Crowding in Central and Eccentric Vision: The Effects of Contour Interaction and Attention

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PURPOSE. To quantify the crowding effect with eccentric stimuli and to determine the relative contribution of neural interaction and attention to crowding in central and eccentric vision.

METHODS. Monocular visual acuity was measured with computer-generated tumbling E and Landolt C targets presented centrally or at 2° in the right visual field. Crowding distractors were designed to cause increasing contour interaction or increasing need for focused attention. A four-alternative forced-choice method of constant stimuli was used. In experiment 2 the distance between the target and the distractors varied.

RESULTS. Data are presented in terms of normalized visual acuity. Crowding in central vision was minimal, mainly caused by contour interaction, and did not occur with distractors more than four stroke widths distant. Crowding in eccentric vision was far greater in magnitude and extent (occurring for distractors as far as 16 stroke widths distant) and was caused by contour interaction and attentional factors.

CONCLUSIONS. The results indicate that eccentric vision differs quantitatively and qualitatively from central vision. The extent of contour interaction effects are consistent with the proposed size of cortical processing zones. The results are discussed with reference to current theories of preattentive and attentive tasks and with reference to subjects with low vision due to central scotoma who use an eccentric retinal locus for fixation. (Invest Ophthalmol Vis Sci. 1999;40:504–512)
resolution (MAR) increased by 1.4X with bars 1.5X stroke widths away, and Chung and Bedell\(^9\) found an increase of 1.12 to 1.38X (0.05-0.14 log units) depending on the type of surrounding contours. Eccentrically (0.5°-10°), Jacobs\(^14\) found that the MAR increased by 1.14 to 2.18X (0.057-0.338 log units), with the differences increasing with increasing eccentricity.

It is the leading, or most proximal, edge of the distractor bars that cause the neural interaction\(^15\) in central vision. The addition of extra contours (from one- to two-bar distractors)\(^12\) or the addition of more eccentrically placed distractors\(^2\) has little effect on crowding in central vision. It appears that central vision is mainly affected by contour interaction and that attention has very little influence. Eccentric acuity behaves differently. Flom\(^2\) suggests that it is not only more disrupted by contour interaction, but is also far more sensitive to the effects of divided attention than is central vision. In eccentric vision, crowding is not only determined by the most proximal edge, but a more eccentrically placed distractor has a greater effect on target recognition than a more centrally placed one.\(^16\)\(^17\)

The extent of the attentional and contour interaction effects on target recognition than a more centrally placed one.\(^16\)\(^17\)

The extent of the attentional and contour interaction effects are also different, with contour interaction dominating with closely placed distractors (e.g., at 1 stroke width) and attention dominating with more widely spaced distractors (e.g., 10 stroke widths).\(^8\) Flom\(^2\) suggests that contour interaction may affect recognition at distances as great as 25 to 50 stroke widths' separation in the periphery and that attentional effects may operate at even greater separations.

The evidence that contour interaction occurs in the cortex is that contour interaction occurs equally with distractors that are presented dichoptically from the target (i.e., the distractor in one eye and the target in the other).\(^5\)\(^16\)\(^18\) However, these studies do not distinguish between contour interaction and attention and may indicate that attention occurs at a higher level, which would be expected. It has been suggested that attention is controlled by the dorsal parietal area.\(^6\)

In this study we attempted to distinguish between contour interaction and attentional effects. Treisman\(^4\) discusses how, in search tasks, a target that is dissimilar to the array of distractors in some feature calls attention to itself and "pops out" of the array immediately. These tasks are known as pre-attentive. In displays in which the targets are not highly discriminable or different from the distractors, attention is required. It has been suggested that the more similar the targets are to the distractors and the more unpredictable the distractors, the more noise or "confusability" there is within the stimulus as a whole.\(^19\)\(^20\) and the more attention must be focused on the target.\(^4\) We used this idea and chose distractors that (a) provided increasing amounts of contour interaction and (b) required increasing focusing of attention. We propose that, as the number of adjacent contours surrounding a target letter increases, so does the amount of contour interaction. We also propose that distractors with increasing similarity to the target and increasing unpredictability of orientation require increased focusing of attention. Because the distractors are more noisy and less discriminable from the target, increased focusing of attention is required to filter out the target from the surrounding noise.\(^19\)\(^22\) Thus, targets surrounded by distractors that are in a unknown and random orientation require more attention than those surrounded by distractors in an upright and predetermined orientation. In experiment 2 we also varied the degree of contour interaction and attentional demand by varying the separation between the target and distractors.

There are few data providing quantification of the extent of contour interaction in the periphery.\(^3\) Jacobs\(^14\) measured contour interaction quantitatively with distractors as distant as five stroke widths and found that contour interaction was still strong at that separation (1.14-1.74X). Many studies have measured the change in the percentage of correct identification\(^2\)\(^6\)\(^11\)\(^12\) rather than determining the acuity threshold. The problem with the former approach is that there is no quantification of the reduction of visual acuity and there may be a ceiling or floor effect on the data (i.e., large changes cannot be measured and compared). Therefore, we chose to measure actual acuity thresholds and thus to quantify the actual loss of acuity caused by crowding in central and eccentric vision, with distractors as distant as 16 stroke widths.

Because of our interest in increasing our understanding of crowding with particular reference to its application to low vision observers, we chose a slightly longer exposure duration of 500 msec. This did not not completely eliminate eye movements. The reason for this choice is that subjects with low vision may make longer fixations during reading and similar acuity tasks than normal observers. Rubin and Turano\(^23\) show data that indicate that roughly 600 msec are required to process the information from one word in subjects with central field loss. Bullimore and Bailey\(^24\) show fixation durations of approximately 500 msec in normal observers and those with low vision when reading text near threshold, and Runnyme and Leat\(^25\) found fixation durations of approximately 300 msec in subjects with a central scotoma. In addition, in visually normal observers, Kooi et al.\(^26\) found that duration did not have a significant effect on the relative difficulty of detecting targets with similar or dissimilar distractors.

**Experiment 1**

**Methods**

**Subjects.** Ten adult observers, 8 women and 2 men (age range, 21-40 years), participated in the experiment. The exclusion criteria were abnormal ocular or general health, amblyopia or strabismus, and a history of eye disorder or corrected visual acuity less than 6/6. All wore their updated refractive correction for the duration of the experiment. Testing was undertaken monocularly. In experiments 1 and 2, the research followed the tenets of the Declaration of Helsinki, and informed consent was obtained after an explanation of the nature and possible consequences of the study.

**Stimuli.** Computer-generated stimuli were used to measure monocular visual acuity with Landolt C and tumbling E targets presented centrally or 2° eccentrically in the right visual field. During eccentric testing, the subject was asked to maintain fixation on an X placed 2° left of the position of the central letter. In four experimental series the target letters were centrally presented Cs, centrally presented Es, eccentric Cs, and eccentric Es. Each target letter was presented in isolation or surrounded by various distractors (Fig. 1A). The letters were generated so that the space between the target and the distractors was 1.2 letter stroke widths (1.2X the gap width for the Cs and 1.2X the stroke widths between the prongs of the Es). This value of 1.2 stroke widths was chosen from consideration of Flom's data\(^2\) in which he shows that crowding is at a maximum
with centrally presented targets when the distractors are at approximately this distance. Jacobs finds that the maximum effect was between 0.5 and 1.25 stroke widths for eccentric targets, but the function is fairly flat. Therefore, we chose a 1.2-distractor separation to obtain the maximum effect for centrally presented targets and at which a significant effect would still be apparent eccentrically. To provide varying amounts of contour interaction, the upright letters I, L, F, C (serif and sans serif), and E were chosen as distractors. A square figure eight was also included to provide maximum contour interaction. To require differing degrees of attentional demand, two additional conditions were included. The tumbling Es were surrounded by Ees placed in an outward orientation or by randomly oriented Es. Similarly, the Landolt Cs were surrounded by outwardly or randomly oriented Cs. The black letters were presented on a white computer screen, with a white surround (to stabilize light adaptation). The Weber contrast of the letters was 94% (C = $I_{\text{max}} - I_{\text{min}}/I_{\text{max}}$, where $I_{\text{max}}$ and $I_{\text{min}}$ were the luminance of the background screen area and the letter, respectively). The luminance of the white computer screen background was 136 candles (cd)/m². The testing distance was 6 m with central targets and 3 m with eccentric targets. The stimulus duration was 500 msec. At the testing distance of 6 m, the range of acuity levels was 0.9 logMAR (6/48) to -0.3 logMAR (6/3) in intervals of 0.1 logMAR, and at 3 m the range was 1.2 logMAR (6/96) to 0 logMAR (6/6).

**Procedure.** One experimental session was composed of acuity measurements for a given target type and location (e.g., centrally presented Cs). The sequence of distractor type was randomized between subjects within this run and included measurements of acuity with no distractor, to minimize practice effects in the averaged results. A four-alternative forced-choice method of constant stimuli was used with 10 presentations at each visual acuity level. To calculate threshold, the running average method was used whereby, at each acuity level, the average of the percentage correct at that level, and the two adjacent levels (the one above and the one below) were calculated. The target threshold was 62.5% correct (halfway between the 25% chance level and 100%). The run was terminated once the running average decreased below 62.5%, because further testing would have no impact on the final calculated threshold. Thus, the number of stimulus levels varied among runs, but was at least four, and more usually, six to eight. The 62.5% level was calculated by extrapolating with a straight line between the running averages above and below 62.5%. This method has low computational demands, and provides results that are close to the linear regression least-squares-fit method (with most thresholds within 0.01 of the linear regression method). Simpson has shown that the linear regression method results in no bias and provides thresholds that are within 0.01 log unit compared with probit analysis and is as accurate as other methods such as normit, $z$-score regres- sion, or logit regression, as long as data from the middle linear part of the graph are used. The running average ensures that data only from the central portion of the curve, on either side of the threshold, are used.

In each session, two practice measurements of threshold were obtained before actual acuity measurements began. This allowed the subject to become familiar with the target and visual field location combination. For centrally presented stimuli, the starting level for the method of constant stimuli was determined by using a rapidly descending staircase method with one presentation at each level. The starting point for the method of constant stimuli was two levels above (0.2 logMAR) that of the first error. For eccentric acuity measurements, the starting point for the method of constant stimuli was 1.2
Normalised Visual Acuity for Central E's

![Graph A](image)

Normalised Visual Acuity for Central Serif C's

![Graph B](image)

FIGURE 2. Visual acuity (VA) normalized against single-letter VA (logMAR crowded VA — logMAR single-letter VA) against distractor type. (A) VA with centrally presented tumbling Es; (B) VA with centrally presented serif (Landolt) Cs. Error bars, ±SE.

Eccentrically Presented Targets. Eccentrically presented Es and Cs are possibly more sensitive to contour interaction, shown by the fact that there was a greater difference between the crowding produced by I distractors and the other distractors. However, increasing the number of adjacent con-

logMAR, because eccentric acuity was poorer and seemed to be more susceptible to practice effects than central acuity, and beginning at the higher acuity level allowed more practice time for the subject before approaching the threshold.

Results

In each subject, the results were normalized against acuity without surround distractors. The mean normalized visual acuity is shown in Figures 2A and 2B for centrally presented targets and in Figures 3A and 3B for eccentrically presented targets. Distractors thought to provide different amounts of contour interaction were analyzed separately from those thought to provide differing attentional demand. The results of the analysis of variance (ANOVA) are shown in Table 1.

Centrally Presented Targets. The results show that with central Es and Cs, there were no consistent effects of distractor type on crowding. With E targets, the ANOVA was significant for distractors that were thought to cause different amounts of contour interaction (P = 0.0367), but a post hoc t-test showed that this was because of the lower crowding elicited by the I distractor (P < 0.05), which would be expected to provide less contour interaction. Similarly, with the C targets, the ANOVA was significant (P = 0.0441), because of the I distractor's eliciting less crowding than the L or the serif C. There were no significant differences among other distractors that were thought to provide increasing amounts of contour interaction (i.e., the presence of additional contours, such as F distractors or square figure eights, did cause not further crowding). With Cs and Es, there was no significant effect of increasing attentional demand, as shown by the fact that the upright distractors and randomly oriented distractors did not cause significantly more crowding than the other letters. Neither was a difference in crowding elicited by the upright, outward, or randomly oriented distractors for Cs or Es (P = 0.136 and 0.227, respectively).

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**TABLE 1. Analysis of Crowding Effect Elicited by Tumbling Es and Landolt Cs**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>ANOVA $F$</th>
<th>ANOVA $P$</th>
<th>Post Hoc Analysis (t-Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central fixation, tumbling E targets; distractors: I, L, F, sans serif C, serif C, upright E, square figure eight</td>
<td>2.442</td>
<td>0.0367*</td>
<td>I distractor elicited less crowding than all except for square figure eight</td>
</tr>
<tr>
<td>Central fixation, tumbling E targets; distractors: upright E, random E, outward E</td>
<td>1.611</td>
<td>0.2272</td>
<td></td>
</tr>
<tr>
<td>Central fixation, Landolt C targets; distractors: I, L, F, sans serif C, serif C, upright E, square figure eight</td>
<td>2.342</td>
<td>0.0441*</td>
<td>I distractor elicited less crowding than L and serif C</td>
</tr>
<tr>
<td>Central fixation, Landolt C targets; distractors: upright C, random C, outward C</td>
<td>2.228</td>
<td>0.1365</td>
<td></td>
</tr>
<tr>
<td>Eccentric fixation, tumbling E targets; distractors: I, L, F, sans serif C, serif C, upright E, square figure eight</td>
<td>13.488</td>
<td>2.798**</td>
<td>I and L distractors elicited less crowding</td>
</tr>
<tr>
<td>Eccentric fixation, tumbling E targets, distractors: upright E, random E, outward E</td>
<td>3.357</td>
<td>0.0577†</td>
<td>Random Es elicited more crowding than upright Es</td>
</tr>
<tr>
<td>Eccentric fixation, Landolt C targets; distractors: I, L, F, sans serif C, serif C, upright E, square figure eight</td>
<td>7.886</td>
<td>4.01***</td>
<td>I distractor elicited less crowding, serif C elicited more crowding</td>
</tr>
<tr>
<td>Eccentric fixation, Landolt C targets; distractors: upright C, random C, outward C</td>
<td>6.921</td>
<td>0.0059*</td>
<td>Random Cs elicited more crowding</td>
</tr>
</tbody>
</table>

Central and eccentric acuity has been normalized against acuity for single targets (no distractors). The results of the post hoc analysis are shown to indicate which distractors elicited these significant differences.

* Significant at $P = 0.05$.
† Borderline significance at $P = 0.05$.


tours (e.g., letters F or square figure eight) did not result in consistently increased crowding. Eccentric acuity was more affected by attentional demand, shown by the finding that there was more crowding with randomly presented distractors than with those in predetermined orientations. This effect was found with both E and C targets (ANOVA, $P = 0.0577$ and 0.0059, respectively).

**Discussion**

In central vision, there was a definite crowding effect produced by all distractors, with the exception of the E targets surrounded by I distractors ($P = 0.207$; t-test). However, an increase in the number of adjacent contours elicited no consistent increases in the crowding effect. The simple presence of any contour adjacent to the target produced crowding. This agrees with the findings of Manny et al. \(^{12}\) Nor was central vision sensitive to attentional effects; there were no significant differences in crowding produced by upright, outward, or randomly oriented distractors. As found by other investigators, the magnitude of crowding in eccentric vision was much greater. Crowding in eccentric vision seemed to be more sensitive to the effects of attention and contour interaction (note the difference between $y$-axis scales in Figs. 2 and 3). We investigated both of these further in experiment 2.

**EXPERIMENT 2**

In experiment 1 eccentric vision was shown to be sensitive to crowding due to contour interaction and attentional demand, whereas central vision showed less crowding, and the effect was caused only by contour interaction. In experiment 2 we attempted to investigate this further by varying the separation of the distractors from the target in central and eccentric vision to determine the spread of attentional and contour interaction. We were particularly interested in eccentric vision. It is possible that the spatial extent of the two effects is not the same, and that we may be able to isolate one effect by varying this separation. Other studies have suggested that the effects of attention have a much greater spatial extent than contour interaction with eccentric targets.\(^{2,4}\) Because experiment 1 indicated that there were no large differences between most of the distractors, we limited the distractor types to I and figure eight (to provide increasing contour interaction) and figure eight, upright, and randomly oriented Cs to provide increasing attentional demand (but similar contour interaction; Fig. 1B).

**Method**

**Subjects.** Ten subjects, 6 women and 4 men (age range, 20–41 years), participated in this section of the study. Exclusion criteria were the same as for experiment 1. Again, all wore their refractive corrections, and testing was undertaken monocularly.

**Procedure.** We used two types of C target for this experiment, serif C (as in experiment 1) and sans serif C (Fig. 1B). We had already shown that many letters elicited equal amounts of contour interaction. Therefore, only a few of these letters were chosen as distractors in experiment 2. For central stimuli, these were the letter I and the square figure eight plus a distractor identical with the target and in the upright position (i.e., sans serif C for sans serif C targets). To investigate the effects of attention, for eccentric stimuli, there was an additional distractor, a randomly oriented letter identical with the target.

The distractors were separated from the target by 1, 2, 4,
Results

The results were normalized against acuity for uncrowded Cs and are shown in Figures 4 and 5.

Central Targets. There was a strong effect of changing separation for serif and sans serif Cs (Figs. 4A and 4B). There was no significant crowding effect with distractors at 8 or 16 stroke widths' separation (ANOVA; sans serif Cs, \( P = 0.011 \) [but in the opposite direction] and 0.86, respectively; serif Cs, \( P = 0.37 \) and \( P = 0.87 \), respectively). The crowding effect was of borderline significance at a separation of 4 (ANOVA; sans serif Cs, \( P = 0.059 \); serif Cs, \( P = 0.021 \)). For closer distractors (1 and 2 stroke widths) the crowding effect was fairly strong, decreasing acuity by 0.1 to 0.15 log units.

There were no consistent effects of type of distractor that would indicate strong effects of increasing contour interaction or attentional demand. We considered the effects of type of distractor at separations of 1 and 2, at which there are definite crowding effects. With sans serif Cs, two-factor ANOVA with

8, or 16 stroke widths. One experimental session was composed of acuity measurements for a given target type and location (e.g., centrally presented serif Cs). The sequence of distractor type was randomized between subjects within this session. Separation distance was then randomized within distractor type. The uncrowded acuity measure (no distractor) was randomly placed between blocks of distractor type.

The experimental procedure was the same as in experiment 1 with the following exceptions: The contrast of the letters was 92%, and the background luminance of the screen was 123 cd/m². These slight differences in contrast and luminance were caused by changes with time but were not sufficient to affect the comparability of the results.\(^\text{27}\) The test distance was 9.6 m with the central targets, 3.8 m with sans serif Cs, and 3 m with serif Cs. These distances were used to ensure that an appropriate range of acuity levels was possible. Pretesting had indicated that acuity for eccentric serif Cs was substantially worse than for sans serif Cs.

\[\text{normalised Visual Acuity for Central Serif C} \]

\[\text{normalised Visual Acuity for Central Sans-Serif C} \]

\[\text{normalised Visual Acuity for Eccentric Serif C's} \]

\[\text{normalised Visual Acuity for Eccentric Sans-Serif C's} \]
replication showed that there was a significant difference between the I and C distractors \( (P = 0.0052) \) but not between the figure eight and I distractors \( (P = 0.099) \) or between figure eight and C distractors \( (P = 0.107) \). Without serif Cs the same analysis was undertaken, including distractors at one, two, and four stroke widths (all of which produced significant crowding). There were no significant differences among I, C, or figure eight distractors.

**Eccentric Targets.** As expected, there was a much stronger crowding effect with eccentric targets than with central targets, with acuity reduced by as much as 0.7 log units in the former case (Fig. 5). The extent of the effect was also much greater, with significant crowding shown, even at the largest separation that we could use, 16 stroke widths. A t-test between single letters and crowded letters showed that there was significant crowding with all distractors. This was true even with I distractors at 16 stroke widths' separation, which created the least crowding (sans serif Cs, \( P = 0.005 \); serif Cs, \( P = 0.027 \)). There was an effect of type of distractor across all separations for serif and sans serif Cs (two-factor ANOVA with replication; \( P < 0.0001 \)). Of most interest was the difference between the random Cs and upright Cs, because it was thought that this represented the effects of attention most clearly. There was a difference between random and upright distractors across all separations for sans serif and serif targets \( (P < 0.0001) \). For serif Cs there was also a difference between figure eights and upright Cs across all separations, but this was not the case with sans serif Cs (two-factor ANOVA with replication; \( P = 0.12 \)). For serif and sans serif Cs, across all separations, I distractors caused significantly less crowding than other distractors.

It is interesting to consider the crowding effects of different distractors at the farthest separation we used. With sans serif Cs, there was a significant difference in the crowding produced by all distractors at 16 stroke widths' separation (two-tailed t-test between upright and random Cs, \( P = 0.013 \); between upright Cs and figure eights, \( P = 0.0165 \); and between I and figure eight distractors, \( P = 0.0059 \)). With serif Cs there were significant differences among all distractors except between upright and random Cs \( (P = 0.357) \).

**Discussion**

These results confirm the findings of other investigators, that central acuity is much less susceptible in extent and amount of crowding than eccentric acuity. Crowding in central vision was not produced by distractors that were eight stroke widths or more distant. The amount of crowding in central vision was approximately 0.15 log units, which means that acuity was degraded by a factor of 1.414. There were no consistent or measurable effects of quantity of contour or attention. The presence of any contour four stroke widths or nearer reduced acuity slightly, and the addition of more contours did not significantly increase the crowding effect. These results are in agreement with those of other investigators who have shown that central visual acuity is compromised by the position of the most proximal edge of the distractor and is not sensitive to its shape or the addition of more contours.\(^{5,12,15,29}\)

Our results are in agreement with those in other studies in the finding that eccentric acuity is far more susceptible to crowding and is still reduced by distractors that are 16 stroke widths distant. In addition, we quantified the amounts of crowding in eccentric vision and found it to be much greater than in central vision, degrading acuity by up to 0.7 log units (a factor of 4.25). Our results also show that crowding in eccentric vision was caused by contour interaction and attentional factors and that, at the farthest separation used, this remained true. This was shown by the difference, at 16 stroke widths' separation, between figure eight distractors (which cause maximum contour interaction) and Cs in random or upright position (which caused less contour interaction but more attentional demand). Similarly, there was a difference between I targets and figure eights. Both of these are dissimilar to the target (therefore, we propose that they cause equal amounts of demand of attention) but cause different amounts of contour interaction.

**GENERAL DISCUSSION**

Considering first the effects of contour interaction, Levi\(^3\) suggests that contour interaction takes place within one processing zone or hypercolumn within the visual cortex. Although the width of each zone remains the same in the cortex (approximately 1 mm), the area of visual field in space varies according to the cortical magnification factor. In foveal vision each zone analyzes an area of 4 to 5 minutes of arc of visual field. At 2° it analyzes approximately 0.5⁰ of the visual field. If we consider the results of experiment 2 in terms of absolute size, we find that, in central fixation, the contour interaction with basic Cs was borderline with distractors at 2.8 minutes of arc, and with serif Cs at a separation of 4.36 to 4.28 minutes of arc. These distractors therefore would fall within only one cortical processing zone. There was no significant contour interaction with distractors at 5.25 to 5.03 minutes of arc with basic Cs and 7.2 to 7.7 minutes of arc with serif Cs. These would fall just outside one zone. At 2° eccentricity, contour interaction effects were present even with the most widely spaced distractors. These are at 19 to 34 minutes of arc with basic Cs and 30 to 43 minutes of arc with serif Cs. These results are therefore compatible with the concept of spatial processing zones that increase in relation to the cortical magnification factor. However, they imply that the spatial extent of the eccentric processing zones is slightly larger than that shown by Levi.

Regarding the effects of attention, the distinction between preattentive and attentive tasks has been described for some time. The presence of a unique feature of the target allows it to be processed in parallel and to "pop out" from the surrounding distractors. This is called a preattentive task. When there is no unique feature, attention to different parts of the stimulus has to be focused serially.\(^4\) Precluing the observer to the part of the visual field where the target will be presented allows attention to be directed there, but targets that are not highly discriminable from the distractors require narrowed attention, even if a preclue is given regarding the visual field location of the target. This seems to have happened in the present study, in which the visual field location was known in advance. It would be interesting to investigate whether performance (attention) can be improved by means of a physical preclue to further direct attention to the correct visual field position. However, the effects of a physical preclue seem equivocal. Nazir,\(^29\) measuring eccentric crowded acuity with targets similar to those in the present study, found no effect of a preclue on gap resolution, even though without the preclue there was
uncertainty of where the target would be presented. Shiu and Pashler25 found that precluing did not improve discrimination of uncrowded targets but only of crowded targets, and they argue that the purpose of attention would be to filter out the noise from the target (see later discussion). Nakayama and Mackeben30 suggest that attention has two components, sustained (voluntary) and transient (involuntary), which are affected differently by sustained and transient preclues. In the present study, subjects knew in advance where the target would appear. Thus, voluntary attention was in operation. We have not yet investigated the effects of a physical preclue to determine whether this would further improve performance.

Our findings of increasing crowding caused by increased similarity between the target and the distractors, which we have suggested requires more focused attention, are similar to those found by Nazir.29 The targets he used were similar to those in the present experiment, and it was shown that crowding in eccentric vision is far more affected by similarity between the target and distractors than in central vision. As the degree of similarity between the target and the distractor in form and size increases, visual acuity decreases. This seems not to be caused by simple inhibitory effects between orientation/line detector elements and is borne out by Nazir's results and the present results. In the present study there were the same number of line segments in the random condition as in the upright conditions and there were more line segments to cause such potential interactions in the square figure eight.

Kooi et al.26 also found decreasing visual acuity with increasing similarity between the target and distractors. They examined the effects of contrast, contrast polarity, orientation, shape, depth, eye of origin, and color. They also showed that it is not the number of contours that elicits contour interaction, which influences the crowding effect, but the way those contours are combined to form a distractor that is similar or dissimilar to the target. Kooi et al.26 call the effect grouping. As the distractors become more similar to the target, they become more part of a perceptual group, making the target and its orientation more difficult to isolate and decreasing the amount of "pop-out." This seemed to occur in the present study, and the present results agree with those of Kooi et al. that perceptual grouping is not an all-or-nothing phenomenon, but a continuum. As the grouping effect increases (i.e., the target becomes grouped with the distractors), the degree of pop-out decreases. Verghese and Pelli2 also suggest that there may be a continuum between preattentive and attentive tasks.

Palmer19 and Carrasco and Frieder20 talk of increasing confusability or noise as more distractors are added, resulting in a greater possibility of a false alarm or a longer time to make a judgment. This could also be an explanation of the data presented here. As the distractors become more similar to the target, the confusability increases. In particular, when the randomly oriented distractors are used, the confusability with a randomly oriented target would be at its greatest.

Any of these descriptions can be understood in terms of the target's positional code.26 It is suggested that positional code is adversely affected by similar shapes nearby. If the target is unique in various ways, its positional code remains intact, but if there are similar shapes in proximity, the code is lost or there is an increase in positional uncertainty. Kooi et al.26 suggest a common mechanism for pop-out, local code, and grouping. Similar features in a part of the visual field cause inhibition. When there is dissimilarity, the target is released from inhibition and can be identified more easily. Whichever of these explanations is used, the present results indicate the presence of a continuum, rather than an all-or-nothing effect.

Lastly, these results have practical application in understanding eccentric vision in cases of low vision when central vision is compromised. We know that, at a given eccentricity, there is a limit on reading speed, even with appropriate magnification.31 The results presented here may help to explain this finding. Even though targets are magnified to be above their acuity limit, crowding still occurs. This is particularly true when magnification of text is estimated from single letters. The substantial effects of crowding make the crowded letters of text less visible. However, there are several differences between the case of low vision and normal use of an eccentric retinal locus. In the case of low vision the subject may have been using the same retinal locus consistently for some time, and attention may already be "directed" toward that eccentric locus, thus reducing the attentional effects of crowding. The subject is therefore practiced at using the eccentric locus. The effects of practice on the relative contribution of attention and contour interaction are not clear. Manny et al.32 have suggested that there is a learning effect in a simple crowded acuity test. They suggest that this is caused by increased attention to local luminance cues. In visual search tasks there is a general learning effect and a specific learning effect shown by better performance on specific stimuli that have been presented earlier (i.e., the subject learns where to look).32 Beard et al.33 show the presence of small practice effects in eccentric vision. Over a period of several days they found an improvement of 9.5% for a resolution task and 20% for a vernier task in the same eye and visual field position. They also found that these effects are sometimes transferable between tasks. We do not think that our present results were contaminated by learning effects, because we allowed practice sessions for each location and target type and deliberately randomized distractor types among subjects to avoid the effects of practice. Furthermore, the practice effects for resolution targets documented by Beard et al. were small (0.04 log unit over a 6-day period) compared with the effects of crowding presented here. However, it is interesting to consider the effects of learning on eccentric vision when a particular eccentric locus is consistently used as in the case of low vision. Alternatively, there may be a limit to the degree of improvement because of increased contour interaction that may occur in certain disorders. We know that eccentric viewing training is advocated in low-vision patients who must learn to use eccentric viewing and that performance in tasks such as reading can be improved.34,35 What we do not know is how much this improvement may be caused by learning to use a more consistent eccentric locus or whether there is any change of attention to a given locus. This has yet to be investigated.

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References


