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Foveal contour interaction on the edge: Response to 'Letter-to-the-Editor' by Drs. Coates and  
Levi

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**Abstract**

Recently, we reported that, when considered as a function of the edge-to-edge target-to-flanker separation in min arc, the spatial extent of foveal contour interaction is the same for high and low contrast acuity targets. This result resolved an apparent discrepancy in the literature, which suggested that foveal contour interaction was absent or reduced for low contrast targets. In commenting on our results, Drs. Coates and Levi suggest a two-mechanism model for foveal crowding that depends on the center-to-center separation between the acuity target and flanking stimuli, and is based in part on a reanalysis of data from our recent work and a number of other studies. In our reply, we show that the spatial extent of foveal contour interaction for both high and low contrast targets is essentially unchanged by the width of the flanking targets when the target-to-flanker separation is depicted in terms of edge-to-edge separation, but varies systematically when depicted in terms of center-to-center separation. We therefore conclude that for foveal contour interaction in the range of a few min arc, edge-to-edge target-to-flanker separation is the more appropriate metric.

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Dear Editor,

We thank Drs. Coates and Levi (Letter to the Editor) for their thoughtful and extensive comments that relate to our recent study of foveal contour interaction for low contrast acuity targets (Siderov, Waugh & Bedell, 2013). The principal aim of our work was to clarify an apparent discrepancy in the literature that suggested foveal contour interaction was either greatly reduced or absent for low contrast stimuli (Kothe & Regan, 1990; Simmers, Gray, McGraw & Winn, 1999; Strasburger, Harvey & Rentschler, 1991), contrary to results found with high contrast foveal targets (e.g., Flom, 1991, Flom, Weymouth & Kahneman, 1963b) and with low contrast targets in peripheral vision (e.g., Coates, Chin & Chung, 2013; Pelli, Palomares & Majaj, 2004; Strasburger, Harvey & Rentschler, 1991; Tripathy & Cavanagh, 2002). Our results clearly show that a comparable magnitude of contour interaction occurs for low as well as high contrast foveal letter acuity targets within a fixed spatial extent, when measured in min arc (Fig. 1 of our paper). Following Flom, Weymouth & Kahneman (1963), we define the extent of contour interaction as the target-to-flanker separation beyond which little or no improvement in target identification occurs. As indicated in our paper, the results do not support an explanation for foveal contour interaction based on pattern masking, which would predict that the spatial extent of contour interaction should scale with the size of the acuity targets. In contrast, our results show that foveal contour interaction occurs over approximately the same angular extent for letter targets that differ in size by 0.4 log units. Recently, we reported a similar constant spatial extent of foveal contour interaction for acuity targets of different luminance that varied in size by approximately 0.5 log units (Bedell, Siderov, Waugh et al, 2013).

Coates and Levi note that our results appear to conflict with previous reports that the extent of foveal crowding found with relatively large, low contrast Gaussian or Gabor targets is proportional to the target size (Levi, Klein & Hariharan, 2002; Hariharan, Levi & Klein, 2005), in agreement with the prediction based on pattern masking. To resolve this apparent conflict, they advance a two-mechanism model for foveal crowding, wherein the extent of interaction,

or critical spacing, remains constant for acuity targets less than approximately 6 min arc and varies in proportion to the size of the target for larger stimuli (Ehrt & Hess, 2005; Levi, Song & Pelli, 2007).

Coates and Levi provide support for their proposal by reanalyzing the extent of contour interaction, or critical spacing, from several previous studies including ours; these data are plotted in their Figure 4 as a function of the center-to-center separation between the acuity target and flanking stimuli. Coates and Levi argued that center-to-center measurements are more appropriate than the edge-to-edge separation, irrespective of whether the stimuli are composed of Gabor or Gaussian targets, or are standard letter targets like those used in our and many other studies. Support for this argument comes from the demonstration by Levi and Carney (2009) in peripheral vision that increasing flanker width, without altering the edge-to-edge separation between the flankers and the acuity target, results in a reduced magnitude of crowding. The conclusion from this study was that flankers of different size produce the same extent of crowding when the center-to-center separation between the target and flankers remains the same. We do not disagree with the assertion made by Coates and Levi that center-to-center angular separation is appropriate to describe *peripheral* crowding, especially as our study addressed only foveal contour interaction. Nevertheless, we note that a number of previous authors defined target-to-flanker separation using an edge-to-edge criterion, including Coates and colleagues (Coates et al., 2013) in a recent paper that investigated contour interaction for targets of different contrast in the fovea and peripherally. As summarized in our paper, Takahashi (1968) reported the results of an experiment at the fovea that was conceptually similar to the one reported by Levi and Carney (2009) and concluded that contour interaction depends on the edge-to-edge separation between the target and flankers. Although Coates and Levi dismiss Takahashi's experimental stimuli as "idiosyncratic," it is of interest that they depict very similar stimuli in their Appendix Figure A1.

Coates and Levi defined the critical spacing by fitting cumulative Gaussian functions to the data for percent correct letter identification as a function of the flanker separation (their Figure

1). Although they express concern that the percentage correct letter identification in our measured contour interaction functions remains greater than the guessing rate of 10% for small flanker-to-target separations, there are neither theoretical nor empirical reasons (Bedell et al., 2013; Liu & Arditi, 2001; Loomis, 1978; Siderov et al., 2013; Simmers et al., 1999) why nearby flanking targets should reduce foveal letter identification to the level of chance, at least until the flankers and letter targets physically overlap (see the center panel in the bottom row of Fig. 1 and the lower left hand corner of Fig. 3 in Coates and Levi). Coates and Levi claim that a single function, which plots percent correct identification in terms of a spacing factor based on center-to-center spacing and the letter size, describes the results of the different contrast conditions reported by Siderov et al. (2013) (see Coates' and Levi's figure 2, which excludes the upturn in percent correct at the smallest letter-to-flanking-bar separation in the high-contrast condition) as well as the data for different luminance conditions presented by Bedell et al. (2013). Although the function proposed by Coates and Levi adequately describes the rising sections of both sets of contour interaction functions reported by Bedell et al. (2013), when all of the data for each contour-interaction function are included it is clear that the empirical results for the different luminances are shifted systematically along the spacing-factor axis (Figure 1). Hence, the function defined by Coates and Levi fails to capture the systematic reduction in the *magnitude* of foveal contour interaction as the luminance of the acuity stimulus is reduced.

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Insert Figure 1 about here

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Defining the appropriate metric for target-to-flanker separation is important because it speaks to the potential mechanism(s) of contour interaction. In addition to the results of Takahashi, there is evidence that in contrast to peripheral crowding (Levi & Carney, 2009) foveal contour interaction does not depend strongly on the width of the flanking targets. For example, Danilova and Bondarko (2007) showed that the extent of foveal contour interaction is essentially identical for Landolt C targets that are flanked by single bars, double bars,

additional Landolt Cs, or blocks of high spatial frequency square wave grating with a width that was equal to the letter size.

We assessed the influence of flanker size more systematically by measuring the magnitude and extent of foveal contour interaction for high and low contrast Sloan letters surrounded by bars that varied in width by a factor of twelve. To do so, we followed the methods described in our previous study, which can be summarized as follows. The stimuli were generated by a commercially available visual acuity test program (Test Chart 2000Pro; Thomson Software Solutions, Herts, UK) using a standard PC platform and were presented one at a time at the center of a 19" Dell monitor under dim ambient room illumination. Two of the authors, who participated also in our previous experiment, provided data. They viewed the monitor monocularly from an optical distance of 10.7 m after reflection from two front surface mirrors. High (-89%) or low (-7.8%) contrast dark Sloan letters were displayed either in isolation or were surrounded symmetrically by 4 flanking bars of equal contrast and length, but with a stroke width that varied among blocks of trials from 0.89 to 10.7 min arc. When presented, the inside edges of the flanking bars were 0 (abutting), 0.45, 0.89, 1.78, 2.68 or 4.50 min arc from the edge of the letter. Screen resolution was 1024 X 768 pixels (refreshed at 100 Hz) and stimuli were presented on a background luminance of 135 cd/m<sup>2</sup>. As in our previous study (Siderov et al., 2013), high and low contrast letters differed in size by 0.4 logMAR. The same angular edge-to-edge separations between the Sloan letters and the flanking bars were used in the high and low contrast conditions, corresponding to a maximum separation of 5 and 2 stroke widths, respectively, for the high and low contrast target conditions.

During each block of 25 trials, letters were presented in a random order. The letter-to-flanking bar separation was randomized between blocks and at least 2 blocks of each condition were completed for each observer. Because the data of the two observers were similar in all of the conditions, we present only the averaged results.

The percentage of correct responses for the high contrast condition is plotted as a function of flanker separation (min arc) in the left hand panels of Figure 2. The results for the low contrast condition are shown in the right hand panels. The two top panels plot flanker separation in terms of edge-to-edge distance, whereas the bottom panels show the flanker separation in terms of center-to-center spacing.

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Insert Figure 2 about here

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Consistent with our earlier report (Siderov et al., 2013), contour interaction is restricted to a spatial extent on the order of 3 – 5 min arc for both high and low contrast letter targets. Although the magnitude of contour interaction is slightly less for low than high contrast letters, this difference is likely to be attributable to the higher rate of correct letter identification for low compared to high contrast targets in the unflanked condition (85% vs. 80% correct).

The top panels in Figure 2 illustrate that the spatial extent of contour interaction is essentially uninfluenced by the width of the flanking targets when the target-to-flanker distance is plotted in terms of the edge-to-edge separation. On the other hand, the extent of interaction increases systematically with the width of the flanking stimulus when the data are plotted in terms of center-to-center separation. The conclusion is that edge-to-edge separation is the more parsimonious metric for describing foveal contour interaction, at least for targets of relatively small size (i.e., in the lower left region of the graph in Coates' and Levi's Figure 4). As shown by Coates and Levi in their Figure 1, if the critical spacing determined from the data of Siderov et al (2013) using a criterion of 80 - 85% correct (i.e., approaching the performance achieved in the unflanked condition) are replotted in terms of edge-to-edge separation, the extent of foveal contour interaction remains nearly constant for the three different letter sizes that were tested. A reanalysis of data reported by Waugh, Formankiewicz, Ahmad and Hairol (2010) also indicate that the spatial extent of contour interaction corresponds to an approximately constant edge-to-edge separation of approximately 5 – 6 min arc between a foveal Landolt C and flanking bars, both in the absence and presence of (+1.00 and +2.00 D) dioptric blur.



Our explanation for earlier reports that foveal contour interaction is greatly reduced or absent for low compared to high contrast targets differs subtly but significantly from the explanation offered by Coates and Levi. Instead of proposing that low contrast acuity targets exceed the critical center-to-center spacing for contour interaction, we suggested that previous authors failed to find robust contour interaction because the edge-to-edge spacing of their flanking targets exceeded the 3 – 6 min arc spatial extent of foveal contour interaction. Flom, Weymouth and Kahneman (1963) proposed that the extent of foveal contour interaction scales with the observer's visual acuity. Based on our results for foveal targets of low contrast and low luminance, we suggest a modification of this proposal: that the spatial extent of foveal contour interaction is proportional to the observer's *optimal* visual acuity, which we presume to be a reflection of the underlying neural processing scale.

In summary, we agree with the proposal that foveal contour interaction may be subserved at different spatial scales by different mechanisms. One mechanism appears to depend on interactions that occur between nearby edges and operates within a limited spatial extent that corresponds approximately to the size of a threshold high contrast acuity target. The second mechanism is presumed to be pattern masking, which occurs primarily at large center-to-center spacing between the target and flankers and was documented by Levi and colleagues (Levi et al., 2002; Hariharan et al. 2005). The more appropriate scaling metric for contour interaction (edge-to-edge vs. center-to-center) appears to differ for these two mechanisms. At present, it remains unclear to what extent this two-mechanism model for contour interaction and crowding can be applied profitably also to peripheral visual targets.

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## References

- Bedell, H.E., Siderov, J., Waugh, S.J., Zemanova, R., Pluhacek, F. & Musilova, L. (2013). Contour interaction for foveal acuity targets at different luminances. *Vision Research*, 89, 90-95.
- Coates, D.R., Chin, J.M. & Chung, S.T. (2013). Factors affecting crowded acuity: eccentricity and contrast. *Optometry & Vision Science*, 90, 628-638.
- Coates, D.R. & Levi, D.M. (submitted). Contour interaction in foveal vision: A response to Siderov, Waugh and Bedell (2013). *Vision Research*.
- Danilova, M.V., & Bondarko, V.M. (2007). Foveal contour interactions and crowding effects at the resolution limit of the visual system. *Journal of Vision*, 7 (2)
- Ehrt, O., & Hess, R.F. (2005). Foveal contour interaction: detection and discrimination. *Journal of the Optical Society of America A*, 22 (2), 209-216.
- Flom, M.C., Weymouth, F.W., & Kahneman, D. (1963b). Visual resolution and contour interaction. *Journal of the Optical Society of America*, 53 (9), 1026-1032.
- Hariharan, S., Levi, D.M., & Klein, S.A. (2005). "Crowding" in normal and amblyopic vision assessed with Gaussian and Gabor C's. *Vision Research*, 45, 617-633.
- Kothe, A.C., & Regan, D. (1990). Crowding depends on contrast. *Optometry and Vision Science*, 67 (4), 283-286.
- Levi, D.M., Klein, S.A., & Hariharan, S. (2002). Suppressive and facilitatory spatial interactions in foveal vision: foveal crowding is simple contrast masking. *Journal of Vision*, 2(2):2, 140-166.
- Levi, D.M., Song, S. & Pelli, D.G. (2007). Amblyopic reading is crowded. *Journal of Vision*, 7(2):21, 1-17.S
- Liu, L. & Arditi, A, (2001). How crowding affects letter confusion. *Optometry & Vision Science*, 78 (1), 50-55.
- Loomis, J.M. (1978). Lateral masking in foveal and eccentric vision. *Vision Research* 18 (3), 335-338.

Pascal, E., & Abadi, R.V. (1995). Contour interaction in the presence of congenital nystagmus. *Vision Research*, 35 (12), 1785-1789.

Pelli, D.G., Palomares, M., & Majaj, N.J. (2004). Crowding is unlike ordinary masking: distinguishing feature integration from detection. *Journal of Vision*, 4, 1136-1169.

Siderov, J., Waugh, S.J. & Bedell, H.E. (2013). Foveal contour interaction for low contrast acuity targets. *Vision Research*, 77: 10-13.

Simmers, A.J., Gray, L.S., McGraw, P.V., & Winn, B. (1999). Contour interaction for high and low contrast optotypes in normal and amblyopic observers. *Ophthalmic and Physiological Optics*, 19 (3), 253-260.

Strasburger, H., Harvey, L.O., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception and Psychophysics*, 49 (6), 495-508.

Takahashi, E.S. (1968). Effects of flanking contours on visual resolution at foveal and near-foveal loci. *PhD Thesis: School of Optometry*, PhD (Berkeley): University of California.

Tripathy, S.P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research*, 42, 2357-2369.

Waugh, S.J., Formankiewicz, M.A., Ahmad, N. & Hairol, M.I. (2010). Effects of dioptric blur on foveal acuity and contour interaction for noisy Cs. *Journal of Vision*, 10(7): 1330.

## Figure Captions

Figure 1. Average percentage correct foveal letter identification for five observers at Anglia Ruskin University (top) and five observers at Palacky University (bottom) are replotted from Bedell et al. (2013) for four luminance conditions (different shaded symbols representing 0,1,2 and 3ND filter conditions). The left- and right-hand panels plot the data in terms of the center-to-center target-to-flanker separation and in terms of the Spacing Factor proposed by Coates and Levi, respectively. Data for the unflanked condition are represented on the abscissae at 'INF' in the left-hand panel and at '1.5' in the right-hand panel. Error bars are omitted to prevent clutter. In contrast to the original plots from Bedell et al. (2013, Fig. 1) in terms of edge-to-edge spacing, note the systematic rightward shift of the contour-interaction functions in all of the panels as the target luminance is reduced.

Figure 2. Percentage correct responses averaged across two observers and plotted as a function of the angular edge-to-edge target-to-flanker separation (top panels) and center-to-center target-to-flanker separation (bottom panels) for 4 different widths of the flanking bars (different size symbols). The left and right hand panels present results for high and low contrast letter targets, respectively. Data at 'INF' on the abscissae represent the unflanked condition.

Figure 1  
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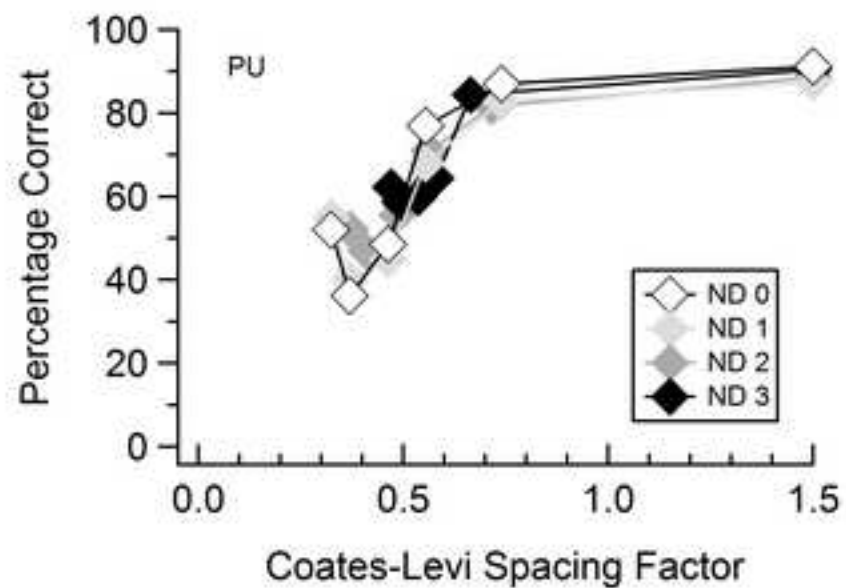
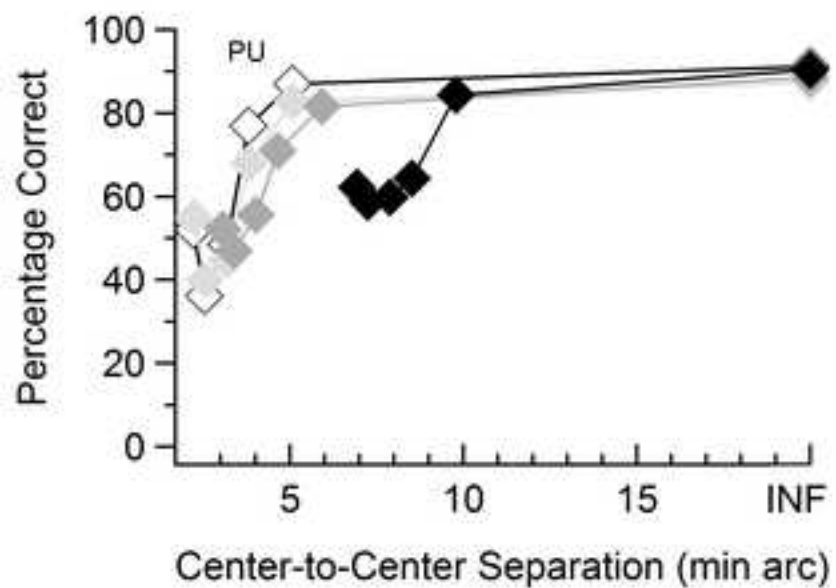
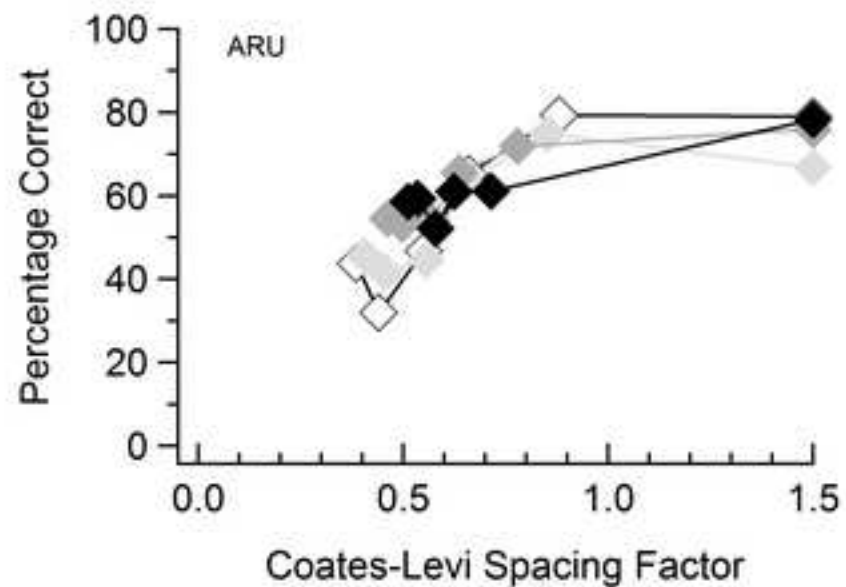
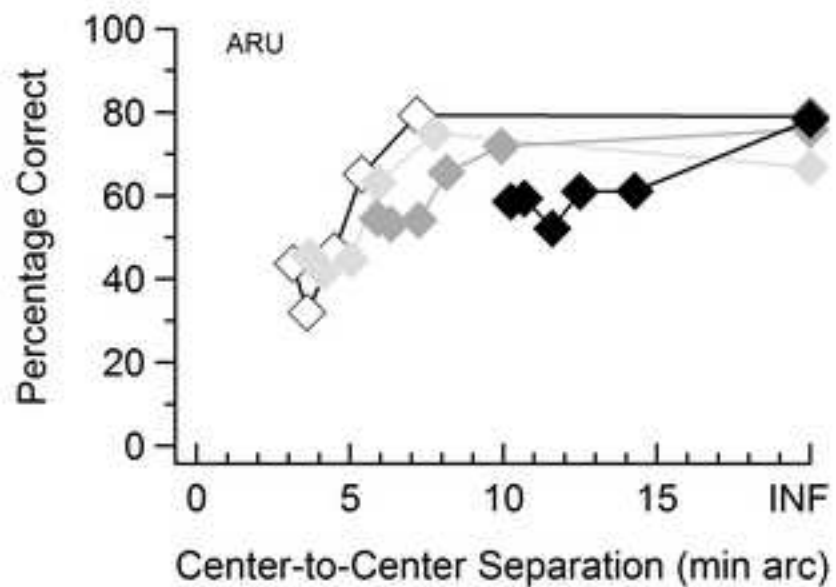


Figure 2  
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