed a specific value of contrast energy (approximately 70%-min arc in the fovea and 320%-min at an eccentricity of 5 deg), the magnitude of contour interaction no longer increases in accordance with the contrast energy of the flanking bars but depends only on the flanking-bar contrast.

Figure 4 presents this interpretation of our results in graphical form. As shown on the left side of the plot, little or no contour interaction is expected for high-contrast letter targets when the contrast energy of the flanking bars is low. The magnitude of contour interaction increases as the contrast energy of the flanking bars becomes greater[25, 27, 28] and, in agreement with the results in Figures 1B and 2B, above, follows essentially the same relationship for different combinations of flanking-bar width and contrast. However, as depicted on the right side of Figure 4, at high levels of flanking-bar contrast energy the magnitude of contour interaction achieves an asymptotic value that depends on flanking-bar contrast, and not contrast energy (Figures 1A and 2A, and Figure 3). Although the specific values of contrast energy and contrast corresponding to the different regions of Figure 4 should vary according to the retinal location, the results we obtained both foveally and peripherally are consistent with the relationships shown in Figure 4.

An alternative explanation for our results is that contour interaction depends primarily on the contrast of the flanking bars, regardless of their contrast energy, but the maximum *retinal-image* contrast of very narrow flanking bars is reduced by the optical point spread function (PSF). Matlab simulations using the image-processing toolbox confirm that the foveal flanking bars used to obtain the results in Figure 1B (i.e., with widths of 0.4, 0.8 and 1.2 min arc) produce almost the same peak retinal-image contrast after convolution with a Gaussian representation of the PSF (SDs = 0.75 and 1 min arc). Hence, the combinations of foveal flanking-bar width and contrast, which resulted in approximately similar magnitudes of contour interaction in Figure 1B, contain not only the same contrast energy but also essentially the same peak retinal-image contrast. Additional simulations using the foveal flanking-bar widths in Figure 1A indicate that flanking bars corresponding to 20% of letter size have a slightly higher retinal-image contrast than flanking bars with a width equal to 40% of letter size (-36% contrast vs. -32% contrast and -27% contrast vs. -25% contrast, using PSFs with SDs equal to 0.75 and 1 min arc, respectively). It is possible that the slightly greater peak retinal-image contrast of the flanking bars corresponding to 20% letter width is sufficient to generate a larger magnitude of foveal contour interaction, compared to wider (40% letter width) flanking bars with the same contrast energy.

However, the results we obtained at 5 deg in the inferior field are not consistent with an explanation of contour interaction that relies only on the flanking-bar contrast. Because little change occurs in the width of the PSF between the fovea and a retinal eccentricity of 5 deg,[30] the PSF would not be expected to exert a major influence on the peak retinal-image contrasts of the wider flanking bars (range: 1.8 to 7.04 min arc) used at that location. The data in Figure 2B indicate no significant differences in the magnitude of contour interaction, despite differences in the peak retinal-image contrast for the 3 tested combinations of flanking-bar width and contrast. Specifically, assuming a PSF with a SD of 1 min arc, the calculated peak retinal-image contrast ranges from -56% to -30% for flanking-bar widths of 10% and 30% of the letter size. We presume that the contrast energy of these peripheral flanking bars falls within the middle portion of Figure 4, where the magnitude of contour interaction depends not on peak retinal-image contrast but on contrast energy. In Figure 2A, high-contrast flanking bars with a width of 20% letter size yield a significantly greater magnitude of peripheral contour interaction than flanking bars with the same contrast energy and a width equal to 40% of the letter size. Calculated retinal-image contrasts for these two flanking-bar conditions (PSF SD = 1 min arc) are -83% and -45%, respectively. For these flanking bars with relatively high contrast energy, unequal retinal-image contrast would be expected to produce dissimilar magnitudes of contour interaction (right side of Figure 4). When the results shown in Figures 1A and 2A are considered in conjunction with our simulations of retinal-image contrast, we note that the difference in retinal-image contrast that is required to produce dissimilar magnitudes of contour interaction may not be the same in the fovea and peripherally, as the result of eccentricity-dependent differences in contrast processing (e.g., Georgeson[31]).

If the interpretation of our results shown in Figure 4 is correct, then the choice made by Flom et al.[5, 11] to assess contour interaction using flanking bars with a width equal to 20% of the threshold-sized letter was logical and fortuitous, as narrower bars would have produced substantially less contour interaction and wider bars would not have affected his results (Figure 3; also Siderov et al.,[15, 23]).

The results of this study probably have little direct impact on standard clinical testing of visual acuity, as the letters and flanking stimuli on virtually all clinical charts have the same stroke width and contrast. However, our results are generally consistent with reports that contour interaction decreases when flanking-bar contrast (and, hence, flanking bar contrast energy) is less than the contrast of the acuity target, compared to when the flanking bars and acuity target have the same contrast[32] (see also Chung, Levi & Legge[25]; Kooi et al.[27], 1994; Rashal & Yeshurun,[28] for similar results using crowding stimulus configurations). Under the reasonable assumption that contour interaction depends primarily on the luminance contrast of the flanking stimuli, our results also are in agreement with those of Ruttum & Covert[33], who reported that amblyopic children exhibited less contour interaction when tested using black HOTV optotypes surrounded by chromatic compared to black flanking bars. Contour interaction was least when the flanking bars were yellow, which would have had the least luminance contrast and, hence, contrast energy.

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Figure legends

Figure 1. Average percent correct letter identification for 5 observers at the fovea is plotted as a function of the target-to-flanker separation in min arc. Panel 1A. Results are shown for 2 combinations of flanking-bar width and contrast with a contrast energy of 72%-min arc: (1) flanking-bar width = 20% of the target letter size, flanking bar contrast = -90% and (2) flanking-bar width = 40% of the target letter size, flanking bar contrast = -45%. Significantly greater contour interaction occurs for the narrower, higher-contrast flanks. Panel 1B. Results are shown for 3 combinations of flanking-bar width and contrast with a contrast energy of 36%-min arc: (1) flanking-bar width = 10% of the target letter size, flanking bar contrast = -90%, (2) flanking-bar width = 20% of the target letter size, flanking bar contrast = -45%, and (3) flanking-bar width = 30% of the target letter size, flanking bar contrast = -35%. The magnitude of contour interaction is marginally greater when the flanking bar width is 30% compared to 10% of the target letter size. The positive or negative error bars plotted in the two panels represent standard errors (SEs) across the 5 observers. In panel 1A no error bars are shown for the condition, flanking-bar width = 20%, flanking-bar contrast = -45%, to minimize clutter. The SEs for this condition are similar to the other two conditions presented in this panel. The rightmost data point of each function at $x = NF$ indicates percent correct letter identification when there were no flanking bars.

Figure 2. Average percent correct letter identification for 5 observers at 5 deg in the inferior visual field is plotted as a function of the target-to-flanker separation in min arc. Panel 2A. Results are shown for 2 combinations of flanking-bar width and contrast with a contrast energy of 317%-min arc: (1) flanking-bar width = 20% of the target letter size, flanking bar contrast = -90% and (2) flanking-bar width = 40% of the target letter size, flanking bar contrast = -45%. Significantly greater contour interaction occurs for the narrower, higher-contrast flanks. Panel 2B. Results are shown for 3 combinations of flanking-bar width and contrast with a contrast

energy of 158%-min arc: (1) flanking-bar width = 10% of the target letter size, flanking bar contrast = -90%, (2) flanking-bar width = 20% of the target letter size, flanking bar contrast = -45%, and (3) flanking-bar width = 30% of the target letter size, flanking bar contrast = -30%. There are no statistically significant differences in the magnitude of contour interaction. The positive or negative error bars in both panels represent SEs across the 5 observers. In panel 2B no error bars are shown for the condition, flanking-bar width = 30%, flanking-bar contrast = -30%, to minimize clutter. The SEs for this condition are similar to the other two conditions presented in this panel. The rightmost data point of each function at *x* = *NF* indicates percent correct letter identification when there were no flanking bars.

Figure 3. Average percent correct letter identification for 5 observers for different flanking bar widths, plotted as a function of the target-to-flanker separation in min arc. Panel 3A. Results at the fovea for 4 flanking-bar widths (10 – 40% of letter size) and a flanking-bar contrast of -90%. Panel 3B**.** Results at 5 deg in the inferior visual field for 3 flanking-bar widths (10 – 30% of letter size) and a flanking-bar contrast of -90%. In each panel only the data obtained using the narrowest flanking bar width (10% of letter size) differ significantly from the other contour-interaction functions. Positive or negative error bars in each panel are SEs across the 5 observers. The rightmost data point of each function at *x* = *NF* indicates percent correct letter identification when there were no flanking bars.

Figure 4. Hypothetical relationships between the magnitude of contour interaction and flanking-bar contrast energy and contrast, based on the results presented in Figures 1 – 3. Flanking bars with low contrast energy are assumed to produce little or no contour interaction (left portion of the plot). For flanking bars with intermediate values of contrast energy, the magnitude of contour interaction is assumed to increase monotonically (middle portion of the plot), regardless of the actual values of flanking-bar contrast or width. For flanking bars with high contrast energy, the magnitude of contour interaction is assumed to achieve an asymptote that depends only on the

flanking-bar contrast (right portion of the plot). The x-axis depicts values of contrast energy used in our foveal experiments (Figures 1A and 3A) and the three curves represent predicted outcomes for flanking bars of different contrast. Data taken at the fovea are superimposed on the figure (closed circles). Similar relationships are assumed to exist between contour interaction, flanking-bar contrast energy and flanking-bar contrast both foveally and peripherally, except for the different values of contrast energy that correspond to the three portions of the plot.

Revised Figures for Bedell et al., OVS18419

- Figure 1A
- Figure 1B
- Figure 2A
- Figure 2B
- Figure 3A
- Figure 3B
- Figure 4

Figure 1A

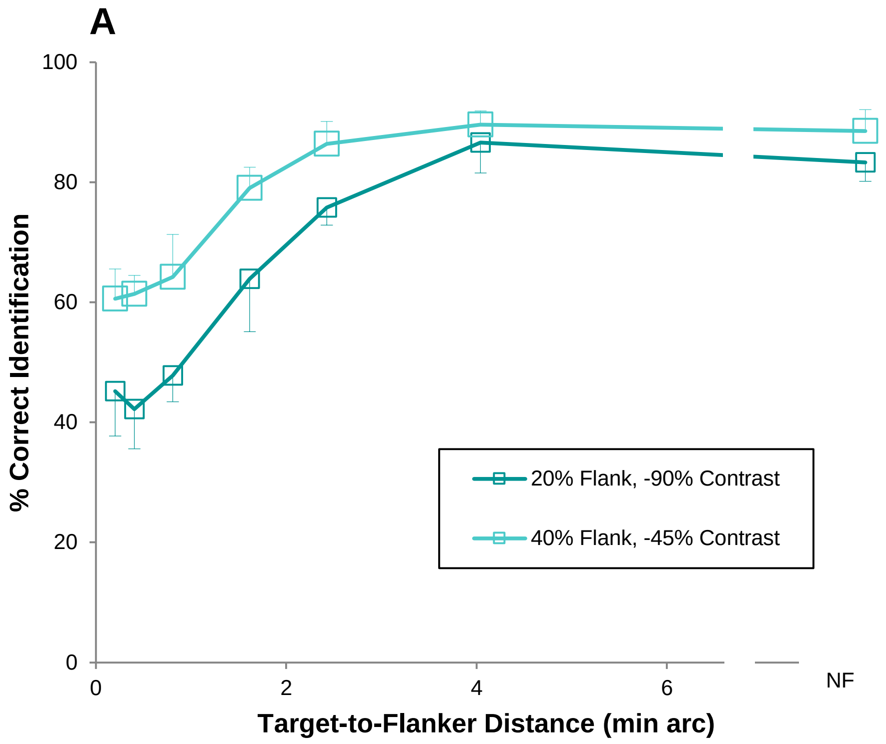

A
% Correct Identification
100
80
60
40
20
0
0
2
4
6
NF
Target-to-Flanker Distance (min arc)
20% Flank, -90% Contrast
40% Flank, -45% Contrast

Figure 1B

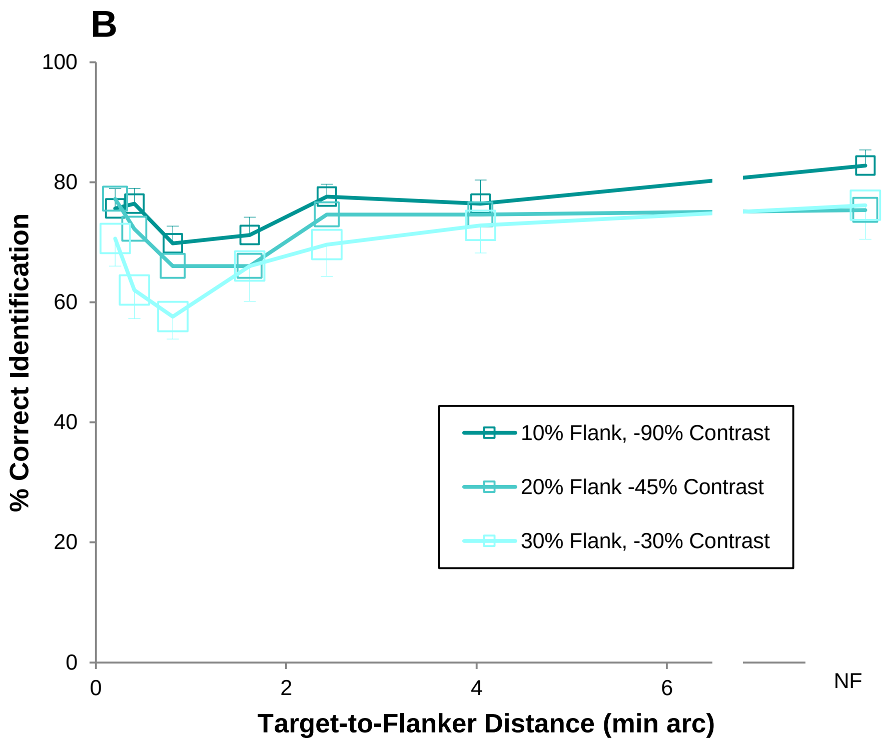

B
100
80
60
40
20
0
% Correct Identification
0
2
4
6
NF
Target-to-Flanker Distance (min arc)
10% Flank, -90% Contrast
20% Flank -45% Contrast
30% Flank, -30% Contrast

Figure 2A

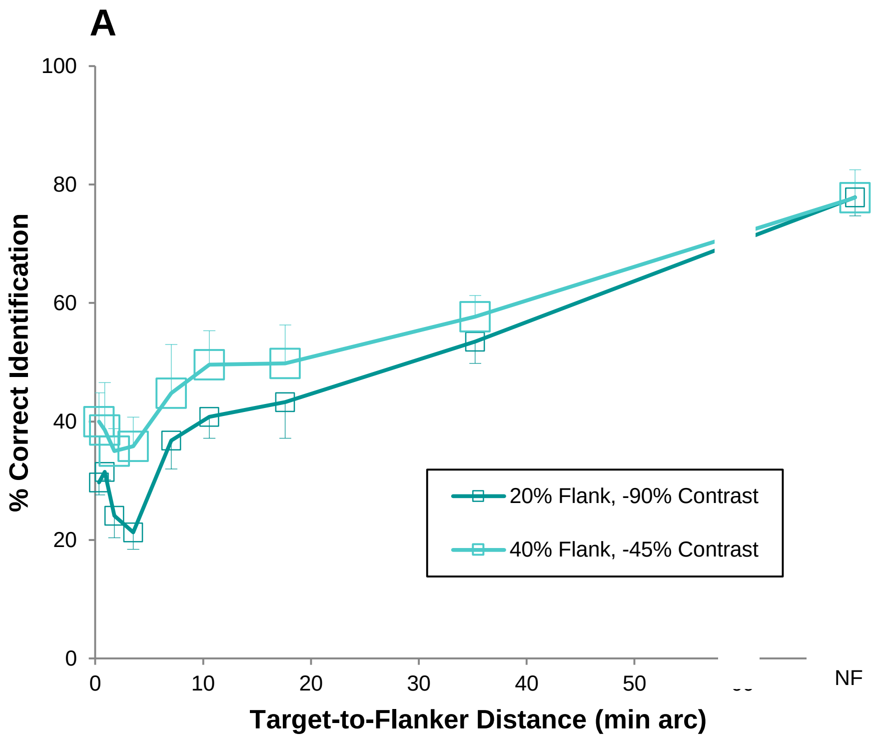

A
100
80
60
40
20
0
% Correct Identification
0
10
20
30
40
50
NF
Target-to-Flanker Distance (min arc)
20% Flank, -90% Contrast
40% Flank, -45% Contrast

Figure 2B

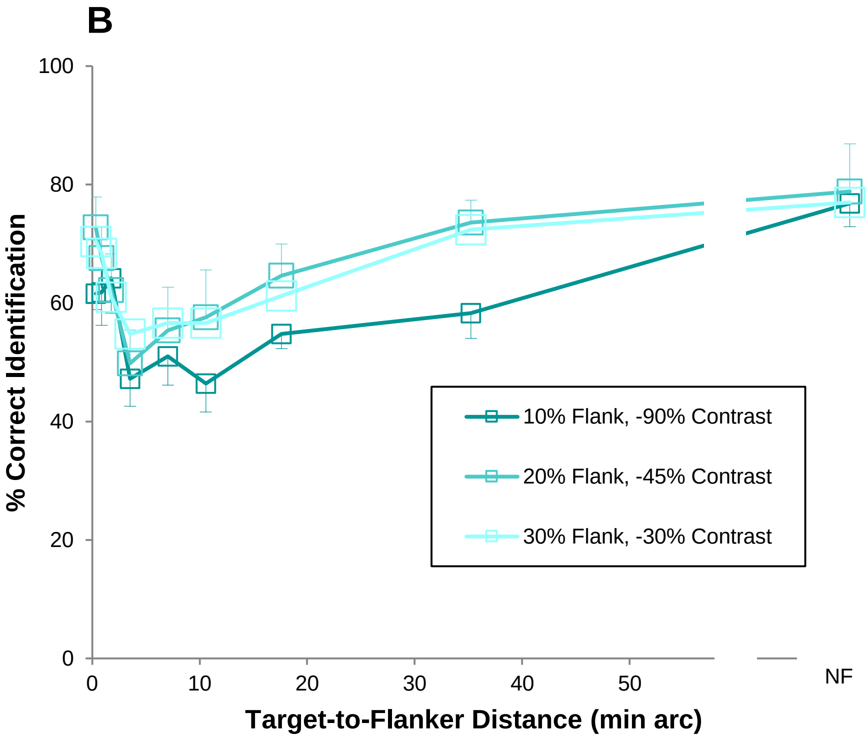

B
100
80
60
40
20
0
% Correct Identification
0
10
20
30
40
50
NF
Target-to-Flanker Distance (min arc)
10% Flank, -90% Contrast
20% Flank, -45% Contrast
30% Flank, -30% Contrast

Figure 3A

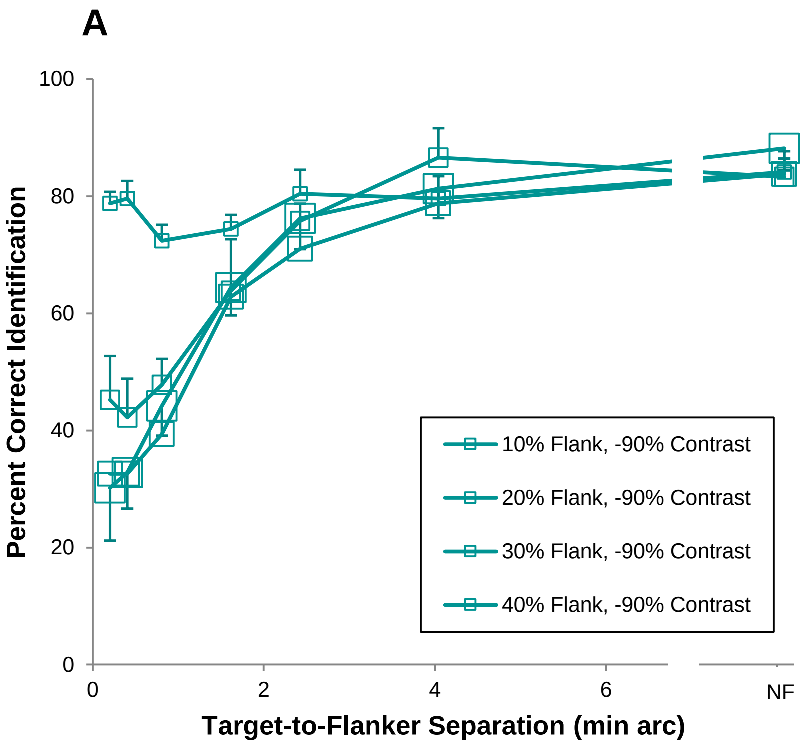

A
Percent Correct Identification
100
80
60
40
20
0
0
2
4
6
NF
Target-to-Flanker Separation (min arc)
10% Flank, -90% Contrast
20% Flank, -90% Contrast
30% Flank, -90% Contrast
40% Flank, -90% Contrast

Figure 3B

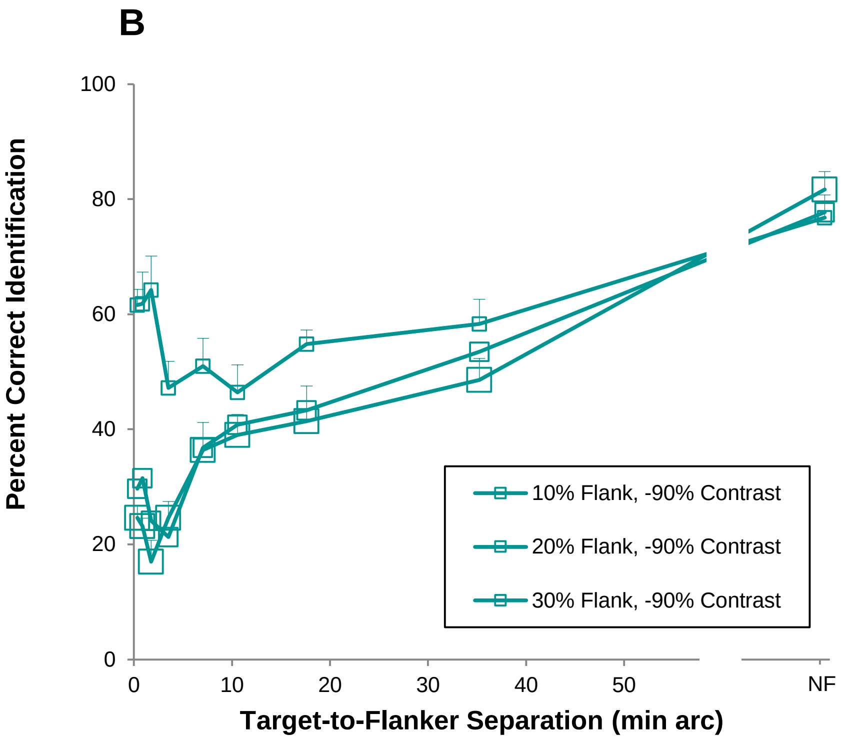
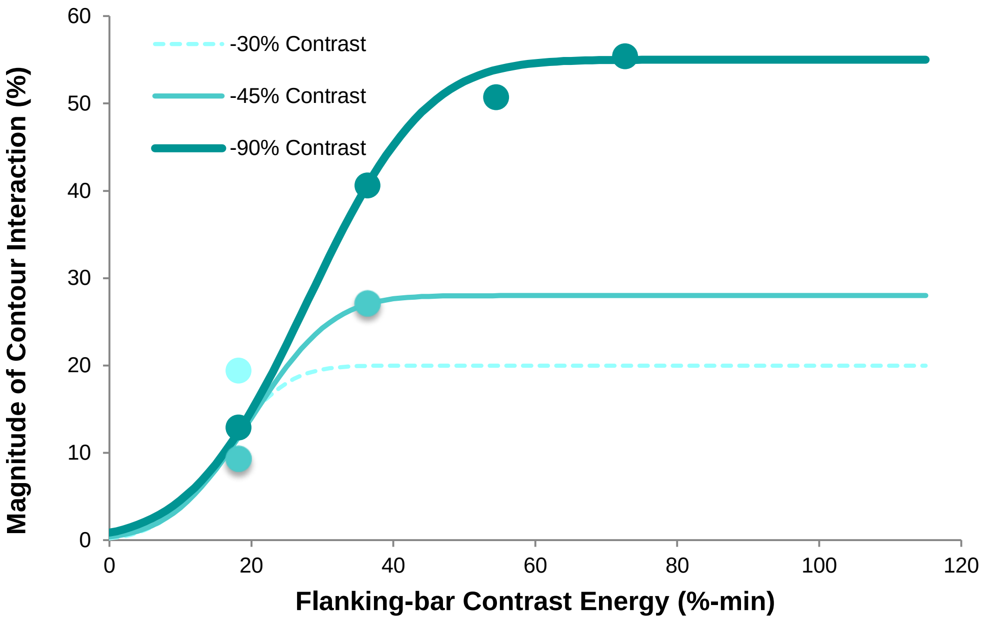

B
Percent Correct Identification
100
80
60
40
20
0
0
10
20
30
40
50
NF
Target-to-Flanker Separation (min arc)
10% Flank, -90% Contrast
20% Flank, -90% Contrast
30% Flank, -90% Contrast

Figure 4


60
50
40
30
20
10
0
Magnitude of Contour Interaction (%)
-30% Contrast
-45% Contrast
-90% Contrast
0
20
40
60
80
100
120
Flanking-bar Contrast Energy (%-min)