Horizontal and vertical asymmetry in visual spatial crowding effects

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The crowding effect is a ubiquitous phenomenon in spatial perception that has been extensively investigated. A notable property of spatial crowding is the radial and tangential asymmetry in which crowding is much more severe for items arranged on a radial line originating from the fixation point compared with items arranged tangentially with regard to the fixation point. Here, we report another asymmetric property of the crowding effect between horizontally and vertically arranged spatial layouts. In multiple experiments using a number of different stimulus patterns (e.g., letter Cs, letter Ts, and parallel/nonparallel line segments), results consistently showed that the crowding effect was significantly stronger when the target and distractors were horizontally rather than vertically arranged. Such a horizontal versus vertical asymmetry was found in all four quadrants of visual space. Importantly, a further visual acuity test did not reveal a horizontal versus vertical asymmetric effect.

Keywords: crowding, asymmetry, horizontal, vertical, visual field, Vernier acuity


Introduction

The crowding effect is a ubiquitous phenomenon in visual spatial perception. When a target stimulus is surrounded by other distractors (flankers), visual discrimination of the target becomes more difficult. This effect has been studied extensively with letters, digits, and gratings (Bouma, 1970; Chung, Levi, & Legge, 2001; Felisbert, Solomon, & Morgan, 2005; Strasburger, 2005; Strasburger, Harvey, & Rentschler, 1991; Stuart & Burian, 1962). Many factors have been found and determined to have significant influences on the crowding effect. For example, the crowding effect can be strengthened by increasing the number of distractors (Felisbert et al., 2005) and the eccentricity of the target (Bex, Dakin, & Simmers, 2003; Bouma, 1970; Jacobs, 1979) or be reduced by increasing the spatial separation (Bouma, 1970; Felisbert et al., 2005; Toet & Levi, 1992) and the dissimilarity between the target and the distractors (Andriessen & Bouma, 1976; Kooi, Toet, Tripathy, & Levi, 1994; Leat, Li, & Epp, 1999; Nazir, 1992). The exact neural mechanism for crowding remains a subject of research. Explanations for this phenomenon include a lateral inhibition between the target and the distractors at the visual feature level ( Bjork & Murray, 1977), improper spatial pooling of the features (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Wilkinson, Wilson, & Ellemberg, 1997), and insufficient visual attention resolution (He, Cavanagh, & Intriligator, 1996, 1997; Strasburger, 2005; Strasburger et al., 1991).

The spatial property and interaction across visual fields have also been extensively examined. For example, several studies revealed better visual performance (Hofmann & Hallett, 1993; Talgar & Carrasco, 2002) and finer attentional resolution in the lower compared with upper visual field (He et al., 1996, 1997; Intriligator & Cavanagh, 2001). Another well-established property of crowding is the radial–tangential asymmetry (Chambers & Wolford, 1983; Toet & Levi, 1992). Toet and Levi (1992) found that the zone of spatial interaction appears to be more or less elliptical in shape in the peripheral visual field, with the long axis along a radial line connecting the fovea to the peripheral location of the test. They also found that, in the lower visual field, the spatial interaction zones were considerably larger when flanking T s were above and below a test T (vertical alignment) than when the flanking T s were on either side of the test T (horizontal alignment; Toet & Levi, 1992). We believe that their manipulation of the target presented a horizontal versus vertical bias in that the target was intrinsically more
difficult to discriminate in the vertical configuration (more on this in the General discussion section).

In the current study, we focused our effort on investigating the asymmetric property associated with crowding, especially between horizontal and vertical configurations. In three experiments, we used different discrimination tasks with letter Cs, letter Ts, and parallel/nonparallel line segments as target stimuli. The results consistently revealed a stronger crowding effect in the horizontal compared with vertical configuration.

**Experiment 1: The crowding effect for horizontal and vertical configurations**

We examined the crowding effect for horizontally and vertically arranged spatial layouts using three types of stimuli: letter Cs, letter Ts, and parallel/nonparallel line segments.

**Methods**

**Observers**

The three types of stimuli were run in different sessions. Eight observers (three women) participated in the experiment using letter Cs; six observers (one woman) were tested using letter Ts; and six observers (one woman) participated in the experiment using parallel/nonparallel line segments. All participants had normal or corrected-to-normal vision. Participants gave written informed consent in accordance with procedures and protocols approved by the human subjects review committee of the University of Minnesota.

**Apparatus**

Stimuli were coded using the psychophysical toolbox (Brainard, 1997; Pelli, 1997) in Matlab and were presented on a 17-in. Sony monitor (1,024 × 768 pixels at 100 Hz).

**Stimuli and design**

In Experiment 1.1, the target and distractor stimuli were both letter Cs, as shown in Figure 1. Each letter C subtended a visual angle of 1.79 × 1.79°, with an angular gap of 45°. The gap could point to any of the four directions (left, right, up, or down). Another two letter Cs served as distractors (with their orientations randomly selected from the four possible orientations, excluding the possibilities where both distractors were in the same orientation as the target), aligned either horizontally or vertically to the central target. The center-to-center distance between the target and the distractor was 1.97° (Figure 1 and the top row of Figure 2). Experiment 1.2 was the same as Experiment 1.1 except that the target was the letter T and the distractors were replaced with squared-theta. Each T subtended a visual angle of 1.1 × 1.1° and could be presented in any of the four orientations (left, right, up, or down). Squared-thetas were used as distractors because they were effective in interfering with the identification of the target due to their similar contours with the letter T (Tripathy & Cavanagh, 2002). The center-to-center distance between the target (T) and the distractor (squared-theta) was 1.25° (Figure 2, middle row). The target in Experiment 1.3 was a pair of line segments, either parallel or nonparallel. Each line segment was tilted 10° from true vertical or horizontal orientations, resulting in eight different combinations (four parallel and four non-parallel), as shown in the bottom row of Figure 2. The upper four pairs were used as the target in the horizontal alignment with distractors, and the lower four pairs were

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Figure 1. Spatial parameters of stimuli used in Experiment 1 using the letter C as an example. The target letter C is shown in the same location (Quadrant 4) in Panels a and b, but the distractors were either horizontally (a) or vertically (b) flanking the target.
used as the target in the vertical alignment with distractors. The distractors were the same as in Experiment 1.2 (squared-theta).

A central dark disc with a pinhole was presented throughout the duration of the experiments, serving as a fixation point. During the experiment, the target and distractors were aligned either horizontally or vertically and were presented on a uniform gray background. The mean luminance of the stimulus pattern and the background was 1.08 and 25.6 cd/m², respectively. In each trial of Experiment 1.1, the stimulus pattern was presented in one of the four quadrants of the visual field with the central target at 7.6° of eccentricity (Figure 1). Thus, each type of stimulus resulted in eight conditions [2 (arrangements: horizontal vs. vertical) × 4 (quadrants)]. In Experiments 1.2 and 1.3, the stimulus pattern was only presented in the third and the fourth quadrants, and all other aspects were the same as in Experiment 1.1. All conditions were mixed randomly within blocks.

**Procedure**

Observers sat 50 cm away from the monitor and viewed the display binocularly. Observers were required to fixate at the fixation point throughout the experiment. At the beginning of each trial, there was a small bar pointing from the fixation point to one of the quadrants, indicating the spatial location where the stimuli would be presented (Figure 3). The central cue was presented for 1,000 ms, followed by the test stimuli presented at the cued quadrant for 250 ms (Figure 3). In Experiments 1.1 and 1.2, observers pressed one of four direction keys to indicate the orientation of the letter C or letter T (left, right, up, or down). In Experiment 1.3, observers were asked to press
one of two keys to indicate whether the line segments were parallel or nonparallel to each other.

**Experiment 1.1 (letter C)** consisted of eight blocks with 64 trials in each block. **Experiment 1.2 (letter T)** and 1.3 (parallel/nonparallel line segment) each consisted of four blocks with 64 trials in each block, and observers were tested in either the lower left or lower right quadrant.

## Results and discussion

**Experiment 1.1 (C)**

Percentages of correct responses to different crowding conditions (horizontal vs. vertical) and different visual fields are shown in Figure 4, and a repeated measures analysis of variance (ANOVA) was carried out with spatial configuration (horizontal vs. vertical) and visual field (four quadrants) as independent variables. Observers’ performance was significantly better when the stimuli were aligned vertically than horizontally, as revealed by the significant main effect of spatial configuration, $F(1, 7) = 9.40, p = .02$. The main effect of visual field (different quadrants) was also significant, $F(3, 7) = 3.41, p = .04$, and observers performed better in the lower compared with the upper visual field. There was no interaction between spatial configuration and visual field, $F(3, 21) = 0.036, p = .99$, suggesting that the crowding effect is more severe in the horizontal configuration in all four quadrants.

**Experiment 1.2 (letter T)**

To further test whether the asymmetric horizontal and vertical crowding effects were specific to the stimulus we used or were a general property of crowding, we used letter T and squared-theta as the target and distractors, respectively, in Experiment 1.2. The stimuli were presented only in the third and the fourth quadrants; all other aspects were the same as in Experiment 1.1.

The results from six observers are shown in Figure 5. Consistent with Experiment 1.1 (letter C), Experiment 1.2 still showed a significant asymmetric crowding effect, $t(5) = 6.20, p = .002$. In other words, the crowding effect was significantly stronger when the target and flankers were arranged horizontally than vertically.

As mentioned earlier, our observation of horizontal and vertical asymmetry is inconsistent with what was reported in a previous study (Toet & Levi, 1992). In the study of Toet and Levi (1992), the letter T was used as the target, but the target T could be in either upright or inverted orientations. We suspected that because the target T is not

![Figure 4](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932848/ on 06/09/2017)
isotropic, discriminating an upright T from an inverted T could be hampered more by distractors on top and below the target than distractors on the left and right sides of it. This is because the critical information for upright versus inverted discrimination is the location of the horizontal bar in the T: Is it on the top or is it at the bottom? A more detailed examination of our data provides strong support for this interpretation. When we reanalyzed our results by separating the data into 2 (horizontal target T vs. vertical target T) × 2 (horizontal crowding vs. vertical crowding) subgroups, we found a significant interaction between the orientation of the target T and the orientation of the spatial configuration (Figure 5, right). A repeated measures ANOVA shows a significant interaction between target orientation (horizontal vs. vertical) and spatial configuration of the flankers, target discrimination with the horizontal T in the horizontal spatial configuration was more severely degraded compared with the vertical T in the vertical spatial configuration (Figure 5, right). The overall effect with the target T was the same as that using the target letter C; crowding is more severe in the horizontal direction than in the vertical direction.

**Experiment 1.3 (parallel/nonparallel line segments)**

Experiments 1.1 and 1.2 revealed a robust asymmetric crowding effect between horizontally and vertically arranged spatial layouts. Because the targets in these experiments were letters (C and T), it is possible that the observed asymmetry applies to letter discrimination only. For instance, when target and distractors were horizontally aligned, the stimuli were more likely to be considered as a trigram, and our usual reading experience could potentially integrate and group this horizontal information more strongly compared with vertical alignment. To test this possibility, we ran a third experiment by replacing the target letters with two line segments that could be either parallel or nonparallel from each other. Similar to Experiment 1.2, the stimuli were presented only in the third and the fourth quadrants. The data obtained from six individual observers, as well as a group average, are shown in Figure 6, and a paired-sample t test clearly showed a significant asymmetric crowding effect, t(5) = 3.49, p = .02,
with better performance for vertical than for horizontal spatial arrangement.

Because the targets for the horizontal and vertical spatial configurations also differed in the target orientations, we also obtained the baseline for discriminating parallel/nonparallel line segments without flankers as a control experiment. The targets (line segments) were presented in the same spatial location as Experiment 1.3 for 50 ms without distractors, and the observers were asked to complete the same discrimination task (parallel or nonparallel). There was no significant difference in this control experiment (77.7% vs. 80.7%), \( t(5) = 1.23, p = .27 \).

Experiment 2: Vernier acuity and bisection

In this experiment, we aimed to investigate whether the asymmetric crowding effect obtained in Experiment 1 was specific to crowding or due to horizontal and vertical asymmetries in visual acuity. Therefore, a Vernier visual acuity test and a three-dot bisection discrimination test were adopted in this experiment, with the same spatial arrangement as in Experiment 1.

Methods

Observers

Eight observers were randomly recruited from those who have participated in Experiment 1. All eight took part in the Vernier acuity test session, and six of them also participated in the three-dot bisection test session.

Stimuli and design

The experimental design and procedure were the same as in Experiment 1, except that the target and distractors were replaced with three dots, as shown in Figure 7. The diameter for each dot is 0.46°, and the center-to-center distance between the two outside dots is 3.94°. In the Vernier acuity test (upper row), the central dot was slightly shifted perpendicular to the straight line connecting the two outside dots. In the three-dot bisection test (lower row), the central dot was slightly shifted along the straight line connecting the two outside dots.
Figure 8. Results of Experiment 2 for the Vernier acuity test (A) and the three-dot bisection test (B). Numbers (1, 2, 3, and 4) indicate the quadrants where test dots were presented. Error bars indicate $\pm 1$ SEM.
dots were presented at the same spatial locations as those of the target and distractors in Experiment 1.

In the Vernier acuity test session, the central dot was slightly shifted perpendicular to the straight line connecting the two outside dots; that is, when the three dots were arranged vertically, the central dot could slightly shift either left or right, and when the three dots were arranged horizontally, the central dot could slightly shift either up or down. In the three-dot bisection test session, the central dot was slightly shifted along the straight line connecting the two outside dots; that is, when the three dots were arranged horizontally, the central dot could slightly shift either left or right from the center, and when the three dots were arranged vertically, the central dot could slightly shift either up or down from the center. Observers were asked to press one of the four keys to indicate the shift direction of the central dot. Each test session consisted of 512 trials, which was divided into eight 64-trial blocks, with the order of each condition randomized.

Results and discussion

Vernier acuity

The results are shown in Figure 8A. ANOVA was applied on these data with spatial configuration and visual field as the two main factors. No significant differences were found for spatial layout (horizontal vs. vertical), $F(1, 7) = 2.10, p = .19$, and visual field (four quadrants), $F(3, 7) = 0.40, p = .75$, nor was there a significant interaction between these two factors, $F(3, 21) = 0.12, p = .95$. Although the difference between horizontal and vertical Vernier performance did not reach statistical significance, we note here that it seems that Vernier acuity was a bit better in the horizontal than the vertical configuration. This is consistent with a recent article showing a “somewhat” better performance for horizontal over vertical Vernier stimuli (Westheimer, 2005). In any case, it is unlikely that the vertical advantage in crowding effect could be explained by a better spatial resolution along the vertical dimension.

Three-dot bisection

Results for the three-dot bisection test are presented in Figure 8B. Similar to the Vernier test, there were no significant main effects for spatial layout, $F(1, 5) = 0.29, p = .61$, and visual field, $F(3, 5) = 0.74, p = .54$, nor was there a significant interaction between them, $F(3, 15) = 0.71, p = .56$. This is also consistent with previous finding (Yap, Levi, & Klein, 1987).

Taken together, both the Vernier test and the three-dot bisection test showed minimal difference between the horizontal and vertical spatial configurations. These results support the idea that the horizontal and vertical asymmetry observed in Experiment 1 is not a property of low-level sensory processing, but likely of a higher level origin.

General discussion

The current study examined the crowding effect for horizontally and vertically arranged spatial configurations. Experiment 1, using letter Cs, letter Ts, and parallel/nonparallel line segments as target stimuli, consistently found that the crowding effect was significantly stronger when the target and distractors were horizontally rather than vertically arranged. This effect was found in all four quadrants of the visual field.

The horizontal and vertical asymmetry in crowding adds to the two other well-known asymmetric properties in spatial crowding—stronger crowding for radial than tangential configuration and stronger crowding from outer than inner flanker. The stimuli in our experiments were placed in diagonal locations in the four quadrants, avoiding the potential confounding effect from tangential and radial asymmetry in testing the horizontal and vertical crowding effects. If the stimuli were centered on the horizontal meridian either to the left or right of the fixation, then the horizontal versus vertical asymmetry and the radial versus tangential asymmetry make the same prediction that the horizontal configuration (at the same time it is a radial configuration) would suffer from a much stronger crowding effect than would the vertical configuration (at the same time a tangential configuration). However, if the stimuli were centered on the vertical meridian either above or below the fixation, then radial versus tangential asymmetry predicts a stronger crowding effect for the vertical spatial arrangement, contradicting the prediction based on findings reported in this article. Under this condition, our preliminary observation suggests that radial/tangential asymmetry is the more significant variable. Thus, for targets placed on the vertical meridian, vertically aligned flankers would still generate a stronger crowding effect than horizontally aligned flankers would.

The results of our second experiment and results from previous studies show that visual acuity (e.g., Vernier and bisection) was not very different in the horizontal and vertical direction, suggesting that the asymmetric crowding effect we observed here is likely due to factors beyond visual spatial resolution. The Vernier acuity measurements in our second experiment and the study of Westheimer (2005) actually indicate a somewhat better performance for the horizontally versus vertically aligned Vernier test.

One factor that may contribute to the horizontal versus vertical asymmetry in crowding effect is that all of our subjects read horizontally. It is possible that our attentional mechanism tends to organize the horizontally arranged items into a single unit (i.e., like a trigram.
word), but such an organization is less likely to occur for the vertically oriented spatial layouts. As a result, there is stronger integration horizontally than vertically. Admittedly, this reading-experience-related explanation is quite ad hoc. Another possibility is that our visual environment is intrinsically more related horizontally than vertically, and consequently, the shape of our attentional window is more elongated horizontally. Indeed, a previous study also suggested that attentional window (distribution) might be elliptical in shape (Pan & Eriksen, 1993). Taking the view that crowding is due to the lack of attentional resolution (He et al., 1991), it follows that more severe crowding would occur horizontally than vertically. No matter what the explanation is, our finding of a stronger crowding effect in the horizontal configuration raises the interesting practical possibility for people who have to use their peripheral vision to read (such as macular degeneration patients): It might be more efficient to present the text vertically in the peripheral. Further studies are obviously required to test this idea.

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