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Spatial Interactions in Interocular and Monocular "Blur Suppression"

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Abstract

Significance: The suppression of blurred images in one eye by clear images in the other eye is thought to contribute to the success of monovision correction. We show that interocular suppression occurs also for low-contrast targets that are not blurred and, to a lesser extent, when clear and low-contrast targets are presented to the same eye.

Purpose: A blurred target presented to one eye may be suppressed when a clear target is presented to the other eye. We sought to determine how this interocular suppression varies according to the separation between the blurred and clear targets and the magnitude of imposed blur. In addition, we examined whether a similar suppression occurs when the clear and blurred targets are imaged in the same eye.

Methods: Subjects (N=4) viewed a clear 20/40 Sloan letter surrounded by four 2 x 10 min arc flanking bars. In different blocks of trials, the gap between the letter and flanking bars varied from 0.5 to 4 bar widths. In addition, the flanking bars were either clear or spatially filtered to simulate 0.5 - 2 D of blur. The contrast required to detect the flanking bars was determined when the letter and flanking bars were presented either dichoptically or monoptically and compared with the thresholds for the bar targets presented alone.

Results: In both dichoptic and monoptic viewing conditions, detection thresholds for the blurred flanking bars are highest for the smallest spatial gap and decrease systematically as the gap increases. Thresholds are uniformly higher during dichoptic than monocular viewing, but the proportional change with the bar-to-letter separation is similar in both conditions. Surprisingly, the magnitude of imposed blur has very little influence on the magnitude of threshold elevation in either the dichoptic or monoptic viewing conditions.

Conclusions: Because threshold elevation is nearly the same in the presence of 0 to 2 D of blur, we prefer to designate the phenomenon we studied as "contrast suppression." The similar spatial characteristics of suppression during dichoptic and monoptic viewing are consistent with contributions from a common neural mechanism.

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Interocular blur suppression refers to the reduced visibility of a blurred image presented to one eye in the presence of a clearer image in the other eye.[1–8] In the studies that compared the magnitude of blur suppression in the two eyes, most observers exhibited little or no difference when the blurred stimulus was presented to the non-dominant or the sighting-dominant eye,[5,9–10] although Schor & Erickson did report exceptions.[11] Interocular blur suppression has been investigated as a potential predictor of success in wearing monovision contact-lens prescriptions.[4,9–10,12–13]

According to Simpson,[2,6] larger targets must be more blurred than smaller targets to undergo suppression by a clear stimulus in the contralateral eye. Schor et al. reported the opposite result;[5] however, in their study the clear and blurred targets were presented at corresponding rather than adjacent locations in the two eyes. Some studies reported that increasing the amount of blur results in greater interocular suppression.[3,6,8] On the other hand, Schor et al. reported that suppression is greater for a target with less blur.[5] Pianta & Kalloniatis determined that the magnitude of suppression for their 0.65 deg foveal stimulus, measured in terms of the elevation of its contrast threshold, increased only up to approximately 2 D of blur and, thereafter, remained constant.[7]

Some of the dissimilar outcomes obtained in previous studies may have resulted from differences in the stimulus configurations that were used. For example, in some studies of blur suppression the blurred and unblurred stimuli overlapped in the visual field.[2–3,5,9] In contrast, the blurred and unblurred stimuli used by Simpson et al.,[6] Pianta & Kalloniatis,[7] and Chima et al.[8] were at non-identical visual-field locations and, therefore, indicate an influence of suppression beyond the physical boundaries of the unblurred target. In the experiments described here, we used the second type of target configuration and systematically varied the angular separation between the blurred and unblurred stimulus elements. The aim of this manipulation was to determine how the spatial relationship between blurred and unblurred targets influences the magnitude of suppression.

Detection of a low-contrast stimulus is impaired when this stimulus is presented near a high-contrast border shown to the same eye.[14–19] This threshold elevation occurs even when the high-contrast border is of negative contrast, which rules out any possible influence of stray light. Potentially, this border effect could be analogous to interocular blur suppression, even though Novak failed to find evidence for a threshold elevation during dichoptic viewing.[20] To determine whether interocular blur suppression and the threshold elevation that results from a nearby border shown to the same eye might be related, a second aim of our study was to compare blur suppression for dichoptically and monocularly presented target configurations with the same range of separations.

METHODS

Two students from the University of Houston (DJ and JP), who were naïve as to the purpose of the study, and two of the authors (JQ and HB) served as observers. All had a best-corrected visual acuity of at least 20/20 in each eye. The observers granted voluntary written informed consent after the procedures of the study and the anticipated extent of their participation had been described to them. Before testing began the experimental protocol was reviewed by the University of Houston Committee for the Protection of Human Subjects.

Stimuli were drawn using a VSG2/5 board housed in a PC computer and presented at the center of a gamma-corrected 20-inch Clinton DS200 Monoray monitor with 864 x 641-pixel resolution. At the observers' viewing distance of 291 cm, each pixel subtended an angle of 0.5 min arc. The three stimulus conditions are illustrated in Figure 1. In the *Bars Only* condition of the principal experiment (Figure 1A), four 2 x 10 min arc bars were presented in a square arrangement to the observers' sighting-dominant eye (right eye for observer DJ, left eye for the other three observers). In the *Dichoptic* Bars + Letter condition, the four bars were presented to the dominant eye (as in the *Bars Only* condition) and the Sloan letter was presented to the fellow, non-dominant eye (Figure 1B). In the *Monoptic* Bars + Letter condition, the four bars surrounded a high contrast Sloan letter, all presented to the sighting-dominant eye (Figure 1C). In all three conditions, the stimuli were presented at the center of a 1.5 deg outline square that was visible to both eyes and served in the *Dichoptic* Bars + Letter condition as a fusion lock. The observers viewed the monitor through ferro-electric shutters that alternated at a rate of 60 Hz per eye. On each trial, all targets were presented concurrently for a duration of 1 s on a homogeneous background (as viewed through the shutter glasses) of 23 cd/m^2. The Sloan letter that was presented in the *Monoptic* and *Dichoptic* conditions had a Weber contrast of −99% and subtended a visual angle of 10 min arc, corresponding to an acuity of 20/40.

To assess the influence of eye dominance, additional data were collected for observers JQ and HB when the bars were presented to the sighting-non-dominant eye (i.e., the right eye of both observers). Specifically, in the *Monoptic* Bars + Letter condition, the bars and Sloan letter were presented to the non-dominant eye and in the Dich*optic* Bars + Letter condition, the bars were presented to the non-dominant eye and the Sloan letter was presented to the sighting-dominant eye.

In all conditions, contrast thresholds for detecting the bars were determined using the Method of Constant Stimuli. Within each set of 90 trials, nine different, non-zero contrasts of the bar targets were presented in random order. After each trial, the observer indicated with a joystick whether (s)he detected the bars. Thresholds corresponding to the Weber contrast at which 50% detection occurred were determined by probit analysis of the aggregated responses. In general, the threshold estimates for each observer and condition represent the average of two or more replications for each tested condition. For each observer, the sets of trials to determine the thresholds for the *Bars-Only*, *Dichoptic*, and *Monoptic* conditions were interleaved.

In separate blocks of trials, the bars were presented at different separations: 0.5, 1, 2 or 4 stroke widths (i.e., 1 to 8 min arc) from the edge of the central letter target. Thresholds were obtained also for the same four bar-to-bar separations in the *Bars Only* condition, i.e., when no central letter was presented (see Figure 1, top). In addition, in separate blocks of trials the bars were presented with one of two levels of simulated dioptric blur (0.5 and 1 D) or with no blur (0 D). Additional thresholds were obtained in the *Bars-Only, Monoptic* and *Dichoptic* conditions for observers JQ and HB using bars with 2D of simulated blur. Each of the observers completed the blocks of trials for the different viewing conditions, magnitudes of simulated blur, and bar separations in different pseudo-random orders.

Although the yes-no psychophysical procedure that we used is subject to criterion effects, we believe that pseudo-randomizing the blocks of trials corresponding to different experimental conditions should have minimized these effects. In addition, we note that the results obtained from the two naïve and the two experienced psychophysical observers were very similar.

Simulated dioptric blur was produced using the method described previously by Akutsu et al.[21] and Bedell et al.[22] Briefly, isotropic spatial filters were created for specific levels of dioptric blur (0.5, 1 and 2 D) by modeling the filter transfer function of the retinal blur produced in the presence of a 4-mm-diameter pupil. The filter transfer functions were modeled as isotropic first-order Bessel functions in a two-dimensional Fourier matrix. Each isotropic spatial filter was then generated by performing an inverse Fourier transform of the filter transfer function. For each level of simulated blur, the bars targets were then individually convolved with the appropriate spatial filter. For targets that underwent simulated blur, Weber contrasts were calculated post-filtering.

Statistical analyses were performed using the Mixed Model Analysis procedure in SPSS (IBM, Armonk, NY). The factors of simulated blur and bar separation were treated as ordinal variables; other factors were treated as categorical. Because the variability of the measured contrast thresholds was proportional to the threshold values, all of the analyses were performed using logarithmically transformed data and, in the figures below, the results are plotted on logarithmically-scaled vertical axes. Each analysis started with a full-interaction model, which assumed a first-order autoregressive structure with heterogeneous variances. The results reported below are from the final models, which were obtained by stepwise backward elimination of non-significant model terms ($P > .05$). Therefore, in most cases, statistical outcomes are reported only for significant effects.

RESULTS

A Mixed Effect model (fixed repeated factors = simulated blur and bar separation, random factor = subject, dependent variable = contrast threshold) in the Bars-Only condition found a significant effect of blur ($F_{2,11} = 6.6$, $P = .013$). Across observers, the average thresholds for the bars in the zero-blur condition (6.41%) were consistently higher than those in the presence of 0.5 D (4.20%) and 1 D (3.85%) of simulated blur (Figure 2). We presume that the higher thresholds in the zero-blur condition resulted from incomplete spatial summation, as the width of the unblurred bars was narrower than most estimates of the foveal Ricco’s diameter.[23] On the other hand, there was no evidence that the spacing between the bars had an influence on contrast thresholds in the *Bars-Only* condition ($F_{3,20} = 2.3$, $P = .11$). For each level of simulated blur, we therefore averaged each observer’s contrast thresholds for the 4 bar separations and normalized the results obtained in each *Monoptic* and *Dichoptic Bars + Letter* condition to these average threshold values.

Figure 3 presents these contrast-threshold ratios, averaged across the 4 observers, in the *Monoptic* and *Dichoptic* Bars + Letter conditions as a function of the bar-to-letter separation. Because thresholds were not obtained for observers DJ and JP with 2 D of simulated blur, only the results for 0, 0.5 and 1 D of simulated blur are included in this figure. Figure 4 separately presents the results of observers JQ and HB for all 4 levels of simulated blur (0 – 2 D). In both Figures, data for the *Monoptic* and *Dichoptic* viewing conditions are connected by solid and dashed lines, respectively, and the results for the different levels of simulated blur are represented by different symbols. A Mixed Model Analysis of the data in Figure 3 confirmed a significant main effect of viewing condition ($F_{1,22} = 123.2$, $P < .001$) that appears in the Figure as uniformly higher *Dichoptic* compared to *Monoptic* threshold ratios. Across all conditions, the average log difference between *Dichopic* and *Monoptic* threshold ratios is 0.29 ± 0.02 [SE]). The statistical analysis also showed a significant main effect of bar-to-letter separation ($F_{3,24} = 69.6$, $P < .001$), seen in the figure as a monotonic decrease in both the *Dichoptic* and *Monoptic* threshold ratios as the bar-to-letter separation increases. The *Monoptic* threshold ratios asymptote at a value close to 1 (average = 0.98 ± 0.08 [SE]) when the bar-to-letter separation is equal to 4 stroke widths, indicating that the central letter exerts no influence on the contrast threshold for the surrounding bars at this large separation. On the other hand, the average value of the *Dichoptic* threshold ratios at the largest bar-to-letter separation is 2.19 ± 0.08, indicating that a high-contrast letter presented to the contralateral eye elevates the contrast threshold for detecting the surrounding bars by a factor of approximately 2 even when the bar-to-letter separation is 8 min arc (i.e., 4 stroke widths).

The statistical analysis also revealed a marginally significant main effect of blur ($F_{2,35} = 4.0$, $P = .027$). Pairwise comparisons indicated a significantly lower threshold ratio for 0 D compared to 0.5 D of simulated blur (mean difference = 0.076 log units, corresponding to a 19% difference in threshold ratios; $P = .039$). None of the other pairwise comparisons between the different values of simulated blur or any of the two-way or three-way interaction terms between viewing condition, blur, and bar-to-letter separation achieved statistical significance.

A separate Mixed Model Analysis of data shown in Figure 4 found significant main effects of viewing condition ($F_{1,16} = 100$, $P < .001$) and bar-to-letter separation ($F_{3,42} = 27.2$, $P < .001$). However, neither the magnitude of simulated blur nor any of the two-way or three-way interaction terms between viewing condition, blur, and bar-to-letter separation achieved statistical significance. Consistent with these outcomes, it can be seen in Figures 3 and 4 that the threshold ratios for bars with different magnitudes of simulated blur essentially overlap and, on logarithmically scaled axes, the results for the *Dichoptic* and *Monoptic* viewing conditions decline more-or-less in parallel as the bar-to-letter separation increases.

For observers JQ and HB, contrast thresholds in the *Bars-Only* condition were higher when viewing with the sighting-non-dominant compared to the dominant eye (for JQ, 9.8% vs. 7.0% contrast; for HB, 6.5% vs. 5.2% contrast, averaged across the different conditions of bar separation and blur). Figure 5 compares these two observers' threshold ratios during *Dichoptic* and *Monoptic* viewing, normalized to the values measured in the *Bars-Only* condition, for bar stimuli presented to the sighting-non-dominant vs. dominant eyes. A

Mixed Model Analysis indicated a significant main effect of the viewing eye; ($F_{1,13}$ = 8.2, P = .013) and a significant interaction between the viewing eye and the viewing condition (*Dichoptic* vs. *Monoptic*: $F_{1,18}$ = 73.3, P <.001). Across all combinations of bar-to-letter separation, simulated blur, and viewing condition, the average threshold ratios were slightly lower (0.016 log units, or approximately 4%) in the non-dominant compared to the dominant eye. Between-eye differences in the threshold ratios in the two viewing conditions were more substantial. As illustrated in Figure 5 both observers' threshold ratios are systematically lower when the bars were presented to the dominant than the non-dominant eye during *Dichoptic* viewing, and systematically higher when the bars were presented to the dominant eye during *Monoptic* viewing.

Consistent with the results of the primary experiment, the analysis of JQ's and HB's results also showed significant main effects of bar-to-letter separation ($F_{3,11}$ = 376.1, P < .001), viewing condition (*Dichoptic* vs. *Monoptic*; $F_{1,15}$ = 2407.4, p < .0001), and magnitude of simulated blur ($F_{2,15}$ = 11.1, P = .001). The effects of bar-to-letter separation and viewing condition, shown in Figure 5, mirror those in the primary experiment, shown in Figures 3 and 4. With respect to simulated blur, the average threshold ratios were significantly lower during 0 D compared to 0.5 and 1 D of simulated blur, but only by an average of 0.032 log units, corresponding to a difference of approximately 7%. Finally, a significant interaction existed between the bar-to-letter separation and the viewing condition ($F_{3,13}$ = 8.6, P = .002), which is attributable to a greater decrease in the log contrast ratio between 0.5 and 1 stroke-width separations in the *Monoptic* (approximately 0.12 log units) compared to *Dichoptic* viewing condition (approximately 0.04 log units).

A surprising outcome is that the mean threshold ratios for the two largest bar separations in the *Monoptic* condition (sighting-non-dominant eye) are less than 1, indicating that the observers' contrast thresholds were lower when the central letter was present than when it was not. We have no ready explanation for this result, except perhaps that the presence of a central, high-contrast letter reduced the observers' uncertainty about the location of the low contrast bars.[24] However, it is unclear why location uncertainty should exert a greater effect on the contrast thresholds for bar targets presented alone to the non-dominant eye compared to the dominant eye (Fig. 5).

DISCUSSION

During *monocular* viewing, a focused, high-contrast letter produces an approximately two-fold elevation of the contrast threshold for nearby targets. The magnitude of this threshold elevation decreases as the separation between the central letter and the surrounding targets increases, such that there is no threshold elevation when the separation reaches approximately 8 min arc. Several previous authors reported that the detectability of a foveal stimulus is impaired over a similar range of angular distances from a dark border presented to the same eye.[16–19] Experiments by Vassilev indicated that detectability is reduced most for elongated stimuli with their long edge parallel to the dark border,[17] like the bar targets used in our study. As these previous studies did not assess the contrast threshold when no edge was present, it is unclear whether facilitation would have occurred beyond a specific edge-to-target separation.

When the high-contrast letter was presented to one eye and the surrounding bars to the other eye, we found up to a three- to four-fold elevation of the contrast threshold, compared to the condition in which no dichoptic letter target is present. As during monocular viewing, the threshold elevation decreases systematically with increasing separation between the central letter and the surrounding targets. However, when the central letter and surrounding targets are separated by 8 min arc, an approximately two-fold threshold elevation persists. Although we did not evaluate separations larger than 8 min arc, logic dictates that at some larger separation the central letter should cease to exert any influence on the contrast thresholds for surrounding targets seen by the other eye.

Perhaps the most provocative aspect of our results is that magnitude of the measured threshold elevation (relative to when no central letter was presented) depends very little on the amount by which the bar targets were blurred. In other words, the targets used in our experiments exhibit essentially the same pattern of threshold elevation regardless of whether the targets were clear or degraded by up 2 D of simulated blur. This near-independence of target blur was observed during both dichoptic and monocular presentation of the letter and bar stimuli. Collins & Goode[25] reported greater interocular suppression in the presence of greater blur, but the average difference in contrast thresholds that they observed in the presence of 1 vs. 2.5 D of blur corresponds to only about 20%. We observed a similar difference between the threshold ratios obtained with 0 and 0.5 D of simulated blur, but no differences between 0.5 D and larger amounts of simulated blur. These outcomes suggests that, for dichoptically presented targets, the term “interocular blur suppression” may be a misnomer and that “interocular contrast suppression” might be a more appropriate descriptor. Our finding that the elevation of contrast thresholds produced by a clear central stimulus is nearly independent of the imposed blur is consistent with this suggestion.

As noted above in the Introduction, Novak[20] found no influence of an adjacent dark border on the threshold of 48 by 131 min-arc test stimulus presented to the other eye. Two possible explanations can be advanced to account for the discrepancy between his results and ours. First, interocular suppression has been reported to be stronger for small compared to large targets.[6,8] It is possible therefore that the substantially larger target used by Novak, compared to those in the current study, was not susceptible to interocular contrast suppression. Second, even at the smallest separation between Novak’s 48-min-arc wide target and the contralateral high-contrast border, the target’s outer edge might have fallen beyond the range of dichoptic contrast suppression.

Chima et al.[8] found a measurable amount of interocular suppression in the presence of 0.5 D of blur that increased systematically up to a blur magnitude of 4 D, which was the maximum amount that these authors used. Both Heath et al.[3] and Simpson[2] found that some of their observers experienced suppression in the presence of 0.5 D of blur, but not others. In contrast, Simpson reported no interocular suppression until the magnitude of blur exceeded 0.5 D.[6] Nevertheless, both Heath et al.[3] and Simpson[2,6] noted that the likelihood of suppression increases with the amount of imposed blur. On the other hand, Pianta & Kalloniatis[7] found that suppression increased up to 2 D of blur, but that greater amounts of blur led to no further increase. It seems likely to us that the apparent inconsistencies in the above-mentioned studies may be attributable to differences in the size of the blurred stimuli along with their location relative to the clear target seen by the contralateral eye.

Unlike the simulated blur used in our experiments, the imposition of dioptric blur reduces target contrast, and more so for small compared to large targets.[26–27] Because suppression occurs more readily for low- compared to high-contrast targets,[5–6] it is therefore not surprising that, for the same amount of imposed dioptric blur, smaller targets are suppressed more readily than larger ones.

For the two observers we tested, interocular suppression was slightly more effective when the bar stimuli were presented to the sighting-non-dominant than to the dominant eye (Figure 5). Previously, Schor et al.[5] found that their 5 observers exhibited very similar magnitudes of suppression when a blurring lens was worn over the dominant or non-dominant eyes. Subsequently, Schor et al.[9] found a highly significant correlation between the amounts of suppression measured in their observers' dominant and non-dominant eyes. In contrast, Schor & Erickson[11] found in 2 of their 6 observers that the subjectively determined depth of focus during binocular viewing with a +1.50 D addition placed over one eye matched that measured during monocular viewing with the dominant eye alone. In these two observers, therefore, a clear image in the sighting-non-dominant eye during binocular viewing failed to suppress the blurred image seen for a range of target vergences in the dominant eye. It is clear that the data of the two observers in our study cannot be taken as definitive; however, in the aggregate, the results reported to date suggest that interocular suppression generally is similar when the clear stimulus is seen by the sighting-dominant and non-dominant eyes.

Binocular rivalry describes the alternating suppression of two dissimilar images that are presented in superimposition to the two eyes.[28–30] A weaker form of alternating suppression, called monocular rivalry, can occur when dissimilar images are superimposed within the same eye.[29,31–33] Evidence suggests that monocular rivalry results, at least partially, from interactions between a fixated stimulus and the negative afterimage produced by the stimulus. [34–35] However, even though suppression is substantially weaker during monocular than binocular rivalry,[29,36–37] the two forms of rivalry exhibit similar characteristics, such as the mutual synchronization of dominance and suppression phases[38–39] and similar dependencies on differences in stimulus orientation, spatial frequency, size, and color.[36–37,40] Based on these similarities, a common visual process has been proposed by some authors to contribute to both binocular and monocular rivalry.[38,40] The comparable influence of bar-to-letter separation that we found on the fall off of dichoptic and monocular (contrast) suppression (Figures 3–5) also suggests that a similar mechanism may be at least partly responsible for these two phenomena.

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REFERNCES

1. Humphriss D The Psychological Septum. An Investigation into its Function. Am J Optom Physiol Opt 1982;59:639–41. [PubMed: 7137303]
2. Simpson T The Suppression Effects of Induced Anisometropia. S Afr Optom 1986;4:117–24.
3. Heath DA, Hines C, Schwartz F. Suppression Behavior Analyzed as a Function of Monovision Addition Power. Am J Optom Physiol Opt 1986;63:198–201. [PubMed: 3963142]
4. Collins MJ, Goode A. Interocular Blur Suppression and Monovision. Acta Ophthalmol, 1994;72:376–80. [PubMed: 7976272]
5. Schor C, Landsman L, Erickson P. Ocular Dominance and the Interocular Suppression of Blur in Monovision. Am J Optom Physiol Opt 1987;64:723–30. [PubMed: 3688174]
6. Simpson T The suppression Effect of Simulated Anisometropia. Ophthal Physiol Opt 1991;11:350–8.
7. Pianta MJ, Kalloniatis M. Characteristics of Anisometropic Suppression: Simple Reaction Time Measurements. Percept Psychophys 1998;60:491–502. [PubMed: 9599998]
8. Chima AS, Formankiewicz MA, Waugh SJ. Investigation of Interocular Blur Suppression using Luminance-Modulated and Contrast-Modulated Noise Stimuli. J Vis 2015;15;22:1–22.
9. Schor C, Carson M, Peterson G, et al. Effects of Interocular Blur Suppression Ability on Monovision Task Performance. J Am Optom Assoc 1989;60:188–92. [PubMed: 2708767]
10. Robboy MW, Cox IG, Erickson P. Effects of Sighting and Sensory Dominance on Monovision High and Low Contrast Visual Acuity. CLAO J 1990;16:299–301. [PubMed: 2249349]
11. Schor C, Erickson P. Patterns of Binocular Suppression and Accommodation in Monovision. Am J Optom Physiol Opt 1988;65:853–61. [PubMed: 3252731]
12. Collins MJ, Bruce AS. Factors Influencing Performance with Monovision. J Brit Contact Lens Assoc 1994;17:83–9.
13. Evans BJ. Monovision: a Review. Ophthal Physiol Opt 2007;27:417–39.
14. Fry GA, Bartley H. The Effect of One Border in the Visual Field upon the Threshold of Another. Am J Physiol 1935;112:414–21.
15. Novak S, Sperling G. Visual Thresholds Near a Continuously Visible or a Briefly Presented Light-Dark Boundary. Opt Acta 1963;10:187–91.
16. Matthews ML. Appearance of Mach bands for Short Durations and at Sharply Focused Contours. J Opt Soc Am 1966;56:1401–02.
17. Vassilev A Contrast Sensitivity Near Borders: Significance of Test Stimulus Form, Size and Duration. Vision Res 1973;13:719–29. [PubMed: 4706347]
18. Lukas FX, Tulunay-Keesey U, Limb JO. Thresholds at Luminance Edges under Stabilized Viewing Conditions. J Opt Soc Am 1980;70:418–22. [PubMed: 7373457]
19. Limb JO, Tulunay-Keesey U. Spatiotemporal Characteristics of Thresholds Adjacent to a Luminance Edge. J Opt Soc Am 1981;71:1209–19.
20. Novak S Invariance of Detection Thresholds across a Light-Dark Boundary using Dichoptic Presentation. J Opt Soc Am 1967;57:1059–60. [PubMed: 6035301]
21. Bedell HE, Patel SS, Chung ST. Comparison of Letter and Vernier Acuities with Dioptric and Diffusive Blur. Optom Vis Sci 1999;76:115–20. [PubMed: 10082058]
22. Akutsu H, Bedell HE, Patel SS. Recognition Threshold for Letters with Simulated Dioptric Blur. Optom Vis Sci 2000;77:524–30. [PubMed: 11100890]
23. Davila KD, Geisler WS. The Relative Contributions of Pre-neural and Neural Factors to Areal Summation in the Fovea. Vision Res 1991;31:1369–80. [PubMed: 1891825]
24. Cohn TE, Wardlaw JC. Effect of Large Spatial Uncertainty on Foveal Luminance Increment Detectability. J Opt Soc Am A 1985;2:820–5. [PubMed: 4009310]
25. Collins MJ, Goode A. Factors Affecting Interocular Blur. Clin Exp Optom 1994;77:206–9.
26. Ogle KN. Foveal Contrast Thresholds with Blurring of the Retinal Image and Increasing Size of the Test Stimulus. J Opt Soc Am 1961;51:862–9. [PubMed: 13730446]

27. Aulhorn E, Harms H. Visual perimetry. In: Jameson D, Hurvich LM, eds. Handbook of Sensory Physiology, VII/4. Visual Psychophysics. New York: Springer Verlag; 1972:102–45.
28. Wheatstone C Contributions to the Physiology of Vision. Part the First. On Some Remarkable and Hitherto Unobserved Phenomena of Binocular Vision. Phil Trans Roy Soc Lond 1838;128:371–94.
29. Breese BB. On Inhibition. Psychol Monogr 1899;3:1–65.
30. Blake R A Primer on Binocular Rivalry, Including Current Controversies. Brain Mind 2001;2:5–38.
31. Atkinson J, Campbell FW, Fiorentini L, Maffei L. The Dependence of Monocular Rivalry on Spatial Frequency. Perception 1973;2:127–33.
32. Campbell FW, Howell ER. Monocular Alternation: a Method for the Investigation of Pattern Vision. J Physiol 1972;225:19P–21P.
33. Campbell FW, Gilinsky AS, Howell ER, et al. The Dependence of Monocular Rivalry on Orientation. Perception 1973;2:123–5.
34. Georgeson MA. Eye Movements, Afterimages and Monocular Rivalry. Vision Res 1984;24:1311–9. [PubMed: 6523751]
35. Bradley A, Schor C. The Role of Eye Movements and Masking in Monocular Rivalry. Vision Res 1988;28:1129–87. [PubMed: 3257015]
36. Wade NJ. Monocular and Binocular Rivalry between Contours. Perception 1975;4:85–95. [PubMed: 1161443]
37. O'Shea RP, Parker A, La Rooy DL, Alais D. Monocular Rivalry Exhibits Three Hallmarks of Binocular Rivalry: Evidence for Common Processes. Vision Res 2009;49:671–81. [PubMed: 19232529]
38. Andrews TJ, Purves D. Similarities in Normal and Binocularly Rivalrous Viewing. Proc Natl Acad Sci USA, 1997;94:9905–8. [PubMed: 9275224]
39. Pearson J, Clifford CW. When your Brain Decides What You See. Grouping across Monocular, Binocular, and Stimulus Rivalry. Psychol Sci 2005;16:516–9. [PubMed: 16008782]
40. O'Shea RP. Effects of orientation and spatial frequency on monocular and binocular rivalry. In: Kasabov N, Kozma R, Ko K, et al., eds. Progress in Connectionist-based Information Systems: Proceedings of the 1997 International Conference on Neural Information Processing and Intelligent Information Systems. Singapore: Springer-Verlag; 1998:67–70.

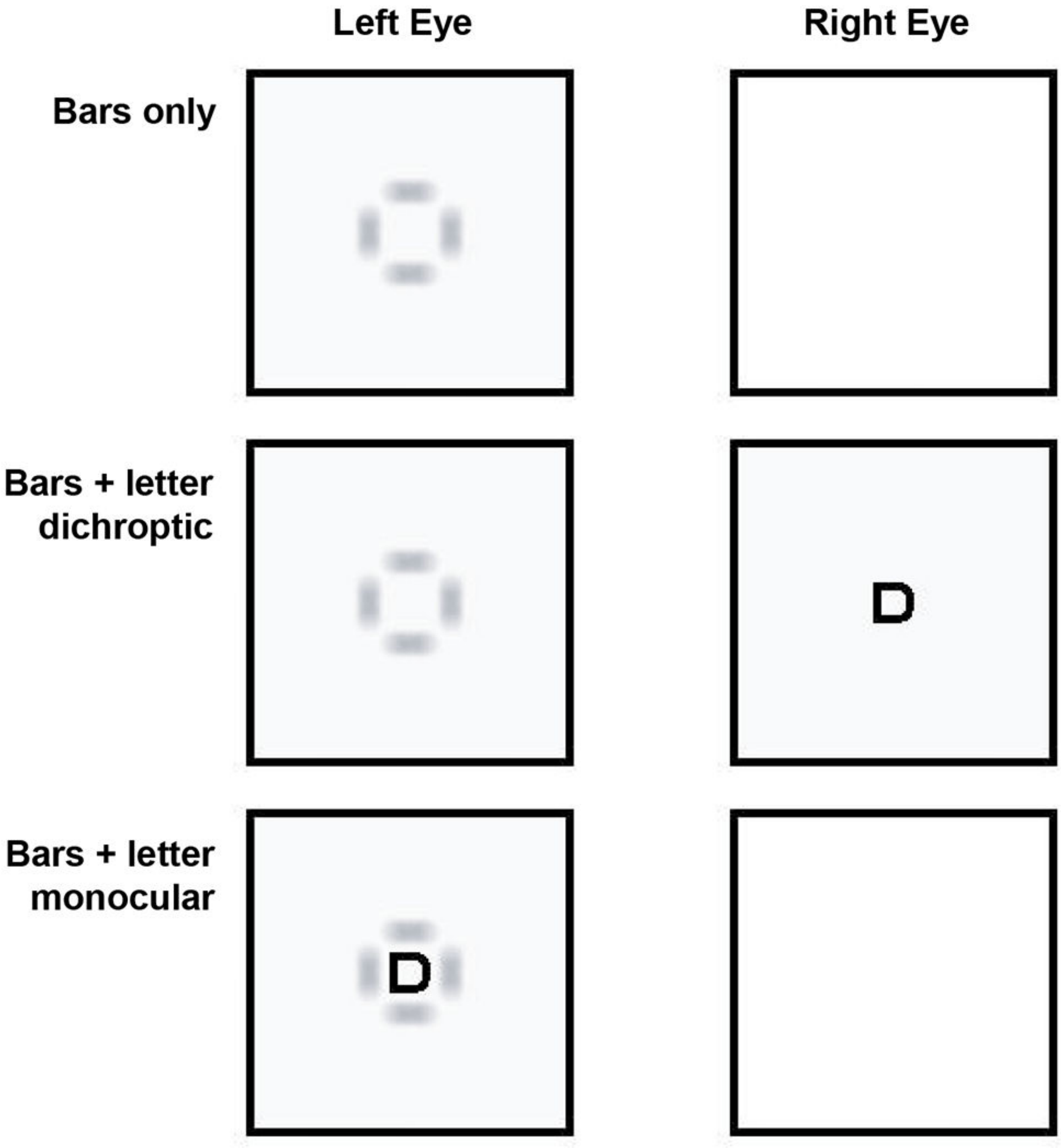

Figure 1.

Examples of the stimuli used in the three experimental conditions (top: *Bars Only*; middle: *Dichoptic*; bottom, *Monoptic*). In this figure, the bars are blurred by 0.5D and the bar-to-letter separation is two bar widths. The square frame has a thickness of one bar width and serves in the *Dichoptic* condition as a fusion lock. The width and height of the frame are 1.5 deg.

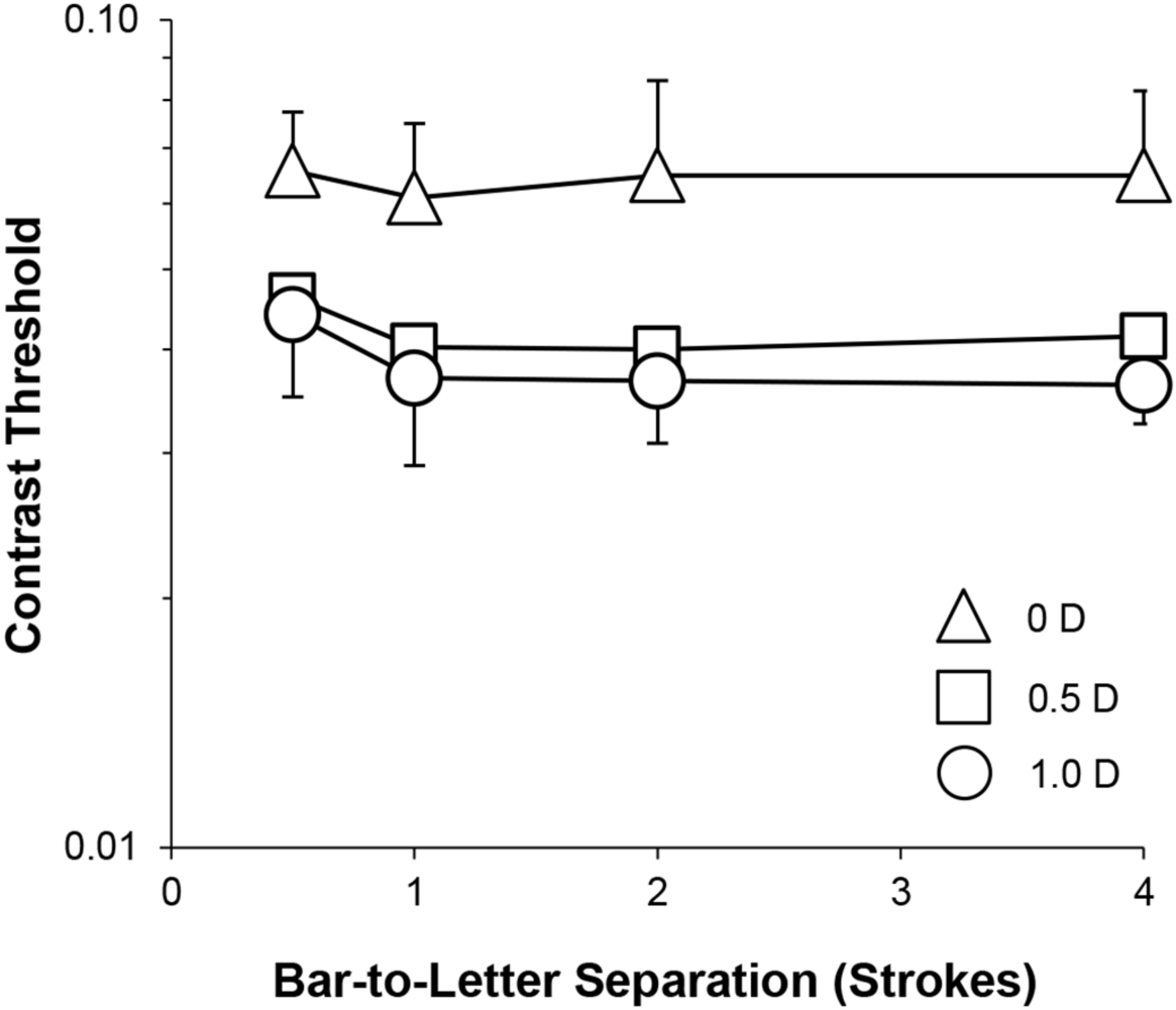

Figure 2.

Average contrast thresholds in the Bars-Only condition are plotted on a logarithmic axis as a function of bar separation, in stroke widths. Although the bars were defined by negative Weber contrast, thresholds are represented in the figure as positive values. Triangles, squares and circles indicate simulated blur of 0, 0.5 and 1 D. Uni-directional standard errors for the 4 observers are included for the 0 and 1 D data. The tick marks on the vertical axis indicate increments in the contrast threshold of 0.01.

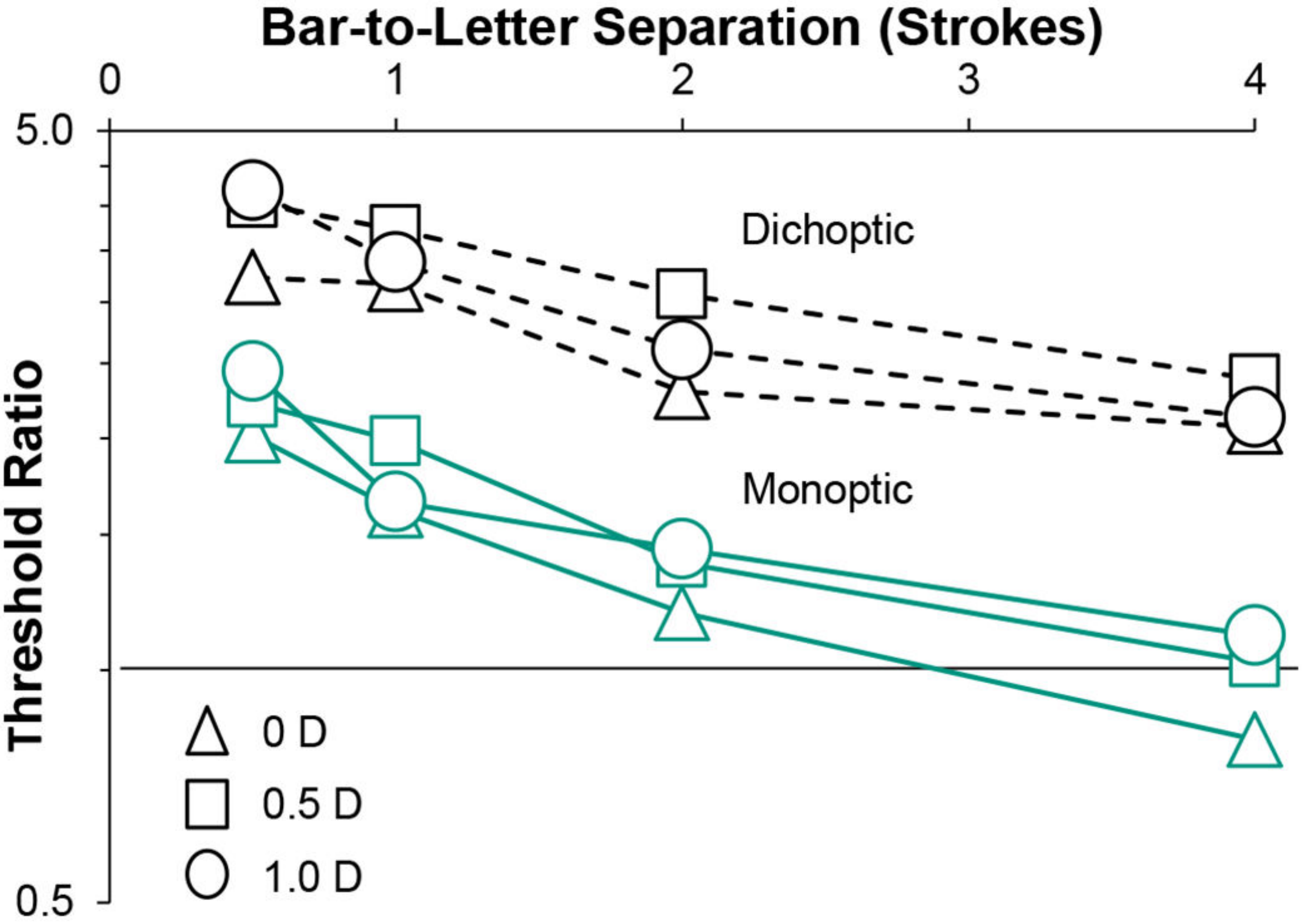

Figure 3.

Average threshold ratios of the 4 observers (*Dichoptic*/*Bars Only* and *Monoptic*/*Bars Only*) are plotted on a logarithmic axis against the edge-to-edge separation, in stroke widths, between the central high-contrast-letter and surrounding bars. Dashed and solid lines depict results from the *Dichoptic* and *Monoptic* conditions, respectively. Triangles, squares and circles indicate simulated blur of 0, 0.5 and 1 D of the bar targets. Standard errors (not included on the plot to prevent clutter) have a median value of 10.7% of the threshold ratio for the *Dichoptic* conditions and 10.6% for the *Monoptic* conditions. The horizontal line indicates a threshold ratio of 1. The tick marks on the vertical axis indicate increments of the threshold ratio of 0.5.

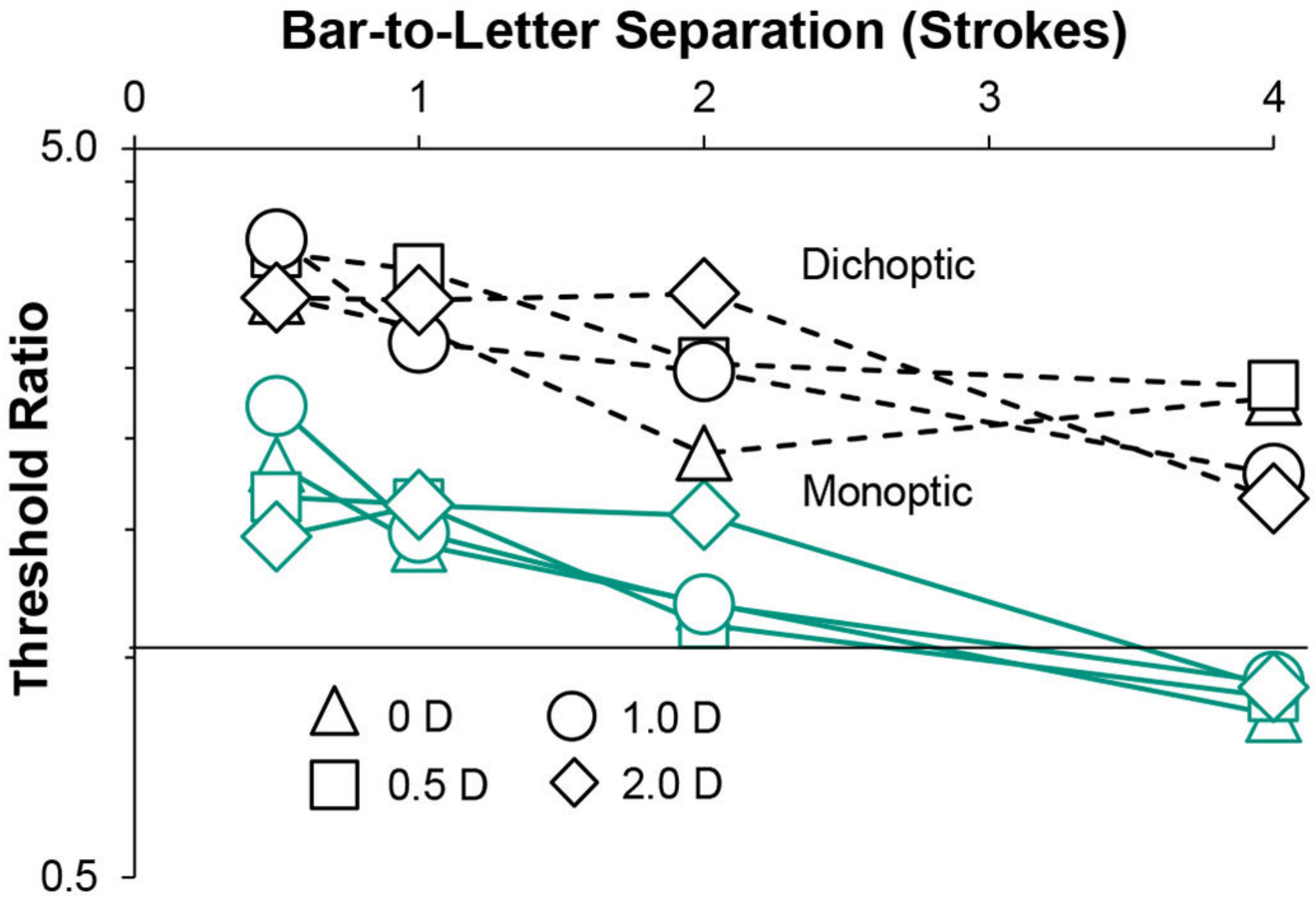

Figure 4.

Average threshold ratios for 2 observers (*Dichoptic*/*Bars Only* and *Monoptic*/*Bars Only*) who provided data for 4 levels of simulated blur of the bar targets are plotted as a function the separation, in stroke widths, between the central high-contrast-letter and surrounding bars. As in Figure 3, dashed and solid lines depict the results of the *Dichoptic* and *Monoptic* conditions, respectively. Triangles, squares, circles, and diamonds indicate simulated blur of the bar targets of 0, 0.5, 1 and 2 D. Median standard errors are 12.2% of the threshold ratio for the dichoptic conditions and 8.9% for the monoptic conditions. The horizontal line indicates a threshold ratio of 1.

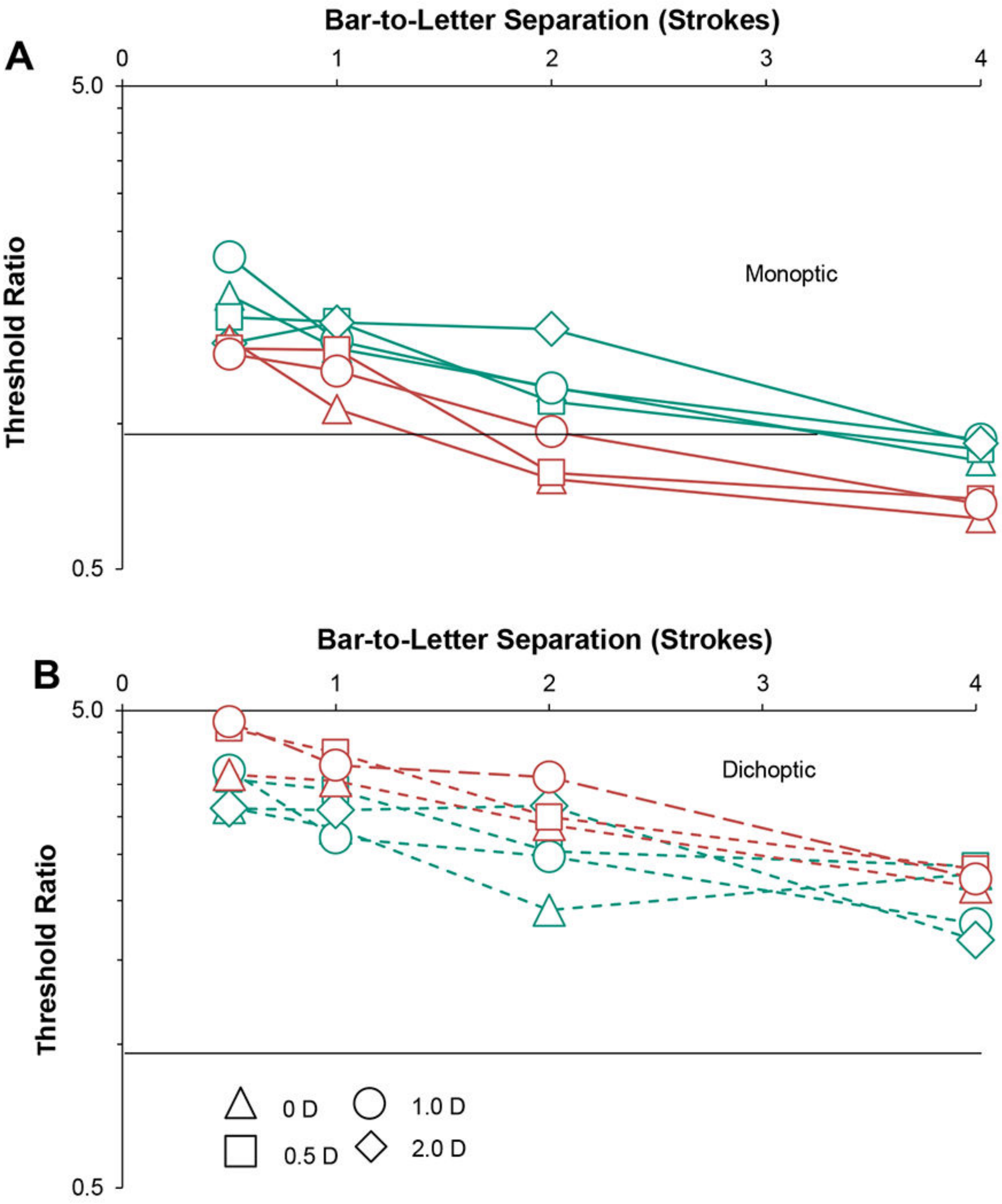

Figure 5.

Average threshold ratios for 2 observers are plotted against the separation, in stroke widths, between the central high-contrast letter and surrounding bars. Threshold ratios in the *Monoptic* and *Dichoptic* viewing conditions are in the top **(A)** and bottom **(B)** panels, respectively. Within each panel, the data for bar targets presented to the sighting dominant and non-dominant eyes are represented by green and red symbols, respectively. As in Figure 4, the triangles, squares, circles and diamonds indicate simulated blur of the bar targets of 0, 0.5, 1 and 2 D. Median standard errors for bar targets presented to the sighting-dominant and non-dominant eyes are 12.2% and 9.9% of the threshold ratio in panel A and 8.9% and 11.2% in panel B. The horizontal line in each panel indicates a threshold ratio of 1.