Crowding is a form of lateral interaction in which flanking items interfere with the detection or discrimination of a target stimulus. It is believed that crowding is a property of peripheral vision only and that no crowding occurs at fixation. If these two claims are true, then there must be a change in the nature of crowding interactions across the visual field. In three different tasks, we determined target size and flanker separation at threshold for eccentricities of 0 to 16° in the lower visual field for 7 relative separations (1.25 to 8 times target size). In all three tasks, the magnitude of crowding increases with eccentricity; there was no crowding at fixation and extreme crowding at 16°. Using a novel double-scaling procedure, we show that the non-foveal data in all three tasks can be characterized as shifted versions of the same psychometric function such that different sections of the function characterize data at each eccentricity. This pattern of results can be understood in terms of size-dependent responses to the target and distance-dependent interference from the flankers. The data suggest that the distance-dependent interference increases with eccentricity.

Keywords: crowding, size scaling, peripheral vision


Introduction

It is well known that eccentricity-dependent stimulus magnification frequently compensates for eccentricity-dependent sensitivity loss. In such cases, any level of sensitivity at the fovea can be matched at any eccentricity given sufficient stimulus magnification. In many cases, the needed magnification (scaling) increases linearly with eccentricity so that if \( s_0 \) is stimulus size at fovea, then \( s_E = s_0 (1 + E/E_2) \) is the stimulus size at eccentricity \( E \) required to elicit equivalent-to-foveal performance; \( E_2 \) is a task-dependent constant. The success of magnification in overcoming eccentricity-dependent sensitivity loss encourages the view that peripheral vision is simply a scaled version of foveal vision, i.e., the mechanisms available at each eccentricity are the same in all respects and differ only in scale (Gurnsey, Poirier, Bluet, & Leibov, 2006; Gurnsey, Roddy, Ouhnana, & Troje, 2008; Makela, Whitaker, & Rovamo, 1993; Rovamo & Virsu, 1979; Watson, 1987; Weymouth, 1958; Whitaker, Latham, Makela, & Rovamo, 1993; Whitaker, Makela, Rovamo, & Latham, 1992; Whitaker, Rovamo, MacVeigh, & Mäkelä, 1992). Such studies address eccentricity-dependent changes in sensitivity to isolated stimuli. In the real world, however, we are rarely confronted with isolated stimuli (i.e., on a homogenous, untextured background).

Therefore, a full understanding of peripheral vision must deal with sensitivity to targets in the presence of non-target items. A large number of studies addressing this question fall in the category of “crowding studies.”

Crowding refers to the deleterious effect of surrounding stimuli (crowders or flankers) on the identification of a target. If peripheral vision were a scaled version of foveal vision, then the effect of crowders on target identification should be the same across the visual field. However, this is clearly not the case. When foveal and peripheral stimuli presented at peri-threshold size are surrounded with flankers of the same size at separations proportional to target size, there is far greater disruption in the periphery than at fixation (Toet & Levi, 1992; for reviews, see Levi, 2008; Pelli, Palomares, & Majaj, 2004). This undermines the notion that the visual system employs mechanisms at each eccentricity that are identical in all respects except scale.

The failure of a single magnification factor to equate performance across the visual field does not invalidate the utility of magnification in explaining the relationship between foveal and peripheral vision. It is well known that uniform, eccentricity-dependent magnifications sometimes fail to equate performance across the visual field (Latham & Whitaker, 1996; Melmoth, Kukkonen, Mäkelä, & Rovamo, 2000; Poirier & Gurnsey, 2002, 2005; Toet & Levi, 1992; Yu & Essock, 1996). Often, more than one...
aspect of a stimulus must be scaled (magnified) with eccentricity to elicit equivalent-to-foveal performance. For example, Toet and Levi (1992) showed that the rate at which interference zones increase with eccentricity is far greater than that at which resolution thresholds increase with eccentricity. Melmoth et al. (2000) showed that both stimulus size and contrast had to be scaled with eccentricity to eliminate eccentricity-dependent variability from their face discrimination data. Poirier and Gurnsey (2002) showed that magnification factors were required to equate sensitivity to subjective contours across the visual field; one scaled the length of the subjective contour and the other scaled the wavelength of the carrier grating.

Latham and Whitaker (1996) explicitly addressed the issue of crowding from a double-scaling perspective and expanded on the work of Toet and Levi (1992). Their subjects were asked to identify the orientation (horizontal or vertical) of a target grating in isolation or surrounded (above, below, and to either side) by identical grating patches that were randomly horizontal or vertical. They determined the stimulus size required to achieve threshold-old-level accuracy (75% correct in a two-alternative, forced-choice task). At each of four eccentricities (0, 2.5, 5, and 10°), threshold was obtained at edge-to-edge separations of 0.25 to 7 times target size, which corresponded to center-to-center separations of 1.25 to 8 times target size. From these data, Latham and Whitaker (1996) were able to express the separation (critical separation, \( s_{\text{crit}} \)) needed to achieve a particular threshold elevation (flanked vs. unflanked size threshold, \( T_{\text{rel}} \)) at any given eccentricity (\( E \)) in terms of two free parameters:

\[
s_{\text{crit}} = \frac{s_2/E_{2H}}{(T_{\text{rel}}-1)}(E+E_{2H}),
\]

where \( T_{\text{rel}} = T_{\text{flanked}}/T_{\text{unflanked}} \), \( s_2 \) is the separation at fixation at which size (resolution) threshold was twice the unflanked threshold, and \( E_{2H} \) is the eccentricity at which the separation eliciting \( T_{\text{rel}} \) doubles. It is clear from this formulation that \( s_{\text{crit}} \) will be proportional to eccentricity when \( E_{2H}/E \) is small, but the exact proportion depends on \( T_{\text{rel}} \). The Latham and Whitaker approach provides the model for the current study, although our data deviate in interesting ways from theirs.

There is an emerging consensus about the features of crowding that distinguish it from other types of interaction that fall under the rubric of masking. Two of these are widely reported. First, crowding is thought to be principally a phenomenon of peripheral vision (Levi, 2008; Pelli et al., 2004), i.e., crowding typically does not occur at fixation and target–flanker interactions at fixation may be understood as simple masking (Levi, Klein, & Hariharan, 2002). Second, the spatial extent of target–flanker interaction is proportional to eccentricity and independent of stimulus size (Bowman, 1970; Levi, Klein et al., 2002). (As noted, this must be true if \( s_{\text{crit}} \) increases rapidly and linearly with eccentricity.)

There are two aspects of the Latham and Whitaker data that tend to challenge the consensus view of crowding. First, Latham and Whitaker found a degree of crowding at fixation, which challenges the notion that crowding is a purely peripheral phenomenon, although the magnitude of foveal crowding was far less than that of peripheral crowding (Pelli et al., 2004; Toet & Levi, 1992).

Second, the relationship between target size at threshold and target–crowder separation at threshold found by Latham and Whitaker (1996) is inconsistent with the notion that critical separation is independent of target size (Bowman, 1970; Pelli et al., 2004; Tripathy & Cavanagh, 2002). If \( s_{\text{crit}} \) were independent of target size, then, in the Latham and Whitaker study, the product of target size and relative separation at threshold should be a constant (\( s_{\text{crit}} = T_{\text{size}} \times \text{relSep} \)). In other words, to keep performance at 75% correct, relative separation must decrease as target size increases to keep \( s_{\text{crit}} \) constant. However, it is clear from the data of Latham and Whitaker (Figure 4) that \( s_{\text{crit}} \) increases as target size decreases. [It should be noted, however, that Latham and Whitaker defined target–flanker separation as edge-to-edge separation, whereas other authors (Levi, Hariharan, & Klein, 2002; Pelli et al., 2004, 2007) define it as center-to-center separation. When defined as center-to-center separation, the size vs. separation curves become steeper (see Figure 7].]

In the present paper, we use the paradigm of Latham and Whitaker to systematically examine the relationship between stimulus size and crowder separation at threshold across the visual field. The following points motivate the present work.

The claims that crowding is non-existent at fixation and independent of target size in the periphery contrast with the data of Latham and Whitaker; as mentioned, there was both crowding at fixation and size dependence at all eccentricities. Because theirs is the only one to employ a double-scaling approach to crowding, it is conceivable that the way crowding is measured has a profound effect on the conclusions one draws. Therefore, we replicate the Latham and Whitaker experiment and also use the same method to test for crowding at fixation using stimuli previously employed by Pelli et al. (2004) and Tripathy and Cavanagh (2002) in the service of showing that crowding is size independent.

Independent of Latham and Whitaker (1996), the twin claims that crowding is non-existent at fixation and independent of target size in the periphery implies that at some eccentricities between fovea and “periphery” crowding is size dependent. In other words, there is unlikely to be a step function between states of no crowding and size-independent crowding. More likely, at intermediate eccentricities, there is a trade-off between target size and target–crowder separation such that larger separations are required to maintain threshold performance as target size decreases. In fact, Tripathy and
Cavanagh (2002) found the same tendency as Latham and Whitaker in this direction, although the change in separation with decreasing size was not as pronounced. Therefore, using the method of Latham and Whitaker (and Poirier & Gurnsey, 2002), we hope to provide a systematic evaluation of the changing nature of crowding across the visual field.

In addition, there is the question of whether critical spacing is proportional to eccentricity. As Latham and Whitaker (1996) pointed out, this is almost certainly true, but the exact proportion of eccentricity will depend on the change in performance used to define critical spacing. However, Pelli et al. (2004) found that for many observers \( s_{\text{crit}} \) was not strictly proportional to eccentricity. Rather, \( s_{\text{crit}} \) tended to increase with eccentricity. Finally, if critical spacing (however defined) represents a hardwired constraint, it is worth asking if it is task independent. Therefore, we bring together three sets of stimuli (drawn from Latham & Whitaker, 1996; Tripathy & Cavanagh, 2002; Pelli et al., 2004) within a common paradigm to address this question.

**Experiment 1**

**Methods**

**Participants**

There were four participants in the experiment (two men and two women, mean age = 29). GR and WC were authors and P1 and P2 were experienced psychophysical observers with no prior experience in crowding experiments. All had normal or corrected-to-normal vision.

**Apparatus**

The experiments were conducted using an Intel MacPro Computer equipped with a ViewSonic 222f 21-inch multi-scan monitor with the refresh rate set to 85 Hz and pixel resolution set to 2048 horizontal by 1600 vertical. All aspects of stimulus generation, presentation, and data collection were under the control of MATLAB (Mathworks) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

**Stimuli and tasks**

Figure 1 shows the stimuli used in the three tasks that were investigated. The first condition was a replication of Tripathy and Cavanagh (2002; Figure 1A). The target was a T and the flankers were thetas. The lengths of the bars making up both target and flanker were five times their width. On each trial, the target T was in one of four orientations (0, 90, 180, 270° from vertical) and the thetas were randomly oriented. The second condition was a replication of Pelli et al. (2004; Figure 1B). The targets and flankers were letters (CDRSVZHKNO) drawn from the Sloan set. The target was chosen at random and the two flankers were chosen randomly from the remaining letters. The third condition was a replication of Latham and Whitaker (1996; Figure 1C). The targets were horizontal or vertical gratings (each bar length is five times its width) as were the flankers. On each trial, the target and each flanker was chosen to be horizontal or vertical at random. In all cases, the luminance of the background (gray) region was 44.8 cd/m² and that of the target (and flanker) regions was 0.687 cd/m².

**Procedure**

In all three conditions, subjects were required to identify the central element of the three- or five-element displays. For the stimuli in Figure 1A, the task was a four-alternative forced choice (4AFC). Subjects pressed the up, down, left, and right arrows to indicate the orientation of the T. For those in Figure 1B, subjects pressed the appropriate keys (CDRSVZHKNO) to indicate their responses in a 10AFC task. The task for the stimuli shown in Figure 1C was a 2AFC. Subjects pressed the up

![Figure 1](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932798/)
and right arrow keys to indicate the orientation of the grating.

Stimuli were presented at 0, 1, 2, 4, 8, and 16° in the lower visual field and subjects viewed them binocularly. The targets were flanked by the non-target items at center-to-center separations of 1.25 to 8× target size in 7 equal logarithmic steps. Stimuli were also tested in isolation, i.e., no flankers. Stimuli were always presented at the center of the screen. Viewing distance depended on eccentricity. Subjects viewed the stimuli from 456 cm for 0° eccentricity, 228 cm for 1° and 2° eccentricities, 114 cm for 4° eccentricity, 57 cm for 8° eccentricity, and 40 cm for 16° eccentricity.

For all eccentricities except 0°, a small green fixation dot was placed above the stimulus. On each trial, stimuli were presented for approximately 333 ms. Following stimulus presentation, the fixation dot turned red until a valid response was given via the keyboard. Incorrect responses were signaled by a 300-ms, 400-Hz tone. Stimulus size was controlled by Quest (Watson & Pelli, 1983) and size thresholds were determined from two runs with a maximum of 100 trials each. Thresholds for the conditions shown in Figures 1A–1C were defined as 72%, 67%, and 82%, respectively. These values correspond to the mean of the underlying Weibull function when normalized to the range of chance to 100% correct.

Results

The average results for conditions 1, 2, and 3 are summarized in Figure 2A. In all three panels, stimulus size at threshold is plotted as a function of relative target–flanker (center-to-center) separation for the six eccentricities. Circles represent conditions in which relative separations were 1.25 to 8× target size. Triangles represent the unflanked condition. For purposes of illustration, data from the unflanked condition are plotted at 16 times target size. The data represent the average of four subjects.

Figure 2B shows size at threshold as a function of target–flanker separation at threshold, i.e., size at threshold times relative separation. As in the first row, these data represent the average of four subjects. (The corresponding data for individual subjects are shown in Figure 3.) In this representation, the curves are shifted up and to the right as eccentricity increases. A general feature of most curves is that size at threshold decreases as separation at threshold...
increases, asymptotically approaching the size thresholds for the unflanked condition. Thus, the upward shifts of the curves correspond to eccentricity-dependent changes in the unflanked size thresholds. For each subject and each condition, we fit the eccentricity-dependent changes in the unflanked thresholds with the equation $s_E = s_0(1 + E / E_2)$, where $s_0$ is stimulus size at fovea, $s_E$ is the stimulus size at eccentricity $E$, and $E_2$ is a task-dependent constant. For the
T-orientation task, the mean $E_2$ was 1.76 ($SEM = 0.05$; 95% confidence interval = 1.59–1.93); for the letter identification task, the mean $E_2$ was 1.35 ($SEM = 0.11$; 95% confidence interval = 1.01–1.69); for the grating discrimination task, the mean $E_2$ was 1.84 ($SEM = 0.04$; 95% confidence interval = 1.72–1.97). These values are in line with previous reports of eccentricity-dependent changes in resolution thresholds (e.g., Latham & Whitaker, 1996).

The critical question is whether a leftward shift, in addition to a downward shift, would be sufficient to collapse all data onto a single curve. We will show that such shifts are sufficient to collapse all data (in each condition) onto a single curve, but the required shifts violate assumptions about the nature of crowding.

The approaches of Latham and Whitaker (1996) and Poirier and Gurnsey (2002) assume that the size vs. separation curves (at each eccentricity) are shifted versions of each other in this two-dimensional space. However, in all three panels of Figure 2B, the most salient feature is that the psychometric functions go from flat at fixation to increasingly steep as eccentricity increases. For all three conditions, these changes reflect essentially no crowding at fixation (size thresholds are independent of all three conditions, these changes reflect essentially no fixation to increasingly steep as eccentricity increases. For feature is that the psychometric functions go from flat at

curves are simply

and Gurnsey (2002). The data at each eccentricity were

version of the data fitting procedure described by Poirier and Gurnsey (2002).

The results of this analysis (not shown) explained 98.3, 98.9, and 98.6% of the variability of the averaged data for the T, letter, and grating conditions, respectively. Although this may seem impressive, it should be kept in mind that eccentricity makes a major contribution to the variability in the data set and so even implausible fits may account for it. Three limitations associated with the linear shifts (Equations 3 and 4) can be seen in Table 1. First, the leftward horizontal shift required to align the data is represented by $E_{2H}$ values on the order of $10^{-7}$, meaning that the rate at which the extent of crowding regions increase with eccentricity is $10^7$ times per degree visual angle. These implausible $E_{2H}$ values are accompanied by $sep_{\text{min}}$ values also on the order of $10^{-7}$, meaning that the center-to-center separation at which size thresholds become unmeasurable involves stimuli of $10^{-7}$ degrees of visual angle. Both of these failures relate to the fact that the size thresholds at fovea (blue dots in Figure 2) show no dependence on target–crowder separation and, thus, do not constrain the leftward shift of the curves. The instability of the fits is shown by the large 95% bootstrapped confidence intervals (upper and lower in Table 1) around these two parameters.

A second failure of the linear model is that the reduction of eccentricity-dependent variability from the data (98.6% on average) disguises the poor fit about the best fitting function. Specifically, the assumption that the required leftward shift is a linear function of eccentricity does not hold. In fact, the required leftward shift seems to accelerate with eccentricity, implying a quadratic component to the fit. Therefore, a second fit was undertaken with Equation 4 replaced by the following equation:

\begin{equation}
sep_{\text{scaled}} = \frac{sep}{1 + E_{2H}/\beta}.
\end{equation}

Figure 4A shows the result of the fitting procedure for each of the three conditions. The fitting procedure does a good job of eliminating eccentricity-dependent variability from the data, explaining 99.7, 99.4, and 99.5% of the variability of the averaged data for the T, letter, and grating conditions, respectively. The $F_{\text{Change}}$ statistics ($F_{\text{Change}} = (R_{NL}^2 - R_{L}^2) / (1 - R_{NL}^2) * (N - k_{NL} - 1) / (k_{NL} - k_{L})$) associated with the change in explained variance from the
five-parameter \((k_L)\) linear (L) model to the six-parameter \((k_{NL})\) non-linear (NL) model were \(F_{\text{change}}(1,42) = 191, 34,\) and \(74,\) for the T, letter, and grating conditions, respectively. Table 2 shows that the fits appear, \textit{prima facie}, more plausible than those in Table 1, and the bootstrapped 95\% confidence intervals are better behaved. From these analyses, one might argue that a linear vertical shift and a non-linear horizontal shift nicely account for the apparent differences between the curves in Figure 2B and all curves in Figure 3. This is consistent with the notion that data from each eccentricity simply reflect different samples of the same underlying curve.

The difficulty with this argument is that the best fitting functions predict stimulus configurations at and near fixation that violate the assumptions about what constitutes crowding. In Figure 4A, the green rectangle in the bottom left of each panel plots the maximum predicted \textit{scaled size} and the corresponding \textit{scaled separation}. Typically, these points correspond to data from 16° eccentricity. When we express the center-to-center spacing in relative terms, we find that for the T-orientation, letter identification, and grating discrimination tasks these correspond to 9.6\%, 23.3\%, and 15.5\% of target size. In all cases then, the predicted separation at fixation required to match the maximum observed size at threshold at 16° is much less than target size. This means that target and flankers would have to overlap, a condition that is outside the bounds of what is considered crowding and into masking territory\(^1\) (Levi, 2008; Pelli et al., 2004).

One may ask then, what the maximum predicted crowding could be at fixation and other eccentricities. To answer these questions, we fit the data from each eccentricity in Figure 2B with a rectangular parabola, and from the fits, we determined \(\mu_E = \text{separation}_E/\text{size}_E = 1.\) We then compared \textit{predicted} size in these conditions \((\mu_E = \text{separation}_E/\text{size}_E = 1)\) with size in the unflanked conditions. For T-orientation, letter identification, and grating discrimination tasks, these correspond to increases at fixation of 27\%, 29\%, and 28\%, respectively, over the unflanked conditions. These increases are dwarfed by the 575\%, 234\%, and 586\% increases seen at 16° in the T, letter, and grating tasks, respectively.\(^2\)

The preceding analysis shows that although it is possible to collapse all data onto a single function the assumptions underlying the fits lead to untenable conclusions. Therefore, we reject the conclusion that the curves at each eccentricity reflect different samples from the same underlying function.

As noted, crowding can only exist for \textit{sep/size} ratios of 1 or greater and so each such ratio represents a distinguished point on each curve shown in Figure 2B and all curves in Figure 3. Therefore, if we were to left shift the data (Figure 2B) by dividing actual separation at each eccentricity by the separation at which \textit{sep/size} is predicted to be 1, we would align the points of maximum possible crowding. To find the point of maximum crowding, we fit each curve in Figures 2B and 3 with a rectangular parabola and, thus, determined \(\mu_E = \text{separation}_E/\text{size}_E = 1.\) \(F_{EH} = \mu_E/\mu_0\) characterizes the relative shifts on the separation axis. Therefore, if we divide all separations at eccentricity \(E\) by \(F_{EH} = \mu_E/\mu_0,\) the curves at each eccentricity will shift leftward. A downward shift can be accomplished analogously. That is, \(F_{EV} = \text{unflanked}_E/\text{unflanked}_0\) expresses the unflanked threshold at each eccentricity relative to the unflanked threshold at fixation. Thus, dividing all sizes at eccentricity \(E\) by \(F_{EV} = \text{unflanked}_E/\text{unflanked}_0\) shifts curves at each eccentricity downward. The results of these shifts are shown in Figure 4B.

### Table 1. Double scaling: Linear fits.

<table>
<thead>
<tr>
<th>Subject</th>
<th>size(_{\text{min}})</th>
<th>sep(_{\text{min}})</th>
<th>(c^2)</th>
<th>(E_{2V})</th>
<th>(E_{2H})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T orientation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate</td>
<td>0.069</td>
<td>3.5E-8</td>
<td>2.6E-10</td>
<td>1.231</td>
<td>2.0E-10</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.004</td>
<td>0.019</td>
<td>19.08</td>
<td>0.143</td>
<td>0.105</td>
</tr>
<tr>
<td>Lower</td>
<td>0.061</td>
<td>-0.038</td>
<td>-77.59</td>
<td>0.942</td>
<td>-0.213</td>
</tr>
<tr>
<td>Upper</td>
<td>0.077</td>
<td>0.038</td>
<td>77.59</td>
<td>1.520</td>
<td>0.213</td>
</tr>
<tr>
<td><strong>Letter identification</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate</td>
<td>0.060</td>
<td>1.3E-7</td>
<td>6.6E-10</td>
<td>1.488</td>
<td>9.3E-7</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.002</td>
<td>0.027</td>
<td>6.832</td>
<td>0.125</td>
<td>0.188</td>
</tr>
<tr>
<td>Lower</td>
<td>0.055</td>
<td>-0.053</td>
<td>-27.78</td>
<td>1.236</td>
<td>-0.380</td>
</tr>
<tr>
<td>Upper</td>
<td>0.065</td>
<td>0.053</td>
<td>27.78</td>
<td>1.739</td>
<td>0.380</td>
</tr>
<tr>
<td><strong>Grating discrimination</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate</td>
<td>0.069</td>
<td>4.6E-8</td>
<td>3.4E-10</td>
<td>1.772</td>
<td>1.7E-7</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.003</td>
<td>0.022</td>
<td>20.58</td>
<td>0.196</td>
<td>0.085</td>
</tr>
<tr>
<td>Lower</td>
<td>0.063</td>
<td>-0.045</td>
<td>-83.70</td>
<td>1.377</td>
<td>-0.172</td>
</tr>
<tr>
<td>Upper</td>
<td>0.074</td>
<td>0.045</td>
<td>83.70</td>
<td>2.167</td>
<td>0.172</td>
</tr>
</tbody>
</table>
In all three panels of Figure 4B, we see that the data from non-foveal conditions seem to conform to the same function. The foveal data are isolated from the rest because there is no evidence that size thresholds increase with decreases in separation (Strasburger, Harvey, & Rentschler, 1991). We then found the best fitting rectangular parabola for these size- and separation-scaled non-foveal data. These fits are shown as continuous black lines in Figure 4B. The fits are very good. We conclude, therefore, that the curves at all eccentricities except 0° shift on to a single curve with appropriate scaling of size and separation. It is important to keep in mind that the range over which scaled size is defined differs across eccentricities.

When the best fitting curves are shifted upward and to the right by multiplying scaled functions (continuous lines in Figure 4B) by $F_{EV} = \frac{E}{E_0}$ and $F_{EH} = \frac{\mu E}{\mu_0}$, respectively, then these best fitting functions can be superimposed on the raw data. These fits are shown as the overlaid continuous black lines in the 12 panels of Figure 3. Again, this simple model matches the data very well.3

Table 3 summarizes the parameters ($\text{sep}_{\text{min}}$, $\text{size}_{\text{min}}$, $c^2$) of the fits for each subject, and the average of the four subjects, in each condition. $E_{2V}$, which characterizes the change in the size thresholds in the unflanked condition, as well as $a$ and $\beta$, which define the necessary leftward shift ($F_H = 1 + E^\alpha/\beta$), is also shown.

Figure 5 plots the average values for $F_{EV} = \frac{E}{E_0}$ and $F_{EH} = \frac{\mu E}{\mu_0}$ in each condition and eccentricity. The magnification factors associated with the vertical shifts change rather modestly and linearly with eccentricity. As noted earlier, these magnification functions ($F_V$) are characterized by average $E_2$ values of 1.76, 1.35, and 1.84, for the T, letter, and grating tasks, respectively. The magnification factors associated with the horizontal shifts change rather quickly and non-linearly with eccentricity. Because of the non-linear change with eccentricity, the concept of $E_2$ does not apply. Nevertheless, the shifts are rather systematic and are nicely captured by $F_H = 1 + E^\alpha/\beta$, as shown in columns 5 and 6 of Table 3.

It has been widely argued that “critical spacing” is proportional to eccentricity (Bouma, 1970; Pelli, 2008),

![Figure 4B](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932798/)
although there are exceptions (Pelli et al., 2004). This claim requires a definition of critical spacing and an assumption, or demonstration, that critical spacing increases linearly with eccentricity. Latham and Whitaker (1996) concluded from their data that no matter what level of threshold elevation (above the unflanked thresholds) was used to define it, critical spacing changed linearly with eccentricity. However, the more stringently one defines critical spacing, the smaller the critical separation becomes. Figure 6A replots the data from Figure 2B as threshold elevation, i.e., at each eccentricity, each flanked threshold (circles in Figure 2) is divided by the corresponding unflanked threshold (triangles in Figure 2). For each eccentricity, one can compute the critical spacing

<table>
<thead>
<tr>
<th>Subject</th>
<th>$size_{\text{min}}$</th>
<th>$sep_{\text{min}}$</th>
<th>$c^2$</th>
<th>$E_{2V}$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T orientation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate</td>
<td>0.045</td>
<td>0.025</td>
<td>0.00029</td>
<td>1.829</td>
<td>1.273</td>
<td>0.270</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.001</td>
<td>0.009</td>
<td>0.00001</td>
<td>0.152</td>
<td>0.028</td>
<td>0.107</td>
</tr>
<tr>
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Table 2. Double scaling: Non-linear fits.

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<th>$size_{\text{min}}$</th>
<th>$sep_{\text{min}}$</th>
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Table 3. Double scaling: Modified non-linear fits.
associated with a given threshold elevation. We did this for each subject for threshold elevations of 1.25, 1.58, and 2 using interpolation. Figure 6B plots these “critical separations” divided by eccentricity ($s_{crit,E}/E$) for each condition and each subject.

The data are somewhat noisy but have interesting features. First, critical spacing does not seem to be strictly proportional to eccentricity. In general, from $2^\circ$ onward, $s_{crit,E}/E$ increases for all threshold elevations. This increase with eccentricity is a consequence of the fact that a non-linear magnification is required to shift the functions leftward onto a common function, whether one uses the double-scaling methods of Latham and Whitaker (1996) and Poirier and Gurnsey (2002) or the method.

Figure 5. Plots of the average horizontal (blue) and vertical (green) scaling factors for each of the three conditions. Error bars represent $\pm SEM$.

Figure 6. (A) Average size threshold elevation as a function of separation at threshold for each eccentricity for each of the three conditions. (B) Average “critical separation” as a function of eccentricity for three threshold elevations (1.25, 1.58, and 2) for each of the three conditions. Error bars represent $\pm SEM$. 
summarized in Figure 4B. Second, as widely recognized, \( s_{\text{crit},E}/E \) depends on the criterion used to define \( s_{\text{crit},E} \); the greater the threshold elevation, the smaller \( s_{\text{crit},E} \) will be. For one to compare critical spacing across tasks and conditions, one would need to establish a uniform definition of critical spacing.

**General discussion**

Within the crowding literature, studies vary widely in terms of task requirements, definition of critical spacing, and subsequent analyses. Therefore, we set out to examine the relationship between crowding zones and resolution limits across the visual field in three different tasks using a single paradigm. The tasks were those previously used by Latham and Whitaker (1996), Pelli et al. (2004), and Tripathy and Cavanagh (2002). We asked whether crowding occurs at fixation and whether double scaling can capture changes in crowding across the visual field. We also asked about the degree to which crowding is size dependent and whether “critical spacing” is proportional to eccentricity.

**Crowding at fixation?**

Figures 2 and 3 show no evidence of threshold elevation at fixation as target–flanker separation decreases. These data are consistent with the arguments of Pelli et al. (2004) and suggest that there is qualitative change in crowding across the visual field. It seems implausible to argue that foveal crowding was not in evidence because the separations tested were not small enough. In fact, our very liberal estimate—based on extrapolated data—shows that the maximum possible threshold elevations were about 30% at fixation.

When comparing actual rather than extrapolated data, we found that our results differ somewhat from those of Latham and Whitaker (1996). At a center-to-center spacing of 1.25 times target size, they found threshold elevations of about 50% (in the right visual field at least), whereas we found a threshold “elevation” of \(-1.62\)% in the same condition; our threshold elevations in this and the other two conditions were not statistically different from 0. It is not clear from their data what degree of foveal threshold elevation Latham and Whitaker found on the lower vertical meridian (as tested here). It must be pointed out, however, that at 10-degree eccentricity they found threshold elevations of more than 200%. Thus, like us, they found that the magnitude of crowding was far greater in the periphery than at fixation. We showed that the difference between foveal and peripheral results cannot be explained as a consequence of having sampled the same underlying curve at different points at different eccentricities.

Previous studies have reported crowding at fixation (e.g., Danilova & Bondarko, 2007; Levi, Hariharan et al., 2002, Liu & Arditi, 2000; Pelli et al., 2007), but in the case of alphanumeric stimuli, these results may be attributed to masking. Levi (2008) suggests that as stimulus and flanker sizes decrease the separations that may lead to threshold elevation fall within the range of internal blur, meaning that target and flankers effectively overlap. Therefore, apparent crowding at the fovea may be interpreted as (at least partly) masking (Levi, 2008; Levi, Hariharan et al., 2002). We show later that the subjects in the Latham and Whitaker study had lower size thresholds at fixation, and therefore, the flankers may have elevated thresholds at small target–flanker separations because of masking arising from internal blur.

**Can double scaling characterize eccentricity-dependent changes in crowding?**

The answer depends on what one means by double scaling. It is clear that a linear scaling factor is sufficient to capture changes in resolution thresholds with eccentricity. We found average \( E_2 \) values of 1.76, 1.35, and 1.84, for the unflanked conditions of the T, letter, and grating tasks, respectively. These results are consistent with a large literature starting with Weymouth (1958). Latham and Whitaker (1996) found average \( E_2 \) values of 1.41 in the lower visual field, so our results are generally consistent with theirs.

Latham and Whitaker (1996) showed that threshold elevation curves (e.g., Figure 6A) could be left shifted and aligned by dividing separation at threshold by \( F_{1H} \approx 1 + E/0.14 \). If these results are applied to the representation shown in Figures 2B and 3, then the conclusion would be that linear shifts in the vertical and horizontal directions—defined by \( F_{1H} \approx 1 + E/1.41 \) and \( F_{1H} \approx 1 + E/0.14 \), respectively—are sufficient to characterize the nature of crowding and resolution limits across the visual field. The curves in Figure 5 corresponding to the horizontal magnifications (blue dots) can be approximated with a straight line with a corresponding \( E_2 \) of 0.1 to 0.2. Therefore, our data show—like those of Latham and Whitaker (1996) and Toet and Levi (1992)—that crowding or interference zones increase far more rapidly with eccentricity than simple resolution limits. It is important to note, however, that a linear magnification does not properly characterize the changing extents of crowding zones. In fact, the needed magnifications grow exponentially with eccentricity (Figure 5). Therefore, it may be that when the needed magnification is very great it will accelerate with eccentricity. We tested further into the periphery than did Latham and Whitaker (16° vs. 10°), and perhaps because of this, the non-linearity is revealed.
We showed that a non-linear, horizontal magnification factor \( F_H = 1 + E^2/\beta \) in conjunction with a linear vertical magnification factor \( F_V = 1 + E/E_2 \) is sufficient to collapse size vs. separation data from all eccentricities onto a single function. Although this kind of double scaling technically eliminates eccentricity-dependent variance from our data set, the implied target–flanker overlap required at fixation to match the observed size threshold in the periphery is inconsistent with the consensus view of crowding, and for this reason, we reject this version of the non-linear model.

Our alternative approach to double scaling involved left-shifting the separation vs. size curves to align the points for which separation\(\text{size} = 1\). These leftward shifts are directly related to the maximum threshold elevation possible without target and flankers overlapping. It is remarkable that when shifted leftward in this way all curves except the foveal curve overlap and are captured by the same rectangular parabola. (See Footnote 2 for a qualification of this conclusion.) In this sense, double scaling does align all but the foveal curve. The nature of the alignment assures that the best fitting curve will not include points for which targets and crowders overlap. Therefore, we conclude that double scaling, in this modified sense, provides a satisfactory characterization of all but the foveal data. Unlike “standard” double-scaling procedures (Latham & Whitaker, 1996; Poirier & Gurnsey, 2002), our fits make explicit that the magnitude of crowding (e.g., threshold elevation) increases with eccentricity. At each eccentricity, the data are fit with a different part of the rectangular parabola. Therefore, with the exception of the foveal data, the changes with eccentricity may be considered quantitative rather than qualitative.

**Is crowding size independent?**

Pelli et al. (2004) argue that the weight of evidence shows that the extent of crowding zones is independent of target size. The work of Tripathy and Cavanagh (2002) is also widely cited in this regard. Figures 3 and 4B show that the data at each eccentricity are well fit by a rectangular parabola. Parts of a rectangular parabola approach size independence (the part parallel to the \( y \)-axis corresponding to small separations and large sizes), but as separation increases (and size decreases), the curve slopes and then becomes parallel to the \( x \)-axis. In this latter part of the curve, size and separation trade off so that as size decreases, larger separations are needed to maintain threshold-level performance. Near fixation, the maximum threshold elevation is relatively modest, and so over most of the curve, there is a trade-off between size and separation at threshold. At further eccentricities, the maximum threshold elevation is much greater and so crowding is size independent over more of the curve. Therefore, it is not generally true that crowding is size independent. At each eccentricity, there are stimulus sizes for which crowding is size dependent. As eccentricity increases, then larger parts of the function are roughly parallel to the size axis. This region represents size independence and the range of sizes for which size independence is seen grows with eccentricity.

We can compare our results with those in the experiments we have replicated. Tripathy and Cavanagh (2002) used stimuli of the sort shown in Figure 1A. Stimuli were presented at 9.2° in the lower visual field and the extent of crowding was measured for a range of stimulus sizes. At each size, stimulus contrast was adjusted to elicit 80% correct performance in the unflanked condition, i.e., stimulus contrast decreased as target size increased. Accuracy was measured at this contrast as a function of target–flanker separation (center to center). The extent of crowding was defined as the target–flanker separation that produced a level of accuracy corresponding to \((\text{Acc}_{\text{unflanked}} - \text{Acc}_{\text{chance}}) \times (1 - 1/e) + \text{Acc}_{\text{chance}}\). Their results for two subjects are plotted in Figure 7A. The data are somewhat noisy for subject ST, but they are quite similar to our data at 8° for the same condition. Their data differ from ours in that there is less evidence at small sizes for a shift from size independence to size dependence. Put the other way around, crowding zones do not get smaller as targets get larger as they do in our data. This difference may well be explained by the negative correlation between stimulus size and contrast (e.g., Strasburger et al., 1991). (We return to this point.)

Figure 7B compares our data (at 0, 2, 4, and 8°) in the lower visual field with those of subject KAT in Pelli et al. (2007) obtained 5° in the lower visual field. In this experiment, an adaptive procedure was used to find the spacing that elicited 80% correct responses in a 10AFC. Although separation thresholds were obtained for four target flanker orientations, we have shown data only for the horizontal separation (see Figure 1B). These data seem generally consistent with other data in the set, showing a tendency for separation at threshold to decrease with stimulus size. The general form of the function seems quite similar to our data obtained at 4°.

Figure 7C compares our data to those of Latham and Whitaker (1996) obtained at 0, 2.5, 5, and 10° in the right visual field. The data are the average of their two subjects’ data. We noted earlier that Latham and Whitaker expressed target–flanker separation as edge-to-edge separation, whereas we have replotted their data as center-to-center separation. As with our data, theirs show an increase in crowding with eccentricity, with rather little crowding at fixation. At fixation, Latham and Whitaker’s subjects show greater sensitivity than ours. (As noted earlier, the threshold increases seen at small separations might reflect masking induced by overlap of the blurred representations of targets and flankers.) Their data at 2.5 and 5° essentially superimpose on ours at 2° and 4°. Their subjects also have greater sensitivity at 10° than ours did at 8°. Because of the difference in sensitivity at fixation,
we attribute the difference at 8 and 10° to subject differences rather than the difference in visual field of presentation. Importantly, the data of Latham and Whitaker, like ours, show a trade-off between size and separation as stimulus size decreases.

Our data, taken together with those just reviewed, suggest two factors contributing to performance: a size-dependent response to the target and a distance-dependent response to the flankers. A model can be conceived in which threshold is determined jointly by the strength of the internal response to the target (determined by target size or target contrast) and target–flanker separation (the deleterious effects of the flankers decrease with distance). [The nature of the target flanker “interference” may take several different forms (Baldassi, Megna, & Burr, 2006; Greenwood, Bex, & Dakin, 2009, 2010; May & Hess, 2007; Nandy & Tjan, 2007; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001).] For large stimuli, flankers must be brought close in order for performance to come off the ceiling. However, for smaller stimuli, the flankers do not need to be as close to bring discrimination accuracy to threshold.

The curves in Figures 2B and 3 may reflect the strength of interference as a function of distance. The suggested trade-off between stimulus size (strength) and separation may explain the difference between our results and those of Tripathy and Cavanagh (2002). We noted that unlike our results, theirs showed little relationship between target size and separation. This may be because the size-dependent increase in (internal) signal strength was offset by a decrease in contrast. This size/contrast trade-off may have held the strength of the internal response to the target constant and, hence, kept constant the separation required to produce the criterion reduction in accuracy. In fact, our experiments can be seen as differently controlled versions of theirs. They found a threshold separation between targets and flankers when contrast is inversely related to target size, whereas we found threshold separation between targets and flankers when contrast is fixed. Therefore, our results confirm their implicit assumption that the extent of crowding would be size dependent when contrast does not covary with target size.

Our model (size-dependent response to the target and distance-dependent response to the flankers) would also predict that for a fixed target–flanker separation a reduction in the contrast or size of the target (only) should elicit reduced accuracy. This remains an empirical question.

This model, however, is apparently contradicted by reports that crowding is independent of almost all stimulus characteristics and dependent only on eccentricity. Pelli et al. (2004) argued that critical spacing is independent of target size in a task that measured contrast sensitivity for a target as a function of target–flanker separation. Using a clipped line function fit by eye to the data, they concluded that the separation at which flankers begin to produce threshold elevation was independent of target size over a six-fold range of sizes (0.32 to 2°) at 4° eccentricity in the right visual field (Pelli et al., 2004, Figure 5). Similarly, for a 0.32° target presented at 4° in the right visual field, the separation at which flankers began to produce threshold elevation for target detection was reported to be independent of flanker contrast.

Although Pelli et al. (2004) present extensive data to support the position that $x_{crit}$ is independent of many differences between target and flankers, the representation of the data makes it difficult to reanalyze. We note, however, that their paradigm and ours are quite different. Their conclusions were based on the effects of flankers on contrast thresholds and ours are based on effects of flankers on size thresholds. It may be that these two paradigms reflect different aspects of neural interactions. One indication that there may be a difference between paradigms is the finding of Pelli et al. (see their Figure 16).
that orientation discrimination is not subject to crowding when the gratings to be discriminated differed by 90°. We found very strong crowding effects under these conditions. Clearly, a direct test of paradigm dependence of crowding is on order. We should also note that there is growing evidence that flanker characteristics make important contributions to the degree of crowding observed (Kooi, Toet, Tripathy, & Levi, 1994; Levi & Carney, 2009; Livne & Sagi, 2010; Nazir, 1992).

Is the critical separation proportional to eccentricity?

Several authors (Levi, 2008; Pelli et al., 2004) have argued that the main goal of crowding research is to establish the critical separation, which is defined as some deviation from performance in the uncrowded condition. Just what this deviation should be is a matter of choice. We have just shown that the magnitude of crowding increases with eccentricity (e.g., Figure 6A). Therefore, if one defines the critical separation stringently (e.g., the separation at which threshold doubles from the uncrowded case), then it may be undefined at some eccentricities. For example, if critical spacing were defined as a threshold doubling, then it would be undefined for some subjects at small eccentricities in our experiments. Pelli et al. (2004) argue that any deviation from the uncrowded threshold should define critical separation. The advantage of this definition is that if crowding exists then critical spacing is defined even if the magnitude of crowding is relatively modest, i.e., does not rise to the level of some specified threshold elevation. The drawback is that in many cases the precision with which we can measure such a point is extremely coarse. Because the tail of any psychometric function approaches chance asymptotically, there is really no point that can be defined as the deviation from chance. Alternatives involve fitting the sloping and asymptotic parts of the curve with straight lines and looking at the point of intersection. Such an approach can do some violence to the data and has an arbitrary quality to it.

Figure 6B demonstrates that in our data the critical spacing depends on the threshold elevation used to define it. It is clear that the more stringent the definition (i.e., larger threshold elevations) is, the smaller the critical spacing will be. As discussed below, critical spacing varies with eccentricity, but we find that even with a rather loose definition (25% increase) the ratio of critical spacing to eccentricity ($s_{crit}/E$) generally remains well below Bouma’s constant of 0.5, which may be considered an upper limit on critical spacing.

Leaving aside the issue of how to define the critical separation, one can ask whether critical separation is proportional to eccentricity. As noted by Latham and Whitaker (1996), if the critical spacing (however defined) changes quickly and linearly with eccentricity, then it must be proportional to eccentricity. That is, if $F_{1E} = 1 + E/E_2$, then $F_{1E}/E = 1/E + 1/E_2$ and this function drops rapidly to an asymptotic value of $1/E_2$. If $E_2 = 0.2$, then $F_{1E}/E$ drops by only 8% from 2 to 16°. Therefore, one might expect crowding to be proportional to eccentricity. However, we find, as did Pelli et al. (2007), that this is not strictly the case. At 1°, critical spacing relative to eccentricity is generally greater than at 2°, but this ratio tends to increase with eccentricity thereafter (Figure 6B). Therefore, we find the notion of Bouma’s constant to be a very rough approximation to the true nature of crowding.

Is crowding task independent?

A salient feature of Figure 2B is that the crowding functions look very similar for the T-orientation and grating resolution tasks and differ from the letter discrimination task in terms of the maximum threshold elevation achieved; this is most clearly seen in Figures 4B and 6A. This difference most likely reflects differences in the number and arrangement of flankers in the three tasks. Indeed, many recent studies have found varied results when configurations or grouping of flankers and targets are manipulated within and across tasks (Danilova & Bondarko, 2007; Levi & Carney, 2009; Livne & Sagi, 2010; Saarela, Westheimer, & Herzog, 2010). Crowding zones are generally elongated, with the principal axis aligned with the center of the fovea. Thus, there is more interference when targets and flankers form a line parallel to the principle axis than when perpendicular to it (Feng, Jiang, & He, 2007; Pelli et al., 2007; Toet & Levi, 1992). In summary, some of the differences between the experiments can be explained by the fact that the arrangement of flankers was different in the letter identification task than in the T-orientation and grating discrimination tasks.

Although it should be possible to fit all results of all three experiments (for each subject) using the same parameters (Melmoth et al., 2000; reducing the overall number of parameters for each subject by two-thirds), such a fit would involve a compromise between parameters of the data sets that are clearly different. For example, as just discussed, there is greater crowding in the T and grating tasks than in the letter identification task. As well, the minimum thresholds achieved across tasks are rather different across tasks (0.0472, 0.0553, and 0.0730 for T, letter, and grating tasks, respectively). These are all statistically different, as are a number of other parameter comparisons. Therefore, a fit that collapses the data from different conditions would obscure these interesting differences between conditions.

Conclusions

1. The maximum threshold elevation ($\mu_E$) increases nonlinearly with eccentricity.
2. Left shifting all curves on the separation axis by \( F_{\text{EH}} = \mu_E/\mu_0 \) and downshifting all curves on the size axis by \( F_{\text{EV}} = \text{unflanked}_E/\text{unflanked}_0 \) aligns all but the foveal curve.

3. These scaled data can be fit with a single curve, thus providing a complete description of the relationship between size and separation at threshold across eccentricities of 0 to 16\(^\circ\).

4. The non-linear change in the extent of crowding implies that the “critical spacing” is not proportional to eccentricity.

5. Furthermore, “critical spacing” depends on the level of stimulus contrast as target size increased, and we did not.

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## Footnotes

1The same problem afflicts the model of Latham and Whitaker (1996). For a threshold elevation of 3, the predicted critical spacing at fixation is 0.0055\(^\circ\), which is far smaller than the target size at threshold in the unflanked condition.

2Note that these numbers should be considered cautiously because they represent extrapolations from the data. When we consider the available data (not extrapolated data), we find that the average differences at fixation between thresholds for the 1.25\(\times\) and unflanked conditions are 1.84\%, 12.33\%, and -1.62\% for the T-orientation, letter identification, and grating discrimination tasks, respectively. None of these differences is statistically significant (\( t_5 = 2.02, 1.09, \) and -0.76; \( p = 0.14, 0.35, \) and 0.50, respectively; effect sizes = 1.02, 0.52, and -0.40, respectively). The corresponding analysis at 16\(^\circ\) yields average increases of 467\%, 171\%, and 394\% for the T-orientation, letter identification, and grating discrimination tasks, respectively. All of these differences are statistically significant (\( t_5 = 5.24, 5.22, \) and 6.24; \( p = 0.014, 0.014, \) and 0.008, respectively; effect sizes = 2.62, 2.61, and 3.12, respectively).

3There is an inconsistency in this formulation that is of little practical consequence. All curves in Figure 4B have been left shifted to align the point at which \( \mu_E = \text{separation}_E/\text{size}_E = 1 \). When we then fit these shifted data with a single rectangular parabola, the value for \( \mu_E = \text{separation}_E/\text{size}_E = 1 \) on the best fitting curve will not equal those used to left shift in the first place. Inspection of Figure 3 shows that this small distortion is of little consequence.

4We thank David Whitaker for this point.

5We must emphasize that on the surface the method used by Tripathy and Cavanagh is exactly the same as ours. In both cases, the objective is to determine the target–flanker separation that elicits criterion-level performance for a range of target sizes. Tripathy and Cavanagh accomplished this by fixing target size and finding the target–flanker separation that elicits criterion-level performance. We accomplished this by fixing the relative separation between target and flankers then varied the size of the entire configuration until criterion-level performance was obtained. In both cases, the procedures sample the iso-performance line that relates target size to target–flanker separation. The only difference between the two methods is that Tripathy and Cavanagh decreased stimulus contrast as target size increased, and we did not.

## References


