

## Upturn of the Contour-Interaction Function at Small Flanking Bar-to-Target Separations

John Siderov,<sup>1a</sup> František Pluháček<sup>b</sup> and Harold E. Bedell<sup>c</sup>

<sup>a</sup>Department of Vision and Hearing Sciences, Anglia Ruskin University, Cambridge, CB1 1PT, UK

<sup>b</sup>Department of Optics, Palacký University Olomouc, 77146 Olomouc, Czech Republic

<sup>c</sup>College of Optometry, University of Houston, Houston Texas 77204-2020, USA

<sup>1</sup>Corresponding author and present address

Dr John Siderov, Department of Optometry and Vision Sciences, University of Huddersfield, HD1 3DH United Kingdom

Email: [j.siderov@hud.ac.uk](mailto:j.siderov@hud.ac.uk)

Phone +44 (0) 1484 471331

Other Authors' e-mail addresses

Harold Bedell: [HBedell@optometry.uh.edu](mailto:HBedell@optometry.uh.edu)

František Pluháček: [Frantisek.Pluhacek@upol.cz](mailto:Frantisek.Pluhacek@upol.cz)

## **Abstract**

Nearby flanking bars degrade letter identification and resolution, a phenomenon known as contour interaction. However, many previous studies found that the relationship between foveal letter identification and flanker separation is non-monotonic, with an upturn in performance at very small target-to-flanker separations. Here, we replicate this observation and show that a similar upturn occurs also for targets presented at 5 deg in the inferior field, if the target-to-flanker separation is sufficiently small. The presence and magnitude of the observed performance upturn depends on the flanking-bar width, being more evident for narrower compared to wider flanking bars. We interpret our results to indicate that neural interactions between nearby contours reduce performance when the target and flanking bars form discrete neural images. At sufficiently small separations, the images of the target and flanking bars can not be distinguished and performance is governed by the contrast of the target in the blended neural image.

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

## 1. Introduction

Contour interaction is a degradation of form processing or visual resolution that is attributable to nearby flanking bars (Flom, Weymouth & Kahneman, 1963, Takahashi, 1968). When more complex flanking targets are used, or when inaccurate eye movements or inappropriate deployment of attention contribute to the degradation, the interaction is known as crowding (Bedell, Siderov, Formankiewicz, Waugh & Aydin, 2015, Flom, 1991). Both contour interaction and crowding can be characterized by an *extent*, i.e., the largest target-to-flanker separation at which performance is impaired, and a *magnitude*, i.e., the maximum degradation in performance that occurs, compared to the condition without flanking targets. The extent of contour interaction and crowding is only a few min arc at the fovea, but increases substantially when the target and flanking stimuli are presented in peripheral vision (Bouma, 1970, Coates, Chin & Chung, 2013, Musilová, Pluháček, Marten-Ellis, Bedell & Siderov, 2018a, Toet & Levi, 1992).

Although crowding typically produces a monotonic worsening of performance as the target-to-flanker separation is reduced (Coates et al., 2013, Danilova & Bondarko, 2007, Formankiewicz & Waugh, 2013, Marten-Ellis & Bedell, 2015) foveal contour interaction functions are not necessarily monotonic. For example, each of the three normal eyes studied by Flom et al (1963) exhibited an improvement in the percentage of correct responses for very small target-to-flanker separations, on the order of 1 min arc and less. A similar upturn in the percentage of correct responses can be seen in the data of three of the four amblyopic observers in the same study. However, as the size of the threshold acuity letter is larger in amblyopic than normal eyes, the upturn tended to occur at larger target-to-flanker separations, which ranged from approximately 1 to 4.5 min arc. The existence of similar upturns in the contour interaction function at different target-to-flanker separations in normal and amblyopic eyes suggests that contour interaction has a neural rather than optical basis.

Many subsequent studies of foveal contour interaction also reported an upturn in performance at small, target-to-flanker separations (Bedell, Siderov, Waugh, Zemanová, Pluháček & Musilová, 2013, Chung & Bedell, 1995, Danilova & Bondarko, 2007, Hess, Dakin, Kapoor & Tewfik, 2000, Jacobs, 1979, Musilová, Pluháček, Bedell & Siderov, 2018b, Siderov, Waugh & Bedell, 2013, Siderov, Waugh & Bedell, 2014,

Simmers, Gray, McGraw & Winn, 1999). Contour interaction is investigated less frequently in peripheral vision, and an upturn in performance at small target-to-flanker separations is reported only rarely (Hess et al., 2000, Jacobs, 1979, Wolford & Chambers, 1984).

Following the seminal study by Flom et al. (1963), the flanking bars used in most studies of contour interaction have a width equal to one fifth of the target letter size, or one stroke width. Siderov et al. (2014) compared foveal contour interaction functions with flanking bars that ranged in width from one to 12 stroke widths. The resulting contour interaction functions were similar, with the exception that only the function obtained using one-stroke-width flanking bars exhibited an upturn at small target-to-flanker separations. A follow-up study that measured contour interaction at eccentricities of 2.5 and 5 deg also reported very similar contour-interaction functions for flanking bars that ranged from one to 8 stroke widths, except that there was no evidence of an upturn at small target-to-flanker separations in any of the functions (Siderov, Beltrao, Gratao de Moraes, Morgado, Bedell & Waugh, 2015).

Takahashi (1968) investigated contour interaction using a two-line resolution target, flanked on each side by additional bar stimuli. As the flanking bars were placed closer to the central resolution target, resolution initially worsened compared to the condition with no flanking bars. However, as the target-to-flanker separation continued to decrease, two-line resolution improved, becoming better than the threshold obtained in the absence of any flanking targets. Additional measurements with the two-line resolution target at horizontal eccentricities of 0.54 and 1.05 deg revealed both a greater magnitude of threshold elevation and extent of contour interaction than at the fovea. However, approximately the same range of narrow target-to-flanker separations resulted in improved resolution at eccentricities of 0.54 and 1.05 deg and at the fovea. Takahashi concluded that the elevation of the resolution threshold produced initially by flanking bars represents a neural interaction. However, because improved resolution occurred for the nearly same range of small target-to-flanker separations at the eccentricities she tested, Takahashi proposed an optical basis for this upturn in performance, specifically a reduction of scattered light.

Coates, Levi, Touch & Sabesan (2018) investigated foveal crowding using a tumbling E target surrounded by 4 flanking E's. Their data reveal an upturn in performance at target-to-flanker separations smaller than 1 min arc, both with and without adaptive-optics (AO) correction of the observers' higher order optical aberrations. These results suggest that, at least for the type of targets used by Coates et al., the upturn in performance at small target-to-flanker separations is unlikely to be the result of optical blurring.

Nevertheless, if optics do contribute to the upturn in performance that occurs at small target-to-flanker separations in (non-AO-corrected) foveal contour-interaction functions, then this upturn may be absent from non-foveal contour-interaction functions because of the way that optotype- and flanking-bar size are scaled when measuring contour interaction non-foveally. In particular, the width of the retinal point-spread function remains nearly constant within the central  $\pm 10$  deg of the retina (Navarro, Artal & Williams, 1993, Navarro, Moreno & Dorronsoro, 1998). Thus, within the central  $\pm 10$  deg of the retina or so, any optical influence on the contour interaction function would be expected to be manifested within approximately the same small angular extent. However, because the angular subtense of a threshold acuity letter increases systematically from less than 5 min arc at the fovea to approximately 25 min arc at an eccentricity of 10 deg (Jacobs, 1979, Mandelbaum & Sloan, 1947, Musilová et al., 2018) both the width of the flanking bars and the range of target-to-flanker separations tested increase systematically with eccentricity from the fovea. Interestingly, Takahashi (1968) observed very similar threshold-elevating and threshold-lowering effects on foveal resolution thresholds using pairs of flanking bars with different widths (range 1.4, to ~55 min arc; her Figure 36).

The principal aim of this study was to examine contour interaction for letter targets using a similar range of narrow target-to-flanker separations at the fovea and at an eccentricity of 5 deg. Limited additional data were obtained at eccentricities of 2.5 and 10 deg. In addition, we sought to assess the influence of the flanking-bar width on contour interaction within the range of small target-to-flanker separations.

## 2. Methods

## 2.1 Observers

The observers in this experiment were 3 males and 2 females (3 naïve, age range 30-69 years old) who reported no ocular pathology and had normal or corrected-to-normal visual acuity in each eye. The study was conducted in accordance with the tenets of the Declaration of Helsinki and received prior approval from the Anglia Ruskin Research Ethics committee. Each observer voluntarily provided written informed consent before participating.

## 2.2 Stimuli

Dark Sloan letters (C D H K N O R S V Z) with a Weber contrast of -90% were presented on a white background, either in isolation or surrounded symmetrically on 4 sides by flanking bars. Each flanking bar had a length equal to the height or width of the central Sloan letter. The width of the flanking bars ranged from one half of a letter stroke (10% of letter height) to two letter strokes (40% of letter height) during testing at the fovea and from one half of a letter stroke to one and a half letter strokes (30% of letter height) for testing at an eccentricity of 5 deg in the inferior visual field. Additional data were obtained for 3 of the 5 observers at the 5-deg eccentricity for a flanking-bar width equal to two and a half letter strokes (50% of letter height). The 4 flanking bars used in each experimental condition were always identical. Stimuli were generated using custom software written by author FP and presented on a flat-screen display that measured 48.5 cm diagonally, with 1280 x 1024 pixel resolution; each pixel was 0.32 mm in size and subtended 0.073 and 0.63 min arc at the 15 and 1.75 m test distances, respectively). Background luminance was 182 cd/m<sup>2</sup> and ambient illumination in the experimental room remained dim. The exposure duration of each stimulus presentation was unlimited for author HB and restricted to 250 ms for the other 4 observers.

## 2.3 Procedures

Testing was conducted monocularly 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. No artificial pupil was imposed and the untested eye was covered with an opaque occluder. Letters were presented one at a time at the center of the display. The observer identified each presented letter by typing his or her response on the computer keyboard. Stimuli were presented either at the

fovea or at 5 deg in the inferior visual field. Additional testing was conducted with observers HEB and JS at eccentricities of 2.5 and 10 deg, also in the inferior visual field. For foveal testing, the stimuli were viewed from an optical distance of 15 m, including reflection from a front-surface mirror. For testing at an eccentricity of 5 deg, the stimuli were viewed without reflection from a distance of 1.75 m. Additional testing of observers HEB and JS at eccentricities of 2.5 and 10 deg was performed, respectively, at viewing distances of 3.5 and 1.75 m. Non-foveal testing was performed by directing the observers' fixation to a small target that was located at the appropriate angular distance above the center of the display.

Preliminary sets of trials, in which the letters were presented without any flanking bars, established the letter size required for each observer to achieve approximately 80% correct identification responses at each tested eccentricity. Averaged across the 5 observers, the average letter sizes used at the fovea and at 5 deg inferior field were  $4.0 \pm 0.36$  (SE) min arc and  $17.6 \pm 1.5$  min arc, respectively. The average letter sizes used for observers HB and JS at eccentricities of 2.5 and 10 deg were  $9.0 \pm 1.0$  and  $25.7 \pm 5.8$  min arc. Subsequently, percent correct letter identification was determined in the absence of flanking bars and for either 6 (foveally) or 8 (at locations in the inferior field) edge-to-edge separations between the letter and the surrounding flanking bars. Data were obtained for target-to-flanker separations between 5% and 100% of the letter size at the fovea (approximately 0.2 to 4 min arc) and between 2% and 200% of the letter size at an eccentricity of 5 deg (approximately 0.35 to 35 min arc). At each eccentricity, performance was determined for the different widths of the flanking bars in separate blocks of trials.

#### *2.4 Simulations*

Simulations were performed in MATLAB using the image-processing toolbox to assess the influence of neural summation within putative visual receptive fields on target appearance for a sample of the letter and flanking-bar stimuli used in this study. The region of neural summation was represented in our simulations by psychophysically determined estimates of Ricco's diameter, taken from the vision literature. Because the stimuli used to estimate Ricco's diameter undergo optical degradation within the eye, virtually all psychophysical estimates of Ricco's diameter include the combined

influence of visual receptive field size and the width of the optical point spread function. Recently, Tuten, et al. (Tuten, Cooper, Tiruveedhula, Dubra, Roorda, Cottaris, Brainard & Morgan, 2018) reported that Ricco's diameter measured at the fovea is essentially the same without and with adaptive-optics correction of ocular aberrations, indicating that the optical contribution to Ricco's area at the fovea is close to negligible. Although Ricco's area increases systematically with retinal eccentricity (Inui, Mimura & Kani, 1981, Khuu & Kalloniatis, 2015, Kwon & Liu, 2019, Levi & Klein, 1990, Smith & Cass, 1989, Volbrecht, Shrago, Scheffrin & Werner, 2001, Wilson, 1970), retinal image quality changes little within the central  $\pm 10$  deg (Navarro et al., 1993, Navarro et al., 1998). Therefore, the contribution of the retinal point spread function to Ricco's area should be even smaller for non-foveal retinal locations.

The letter sizes used for our simulations were 4 min arc at the fovea and 17.6 min arc at an eccentricity of 5 deg in the inferior visual field. Published estimates of Ricco's diameter vary widely, between 1.8 (Levi & Klein, 1990) and 12.1 min arc (Khuu & Kalloniatis, 2015) at the fovea, and between 4.0 (Levi & Klein, 1990) and 20.0 min arc (Volbrecht et al., 2001) at an eccentricity of 5 deg (Table 1). For our simulations we used the median of the reported values for Ricco's diameter at the fovea (Blackwell, 1946; Chung, Levi & Bedell, 1996, Dalimier & Dainty, 2010, Davila & Geisler, 1991, Inui et al., 1981, Glezer, 1965; Khuu & Kalloniatis, 2015, Levi & Klein, 1990, Tuten et al., 2018, Volbrecht et al., 2001) and at an eccentricity of 5 deg (Inui et al., 1981, Khuu & Kalloniatis, 2015, Kwon & Liu, 2019, Levi & Klein, 1990, Smith & Cass, 1989, Volbrecht et al., 2001, Wilson, 1970). For studies that assessed Ricco's diameter at peripheral locations that did not include 5 deg, we obtained a value for an eccentricity of 5 deg either using the authors' best-fit line to Ricco's diameter as a function of eccentricity or by linear interpolation. The median values of Ricco's diameter were 3.0 min arc at the fovea and 8.9 min arc at an eccentricity of 5 deg. Mean values from the studies cited above were 35% (eccentricity = 5 deg) to 73% (fovea) larger. To perform simulations, we assumed that neural summation occurs within a Gaussian profile and used the relationship proposed by Levi & Klein (1990) to determine the standard deviation (SD) associated with the median estimates of Ricco's diameter:  $SD = \text{Ricco's diameter} / \sqrt{2\pi}$ . The results of convolving representative contour-interaction stimuli with



Gaussian profiles having SDs of 1.18 (fovea) and 3.57 min arc (5 deg inferior visual field) are presented in Figure 3, below.

Insert Table 1 about here

### 2.5 Data Analyses

Separate repeated-measures ANOVAs were performed on the aggregated results of the 5 observers for the combinations of target-to-flanker separation and flanking-bar width that were examined at each eccentricity. For each ANOVA, the various target-to-flanker separations were represented as percentages of the target-letter size. However, to plot the results in Figs. 1 and 2, below, these target-to-flanker separations were converted to min arc and averaged across observers. All statistical analyses were performed using SuperANOVA software (Abacus Concepts, Berkeley, CA, USA). If necessary, Huynh-Feldt corrections were applied for significant departures from sphericity. The inclusion of a correction for sphericity is indicated by the reporting of fractional values of degrees of freedom in the Results section, below.

### 3. Results

The left side of Figure 1 presents the average percent correct letter identification at the fovea as a function of the target-to-flanker separation, in min arc, for widths of the flanking bars that range from 10% to 40% of the letter size. The variability (standard error) in the average percent correct performance and in the average target to flanker separations across observers is indicated by vertical and horizontal error bars, respectively. Foveal contour interaction is revealed by a significant reduction in percent correct for target-to-flanker separations less than approximately 3 – 4 min arc ( $F_{df=2.4,9.5} = 32.28$ ,  $p < 0.0001$ ). Clearly, the magnitude of contour interaction increases with the width of the flanking bars (flanker width x separation interaction,  $F_{df=18,72} = 10.81$ ,  $p < 0.0001$ ). In addition, when the flanking-bar width is equal to 10% of the letter size an upturn in performance is apparent at the two smallest target-to-flanker separations (0.2 and 0.4 min arc). A smaller upturn may be seen (present in the individual results of 3 of the 5 observers) when the width of the flanking bars is equal to 20% of the letter size, or one stroke width. Wider flanking bars result in a monotonic worsening of percent correct

letter identification as the target-to-flanker separation decreases from 100% to 5% of the target letter size.

The right side of Figure 1 shows comparable data obtained at an eccentricity of 5 deg. At this eccentricity, percent correct letter identification is impaired for target-to-flanker separations of at least 40 min arc. However, a clear upturn in percent correct letter identification is observed for the narrowest two target-to-flanker separations, which correspond to 0.35 and 0.88 min arc, when the width of the flanking bars is equal to 10% of the letter size. As at the fovea, the magnitude of contour interaction becomes greater as the width of the flanking bars increases from 10% to 20% and 30% of the letter size (flanker width x separation interaction,  $F_{df=12.4,49.7} = 10.43$ ,  $p < 0.0001$ ). Even so, small improvements in performance are evident at the two narrowest target-to-flanker separations when the flanking-bar width is 20% and 30% of the letter size (present in the data of 4 of the 5 observers for each bar-width condition). The lowest function in the right side of Figure 1 shows data for just 3 of the 5 observers when the flanking-bar width is increased to 50% of the letter size. Performance is better for the target-to-flanker separations of 0.35 and 0.88 min arc, compared to 1.6 min arc for all 3 observers.

Figure 2 shows the averaged data for observers HEB and JS for eccentricities of 0 – 10 deg when the width of the flanking bars is equal to 10% of the letter size. The plots are presented on a logarithmic x-axis to alleviate compression of the functions at the small target-to-flanker separations. **As in Fig 1., variability (standard error) in the average percent correct performance and in the average target to flanker separations across observers is indicated by vertical and horizontal error bars, respectively.** The results, which are similar for the two observers, show that an upturn occurs at each eccentricity tested for a range of small target-to-flanker separations. However, the performance upturn begins at larger target-to-flanker separations (approximately 1.4, 3.6, 3.2 and 26 min ac) as the eccentricity of testing increases. The most prominent upturn in percent correct at small target-to-flanker separations occurs at an eccentricity of 10 deg.

#### 4. Discussion

Although this study investigated a smaller range of flanking-bar widths than Siderov et al. (2014), the resulting foveal contour-interaction functions are similar. In particular, the contour-interaction functions obtained with relatively narrow flanking bars exhibit an upturn in performance at small target-to-flanker separations, whereas the results obtained with wider flanking bars do not. Like the data reported by Siderov et al. (2014), the *extent* of contour interaction, i.e., the range of target-to-flanker separations that produces an impairment of letter-identification performance, is essentially the same for all the flanking-bar widths tested, when the target-to-flanker distance is expressed in terms of the edge-to-edge separation in min arc.

Unlike the contour-interaction functions that we measured at an eccentricity of 5 deg (Figure 1, right), none of the functions reported by Siderov et al. (2015) exhibit an upturn in performance at small target-to-flanker separations. We attribute this difference primarily to the failure of Siderov et al. to measure contour interaction at sufficiently small target-to-flanker separations. Specifically, the smallest target-to-flanker separation used at an eccentricity of 5 deg in the study by Siderov et al. (2015) was 2.0 min arc, corresponding to 10% of the threshold letter size, whereas the smallest target-to-flanker separation in the present study was 0.35 min arc. For flanking-bar widths equal to 20% of the letter size or larger (i.e., the flanking-bar widths used by Siderov et al., 2015), the observed upturn in performance that we observed at an eccentricity of 5 deg occurred at a target-to-flanker separation on the order of 1.7 min arc. Therefore, it is likely that the identification of a performance upturn at small target-to-flanker separations requires the presentation of smaller target-to-flanker separations than are usually tested when measuring peripheral contour interaction.

Takahashi (1968) proposed that optical scatter, from the region between a central resolution target and the surrounding flanking bars, should be reduced when the target-to-flanker separation is small and that this reduction of scattered light is responsible for the improvement in two-line resolution that she observed. However, unlike the results reported by Takahashi (1968), an upturn in performance did not occur at the same small target-to-flanker separation at each of the eccentricities that we tested. To some extent, this may be because the range of eccentricities examined by Takahashi was extremely small (0 – 1.05 deg). Nevertheless, as the width of the optical

point spread function remains relatively constant over approximately the central  $\pm 10$  deg of the retina (Navarro et al., 1993, Navarro et al., 1998), our results are not consistent with the explanation based on light scatter that Takahashi proposed for the upturn in performance at small target-to-flanker separations.

Liu (2001) assessed foveal contour interaction for 4-position Cs flanked by pairs of bars either parallel or orthogonal to the side of the C that contained the gap. When the flanking bars were *parallel* to the side of the C with the gap, performance worsened monotonically for target-to-flanker separations less than approximately 2.5 stroke widths. At the smallest separation of the parallel flanking bars that Liu tested (0.3 stroke width), performance fell below chance. When the flanking bars were *orthogonal* to the side of the C that contained the gap, performance declined modestly for target-to-flanker separations between approximately 5 and 3 stroke widths and improved for smaller separations. Liu (2001) also assessed performance with 4 flanking bars and found that it was approximately equal to the averaged results for pairs of bars parallel and orthogonal to the gap in the C. On the basis of his results, Liu suggested that the parallel and orthogonal pairs of flanking bars stimulated independent neural mechanisms, both of which contribute to the contour interaction that is measured when the central C is surrounded by 4 flanking bars.

Unlike a letter C, the location of the specific features responsible for the discrimination of most Sloan letters is not immediately obvious. Nevertheless, Musilová et al (2018) found better performance at small target-to-flanker separations when a pair of horizontal bars flanked a central Sloan letter, compared to when the pair of flanking bars were oriented vertically. Unlike the outcome reported by Liu (2001), performance with 4 flanking bars generally was poorer than when the central letter was flanked by pairs of either vertical or horizontal bars. Thus, for Sloan letters, the contour interaction produced by 4 flanking bars does not represent the average of the separate effects produced by pairs of horizontal and vertical flanking bars.

In agreement with Liu (2001) and others (Danilova & Bondarko, 2007, Flom et al., 1963, Takahashi, 1968), we subscribe to the idea that contour interaction results from inhibitory interactions between the neural representations of the central target and flanking bars. As the target-to-flanker separation becomes smaller, one might therefore

expect that the deleterious influence of contour interaction on performance should become progressively stronger, as was reported by Liu (2001) for a letter C presented between two parallel flanking bars. However, at some point the target and flanking bars should become close enough that their optical and neural images overlap, blending into a single, unarticulated image. At this point, when the images of the central target and flanking bars are no longer neurally separate and distinguishable, one might anticipate that the neural interactions responsible for contour interaction would first weaken and then cease to occur. Instead, when the images of the flanking bars and the central target overlap, the flanking bars should produce essentially a contrast pedestal upon which the image of the central target is superimposed (Fig. 3a, b, e, f). If we are correct that inhibitory neural interactions become ineffective when the target-to-flanker separation is very small, then performance for these small separations should depend primarily on the visibility of the central target with respect to the flanker-produced contrast pedestal.

When the nearby flanking bars are narrow, image spread produced by the retinal point spread function should cause the contrast of the flanker-produced pedestal to be low. Under this condition, the superimposed target letter should remain relatively identifiable, allowing for an upturn in performance compared to somewhat larger target-to-flanker separations at which the images of the target and flankers are distinguishable and inhibitory contour interaction occurs (compare Figure 3a, e, to Figure 3c, g). On the other hand, wider flanking bars should produce a pedestal of higher contrast when the target-to-flanker separation is very small, rendering the central letter less identifiable and resulting in poorer performance (Figure 3b, f). Indeed, when the flanking bars are sufficiently wide, performance might be expected to decrease monotonically as the target-to-flanker separation is reduced, as seen, for example in left side of Figure 1. For flanking bars that exceed a certain width, the pedestal contrast for very small target-to-flanker separations may be sufficiently high that no further degradation in performance occurs.

The above explanation attributes only the reduced performance at target-to-flanker separations greater than approximately 1 min arc at the fovea (and at larger minimum separations at increasing eccentricities) to an inhibitory neural mechanism.

Performance for smaller target-to-flanker separations (i.e., less than 1 min arc at the fovea) is suggested to reflect simple contrast detection. Whether the contour-interaction function exhibits an upturn or a further reduction in performance at these small separations depends on whether the flanking bars are narrow or wide, and not on a neural interaction between the contours of the flanking-bars and target. The strong dependence of the upturn in the contour-interaction function on flanking-bar width differs from the results of Takahashi (1968), who reported only minor differences in the shape of the foveal contour-interaction functions that she obtained using flanking-bar widths of 1.4 and 4.3 min arc. However, the improvement in foveal two-line resolution observed by Takahashi occurred for target-to-flanker separations on the order of 1.4 min arc, which are wider than the separations at which an upturn in foveal performance occurred in the current, and previous, studies (Bedell et al., 2013, Chung & Bedell, 1995, Danilova & Bondarko, 2007, Hess et al., 2000, Jacobs, 1979, Liu, 2001, Musilová et al., 2018a, Siderov et al., 2013, Siderov et al., 2014, Simmers et al., 1999). Takahashi noted that her results are consistent with a decreased influence of scattered light on two-line resolution at small target-to-flanker separations. Our data indicate that letter identification improves at very small target-to-flanker separations only when the flanking bars are narrow, which is not consistent with an explanation based on stray light.

Because visual acuity declines systematically between the fovea and the peripheral retina, both the size of the letter targets and the range of flanking-bar widths that comprise our contour-interaction stimuli increase systematically as a function of eccentricity. Nevertheless, an upturn in the contour-interaction function continues to exist during peripheral testing for small target-to-flanker separations. The use of larger, more detectable letter targets in the periphery and/or differences between foveal vs. peripheral contrast processing (Georgeson, 1991) may account for the observation that the upturn in performance at small target-to-flanker separations occurs for (relatively as well as absolutely) wider flanking bars at 5 deg compared to the fovea (Figure 1). In addition, the upturn in performance occurs for a greater range of target-to-flanker separations as the tested eccentricity increases (Figure 2). As noted above, the extent of the retinal point spread function is similar within the range of eccentricities examined in this study (Navarro et al., 1993, Navarro et al., 1998). Therefore, we conclude that the

blurring together of a central letter target with nearby flanking bars includes both an essentially constant optical component, attributable to the retinal point spread function, and a neural component that enlarges with retinal eccentricity, presumably as the result of integration within localized receptive fields. In agreement with this interpretation, the locations of the upturn in the contour-interaction functions measured at 2.5, 5 and 10 deg in the inferior visual field (Figures 1 and 2) are consistent with some, (Khuu & Kalloniatis, 2015, Smith & Cass, 1989, Volbrecht et al., 2001) although not all (Inui et al., 1981, Kwon & Liu, 2019, Levi & Klein, 1990, Wilson, 1970), of the published estimates of peripheral Ricco's diameters.

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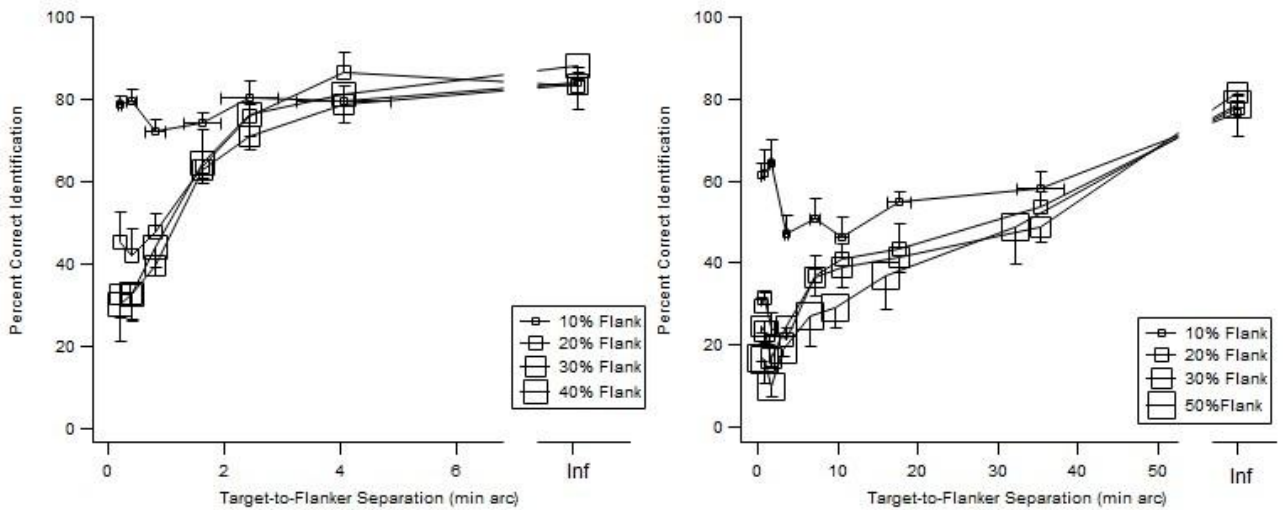
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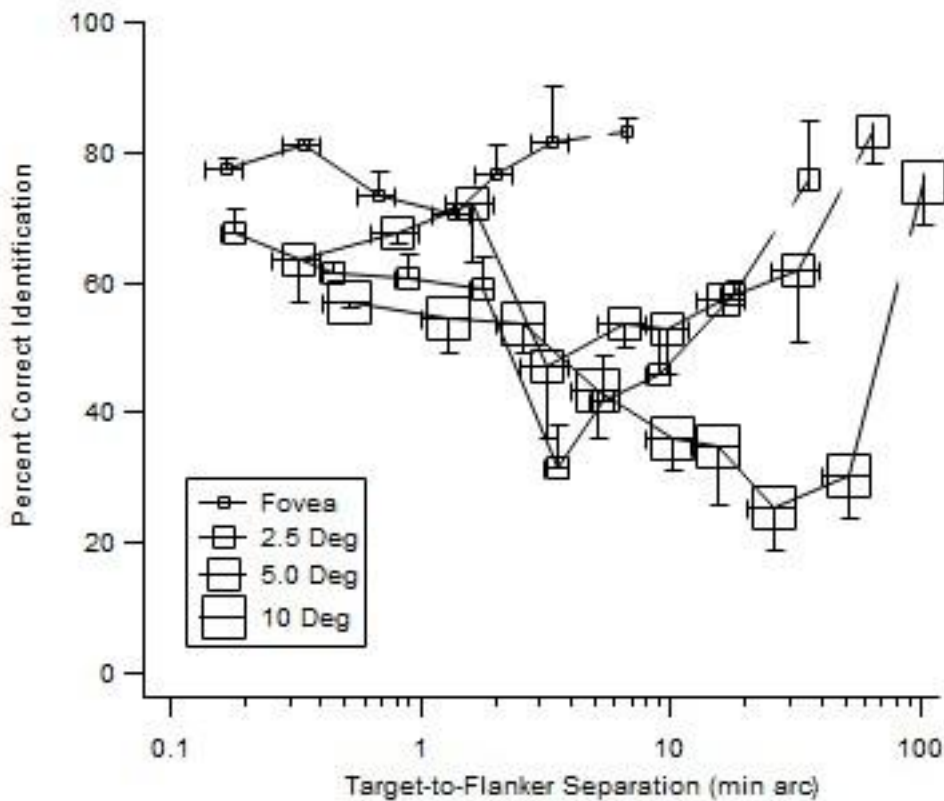
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Figure 1



**Figure 1.** Average percent correct letter identification for 5 observers is plotted as a function of the **average** target-to-flanker separation in min arc for targets presented at the fovea (**left**) and at 5 deg in the inferior visual field (**right**). In each panel, the symbols increase in size according to the width of the flanking bars. Note that in the right panel only 3 of the 5 observers contributed data for the contour interaction function with a flank width equal to 50% of letter size. Positive or negative **vertical** error bars represent standard errors (SEs) in percent correct across observers. **Horizontal errors bars (shown only on the '10% Flank' data) indicate standard errors (SEs) in target-to-flanker separation across observers. These SEs were the same for each flank condition.** The rightmost data point of each function at  $x = inf$  indicates percent correct letter identification when the flanking bars are absent.

Figure 2



**Figure 2.** Average percent correct letter identification is plotted as a function of the target-to-flanker separation in min arc for targets presented at the fovea and at 2.5, 5 and 10 deg in the inferior visual field. Greater eccentricities are represented by symbols of larger size and a logarithmic x-axis is used to prevent compression of the data obtained for the small target-to-flanker separations. At each eccentricity, the flanking bars had a width equal to 10% of the letter size. Each data point represents the average of two observers. The vertical error bars plotted on the functions for the fovea and 10-deg eccentricity represent SEs across the two observers. Error bars are similar in size for the functions obtained at eccentricities of 2.5 and 5 deg. Horizontal errors bars indicate standard errors (SEs) in target-to-flanker separation across the two observers at each retinal location. The rightmost data point of each plotted function (after the broken line) indicates percent correct letter identification when the flanking bars are absent.

**Figure 3**

**Panels a, b**



**Panels c, d**



**Panels e, f**



**Panels g, h**

**Figure 3.** Representations of threshold-size letter Cs at the fovea (4 min arc; images a - d) and at 5 deg inferior visual field (17.6 min arc; images e - h), surrounded by four narrow (10% of letter size; images a, c, e, g) or wide (40% of letter size; images b, d, f, h) flanking bars. Each image represents a simulation in which a clear image of the letter C and flankers is convolved with a Gaussian distribution representing the median size of Ricco's diameter, taken from the literature, at each eccentricity. Foveal target-to-flanker separations are 0.4 min arc in images a, b and 0.8 min arc in images c, d. Target-to-flanker separations at 5 deg inferior field are 1.6 min arc in images e, f and 3.5 min arc in images g, h. Gaussian functions representing Ricco's diameter have standard deviations of 1.18 min arc at the fovea and 3.57 min arc at 5 deg. After convolution, note that the letter and flanking bars blur together in images a, b, e, f, but less so in images c, d and g, h. Note that the images shown in the figure are not to scale.

**Table 1:** Summary Results of Studies of Ricco's Diameter.

<u>Study*</u>	<u>Stimuli</u>	<u>Retinal Location</u>	<u>Ricco's Diameter (min arc)</u>	
			<u>Fovea</u>	<u>5°</u>
Blackwell, 1946	Bright, dark spots	Fovea	8.2	--
Glezer, 1965	Bright spots	Fovea	1.6	--
Wilson, 1970	Bright spots	5° – 15°	--	8.9
Levi & Klein, 1980	Dark blurred lines	0° - 10°	1.8	5.3
Inui, 1981	Bright spots	0° – 10°	3.6	7.1
Smith & Cass, 1989	Two bright lines	0° – 7°	12.0	16.5**
Davila & Geisler, 1991	Bright squares	Fovea	2.6	--
Chung et al., 1996	Dark Lines	Fovea	2.6	--
Volbrecht et al., 2000	Bright spots	0° – 20°	7.7	20.0**
Dalimier & Dainty, 2010	Bright squares	0.2°	2.5	--
Khuu & Kalloniatis, 2015	Bright spots	0 – 20°	12.1	18.7
Tuten et al., 2018	Bright spots	Fovea	3.0	
Kwon & Liu, 2019	Bright spots	4 – 18.5°	--	7.2
Mean Diameter			5.2	12.0
Median Diameter			3.0	8.9

\* Only studies that assessed Ricco's Diameter on a photopic background field are included.

\*\* Value of Ricco's diameter is interpolated from surrounding eccentricities.

CREDIT Author statement

John Siderov Conceptualization, methodology, investigation, writing- original draft, writing – review and editing, visualization

František Pluháček Conceptualization, methodology, software, writing – review and editing,

Harold E. Bedell Conceptualization, methodology, investigation, formal analysis, writing- original draft, writing – review and editing, visualization