Evidence for an eye-movement contribution to normal foveal crowding

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Figures: 4
Tables: 2
Abstract

**Purpose.** Along with contour interaction, inaccurate and imprecise eye movements and attention have been suggested to contribute to poorer acuity for “crowded” vs. uncrowded targets. To investigate the role of eye movements in foveal crowding, we compared percent correct letter identification for short and long lines of near-threshold letters with different separations.

**Methods.** Five normal observers read short (4–6 letters) and long (10–12 letters) lines of near-threshold, Sloan letters with edge-to-edge letter separations of 0.5, 1 and 2 letter spaces. Percent correct letter identification for the 2–4 interior letters in short strings and the 8–10 interior letters in long strings was compared to a no-crowding condition.

**Results.** Letter identification was significantly worse than the no-crowding condition for long letter strings with a separation of 1 letter space, and for both long and short letter strings with a separation of 0.5 letter spaces. Observers more often reported the incorrect number of letters in long than short letter strings, even for a separation of 2 letter spaces. Similar results were obtained during straight-ahead gaze and while viewing in 30–40 deg left gaze, where 2 of the 5 observers exhibited an increase in horizontal fixational instability.

**Conclusions.** We argue that lower percent correct letter identification and more frequent errors in reporting the number of letters in long compared to short letter strings reflect an eye-movement contribution to foveal crowding.

**Key words.**

Crowding, contour interaction, visual acuity, eye movement, fixation.
Contour interaction is an impairment of fine spatial tasks, such as visual acuity, that occurs in the presence of nearby flanking contours. In addition to contour interaction, inaccurate and imprecise eye movements and divided or misplaced attention have been suggested to degrade visual acuity when measured with letter charts in amblyopic eyes. For example, Flom et al. reported that amblyopic eyes exhibit shallower psychometric functions and poorer visual acuity using ‘S charts’, composed of 8 Landolt C targets surrounded on all sides by tumbling Es, than for individual Landolt Cs surrounded by flanking bars. Eyes with normal vision exhibit little or no difference in the psychometric function for these types of acuity targets. In the aggregate, the deleterious influences of contour interaction, eye movements and attention on object discrimination and recognition are referred to as crowding.

Additional evidence for an effect of eye movement and/or misplaced attention on the measurement of foveal visual acuity comes from comparisons between standard clinical and repeat letter acuity charts. Repeat letter charts were developed to eliminate the effect of inaccurate eye positioning on the assessment of visual resolution. Indeed, measured visual acuity typically is better using repeat letter charts compared to standard clinical charts in populations with abnormal eye movement control, such as observers with amblyopia, nystagmus, central field loss, and young children. In contrast, adults with normal vision exhibit only a very slight acuity improvement, on the order of 1 to 1.5 letters, on repeat compared to standard letter charts. Instead of an eye-movement effect, this small acuity improvement in adults could be attributable to probability summation that results from multiple concurrent views of the same letter.

In normal adult observers, the range of eye movements during foveal fixation is larger than the spacing between adjacent threshold-sized letters on an acuity chart. Further, the saccadic
eye movements between closely spaced targets within an array typically are neither accurate nor precise.\textsuperscript{19,20} These observations suggest that, during the measurement of visual acuity, normal adults may sometimes fixate on a letter other than the one they are attempting to read. It seems a legitimate question to ask why these fixation errors don’t interfere with normal observers’ acuity, when measured with standard clinical letter charts compared to repeat letter charts or isolated letters. One reason may be that most modern clinical acuity charts include 5 or fewer letters of the same angular size per line.\textsuperscript{21-23} Normal adults can quickly, confidently, and accurately judge numerosity for up to approximately 5 items within a visual display;\textsuperscript{24,25} they may therefore be able to identify the location of a letter they are attempting to read even when the fovea is directed momentarily somewhere else. For displays that contain more than 5 items, observers are slower to determine numerosity and more likely to misperceive the number of items.\textsuperscript{24,25} These observations suggest that inaccurate fixation and/or misplaced attention within a line of acuity letters may be more likely to produce miscalls if the number of letters on the line is increased.

The purpose of this study was to infer the role of eye movements and/or attention in normal foveal crowding by comparing performance for short and long horizontal strings of letters with the same letter-to-letter separation, which should therefore produce equivalent amounts of contour interaction. We assessed foveal letter identification both in straight ahead gaze and while the observers fixated in left lateral gaze, where fixation was expected to become more variable. Objective eye-movement recordings indicated that this latter expectation was fulfilled only partially.

\textbf{Materials and Methods.}

\textit{Observers.}
Five adult observers with normal or corrected-to-normal vision participated after granting voluntary written informed consent. Experimental procedures were reviewed and approved by the Ethics Committee of Anglia Ruskin University. Four of the observers were female (3 students and one older adult, age range 21 – 62 years old), all of whom remained naïve as to the experimental hypotheses that were tested in the study. The fifth, non-naïve observer was author JS, who was 51 years old. All testing was performed monocularly, using the left eye. One of the observers (SA) was emmetropic. The other four observers had refractive corrections in the tested left eye of -1.75 sph (JC), -6.50/-1.50x100 (JH), -3.00/-0.50x150 (JS), and +1.75 sph (NB), which were provided during the experiments by ophthalmic trial lenses. The non-viewing right eye was occluded with an opaque patch.

**Psychophysical Methods.**

Observers viewed dark Sloan letters presented on a 19-inch Clinton Monoray monochrome monitor from an optical distance of 9.5 m, after reflection from two mirrors. The screen resolution was 1024 by 768 pixels and the frame rate was 120 Hz. At this viewing distance, the dimensions of the monitor screen corresponded to 2.33 by 1.75 deg. Background luminance was 110 cd/m² and letter contrast, calculated using the Weber formula, was -99%. A letter size corresponding to -0.2 logMAR (3.16 min arc) was used in all of the experimental conditions, as each observer identified approximately 75% of the letters of this size correctly in preliminary, uncrowded trials (see below). The observers viewed the letters foveally under two conditions of gaze, either straight-ahead or, for observers JC, JH, NB and SA, at 40 deg in left gaze. Subject JS could not comfortably sustain fixation at 40 deg left gaze and was tested at 30 deg left gaze instead. For logistical reasons, data collection began in left gaze only after testing in straight-ahead gaze was completed. Head position was maintained in each gaze position using a head and
chin rest. For the observers who required refractive correction, trial lenses were mounted on a flexible arm, which allowed them to be placed close to the eye and aligned with the visual axis in both straight-ahead and left gaze.

Random sequences of Sloan letters, with the stipulation that adjacent letters on the screen were never the same, were presented for an unlimited viewing duration in 3 types of trials. On each short-string trial, 4, 5 or 6 letters were presented at one time, with a horizontal edge-to-edge letter spacing of 0.5, 1 or 2 letter widths (i.e., 1.58, 3.16 or 6.32 min arc). On each long-string trial, a sequence of 10, 11 or 12 letters was presented, also with a horizontal edge-to-edge letter spacing of 0.5, 1 or 2 letter widths. The minimum separation between the edge of the monitor and the edges of the first and last letter in the longest letter strings was 3 letter spaces. For each direction of gaze, observers completed 108 short-string trials (36 each with 4, 5 and 6 letters) and 36 long-string trials (12 each with 10, 11 and 12 letters). The numbers of short- and long-string trials were chosen so that performance in the two conditions was based on the same total numbers of letters. Short- and long-string trials were presented in blocks of 36 and 12, respectively. Within a block of short- or long-string trials the letter-to-letter separation remained constant at 0.5, 1 or 2 letter widths and the strings with different numbers of letters were presented in a random order. Observers were instructed to read all of the letters in each string in sequence from left to right. Although the observers were informed that different numbers of letters would be presented on different trials, they were not told about the length of each letter string either prior to or after a trial. A single trial lasted between approximately 5 and 15 s and each block of 12 or 36 trials had a total duration of between 5 - 10 minutes. The experimenter used the computer keyboard to record the observers’ letter responses in order and subsequently compared the responses to the presented sequences of letters. Because crowding is reduced for
letters at the left and right ends of a line,\textsuperscript{26,27} performance was calculated by scoring only the interior 2, 3 or 4 letters for the trials with 4, 5, and 6 letters, respectively, and only the interior 8, 9 or 10 letters for the trials with 10, 11, and 12 letters. Letters had to be read in the correct order to be scored as correct.

For comparison with the short- and long-string trials, each observer first completed six blocks (one for each combination of letter separation and gaze direction) of 34 \textit{uncrowded} trials. On each uncrowded trial, three letters were presented with an edge-to-edge spacing of 5 letter widths (i.e., 15.8 min arc), a distance well beyond the extent of foveal crowding.\textsuperscript{1,6,28} Because crowding was assumed to be absent in this condition, all 3 letters presented on each trial were scored. As above, the letters had to be read in the correct order to be scored as correct.

\textit{Eye Movement Recording.}

To evaluate the influence of gaze direction on fixational eye movements, the horizontal and vertical positions of each observer’s left eye were recorded at a sampling rate of 250 Hz using an EyeLink 1000 Eyetracker with remote camera. Eye movement recordings were obtained in a separate session from the psychophysical measurements. During each trial, the observer fixated for 20 s at the center of a 3 to 5 letter string, displayed at a distance of 1 m on a 19-inch Sony Trinitron monitor. Four recordings were made while the observer viewed in straight-ahead gaze and another four were made during foveal fixation at 40 deg (observers JC, JH, NB and SA) or 30 deg (observer JS) left gaze. For each direction of gaze, head position was maintained using a head and chin rest.

Subsequently, two 5-s intervals without blinks were selected from each fixation file for further analysis: (1) calculation of the standard deviations (SDs) of the horizontal and vertical eye positions during each interval and (2) counts of the number of fixational saccades. The eye
movement results for each observer were summarized by taking the mean horizontal and vertical SDs and the mean number of fixation saccades during the 8 separate fixation intervals (i.e., 4 fixation trials x 2 intervals per trial).

Data Analysis.

To perform statistical analyses, the observers’ percent correct letter identification for each experimental condition was converted to a z score, as between-observer differences in z scores for the different experimental conditions are more similar than the differences in percent correct. A three-way repeated-measures ANOVA assessed the effects of string length (single letters, short strings and long strings), letter separation (0.5, 1 and 2 letter widths), and gaze direction (straight-ahead and left gaze). A separate two-way repeated-measures ANOVA evaluated whether string length and direction of gaze affected the percentage of trials on which the observers reported the correct number of letters. A Huynh-Feldt correction was applied to statistical tests when a departure from sphericity occurred. Although the statistical analyses were performed using z scores, for ease of presentation the results were transformed back to percent correct letter identification when plotting Figures 1–3, below.

Results.

Letter Identification.

The average z scores for letter identification in the uncrowded condition were 0.64 in straight-ahead gaze and 0.43 in left gaze, corresponding to 73.8% and 66.5% correct, respectively. These percentages did not differ significantly according to the letter position in the three-letter array (range: 72.0% – 74.3% in straight-ahead gaze; 63.4% – 66.6% in left gaze), confirming the absence of contour interaction in this condition. When the edge-to-edge separation between adjacent letters was 2 letter spaces, performance in the short- and long-string
conditions did not differ from that in the uncrowded condition (Figure 1 top panels). However, letter identification was poorer when the separation was less than 2 letter spaces, as indicated by a significant effect of separation ($F_{df=2,8} = 16.95$, $p = 0.0013$). The ANOVA also revealed a significant 2-way interaction between letter separation and string length ($F_{df=4,16} = 10.53$, $p = 0.011$). Compared to the uncrowded condition, $z$ scores were lower for long letter strings when the separation was 1 letter space ($F_{df=1,16} = 13.19$, $p = 0.019$), and for both the long and short letter strings when the separation was 0.5 letter spaces (for long letter strings, $F_{df=1,16} = 61.81$, $p = 0.0006$; for short letter strings, $F_{df=1,16} = 29.08$, $p = 0.0039$). These effects are visible in the data collected both in straight-ahead and left gaze in the middle and lower panels of Figure 1. Figure 2 replots the percent correct letter identification in straight ahead and left gaze, averaged across subjects, as a function of the letter separation and shows clearly that the magnitude of crowding is greater for the long compared to short letter strings.

Neither the direction of gaze nor the interactions between gaze direction and letter separation or string length exhibited a significant effect on letter identification. However, the ANOVA revealed a significant 3-way interaction between direction of gaze, letter separation, and string-length ($F_{df=4,16} = 3.03$, $p = 0.049$). Means comparisons indicated that this interaction resulted from significantly better performance in straight-ahead compared to left gaze for long strings when the letter separation was 2 letter widths ($F_{df=1,16} = 13.56$, $p = 0.0020$).

In a second analysis, we compared the percentage of trials (again, converted to $z$ scores) on which the observers reported the correct numbers of letters in the short- and long-string conditions. As anticipated, a three-way repeated-measures ANOVA found that observers reported the correct number of letters less frequently on long-string than short-string trials ($F_{df=1,4} = 145.96$, $p = 0.0003$). Observers also reported the correct number of letters less often as the
separation between adjacent letters decreased from 2 to 0.5 letter widths ($F_{df=1,4} = 26.41, p = 0.0014$). These trends can be seen in the results for both straight-ahead and left gaze, which are plotted in Figure 3. Of particular interest is the observation that observers reported the correct number of letters on a significantly lower proportion of long- compared to short-string trials even with a separation of two letter widths ($F_{df=1,8} = 12.59, p = 0.0075$). Although the observers generally reported the correct number of letters less frequently in left lateral compared to straight-ahead gaze (Figure 3), this difference did not achieve statistical significance ($F_{df=1,4} = 6.05, p = 0.070$). More detailed information is presented in Table 1, which summarizes the percentage of trials on which the observers reported fewer or more than the correct number of letters for each of the experimental conditions. Overall, when the observers did not report the correct number of letters, they erred more often (~60:40) by reporting too few rather than too many letters, both for the short and long letter strings.

When the observers reported too few letters, the majority of the time they reported one letter too few (73% of errors for long strings; 97% of errors for short strings). Similarly, when the observers reported too many letters, on the majority of trials they reported one extra letter (88% of trials for long strings; 98% of trials for short strings). On the remainder of the trials when an incorrect number letters was reported, the observers either omitted or added 2 (13% of trials) or 3 letters (1.6% of trials), primarily on long-string trials.

Examination of the responses on trials when the observers reported the incorrect number of letters indicated that errors of omission or insertion occurred almost always at interior positions in the string. The modal locations of these errors were letter places 6 (omissions) and 8 (insertions) in the long strings (accumulated across strings of 10, 11 and 12 letters), and place 4 (omissions and insertions) in the short letter strings (accumulated across strings of 4, 5, and 6 letters).
letters). When the observers reported one or more extra letters within a string, they typically reported a pair of confusion letters for one letter within the string, such as both ‘N’ and ‘R’ for the occurrence of an ‘R’ or both ‘D’ and ‘C’ for the occurrence of an ‘O.’

Observers would be expected to make more errors in reporting the correct number of letters for long compared to short letter strings, simply because the long strings include more letters to report. However, the following analysis reveals that merely increasing the average number of letters in the string does not account for our results. Assume the probability of incorrectly reporting each letter, either by omitting the letter or reporting an additional letter, is the same regardless of the string length. Further, assume that this probability, which we will designate as $p_e$, depends on the separation between the adjacent letters in the string. For each letter separation, we can estimate the value of $p_e$ from the percentage of reporting errors made when reading short letter strings, $p_5$. Specifically, if each short letter string is assumed to comprise 5 letters, then

$$(1 - p_e)^5 = 1 - p_5$$

and the predicted percentage of errors when reading strings of 11 letters, $p_{11}$, is

$$p_{11} = 1 - (1 - p_e)^{11}.$$  

For example, when the letter separation is 2 letters in straight-ahead gaze, summing the percentages of reporting too few and too many letters in the short-string condition yields $p_5 = 0.023$ (Table 1) and $(1 - p_5) = 0.977$. Based on this result, the predicted probability of reporting an incorrect number of letters in the analogous long-string condition, $p_{11}$, is 0.05. The observed probability of reporting the incorrect number of letters in this long-string condition was 0.15, which is significantly higher ($z = 3.55$, $p = 0.0004$) than the predicted value. The observed probabilities of reporting the incorrect numbers of letters in the long-string condition also is
significantly greater than the predicted probabilities (p < 0.0001) for the other 5 conditions of letter separation and gaze direction.

**Fixational Eye Movements.**

During fixation in straight-ahead gaze, the average standard deviations (SD) of both the horizontal and the vertical eye position measurements were approximately 0.16 deg (i.e., 9.5 min arc; Table 2). Although four of the five observers (all except JH) exhibited a small endpoint nystagmus when fixating in left gaze (Figure 4), only two of them exhibited a noticeable increase in the SD of horizontal eye position: for observer JS from 0.13 to 0.19 (± 0.02 SE) deg and for observer NB from 0.19 to 0.27 (±0.02 SE) deg. The SDs of vertical eye position were either unchanged in left compared to straight-ahead gaze or decreased (from 0.24 to 0.11 deg for observer JC). However, consistent with the observed endpoint nystagmus in left gaze, the average number of saccades during fixation in left gaze was significantly greater than the number of saccades during fixation in straight-ahead gaze (mean difference = 2.58 saccades/5 s, t_{df=4} = 3.10, p = 0.036).

We compared the change in correct letter identification between straight-ahead and left gaze in observers JS and NB, who showed an increase in the SD of horizontal eye position, to the change in performance of the other three observers. We focused on the change in z scores for long letter strings separated by two letter widths because, as reported above, this condition produced a significant gaze-dependent effect on crowding. The average change in z score from straight ahead to left gaze was 0.75 ± 0.08 for JS and NB, compared to 0.10 ± 0.19 for the other three observers.

**Discussion.**
In normal observers, contour interaction does not occur in the fovea for targets separated by more than 3 – 6 min arc, which corresponds approximately to the width of a high-contrast threshold acuity letter. On this basis, we conclude that only the immediately adjacent letters within each string contributed to contour interaction and that the magnitude of contour interaction was identical for the interior letters in the short- and long-string stimuli in our experiment. The greater magnitude of crowding that we observed for strings of 10, 11 and 12 letters than for strings of 4, 5 and 6 letters for a separation of 0.5 and 1 letter space (Figure 2) therefore can not be attributed to an increase in contour interaction.

Inaccurate and imprecise eye movements are a potential contributor to foveal crowding. The imprecision of normal fixation is large enough to encompass more than a single letter, even in the letter strings with a separation of two letter spaces between the adjacent letters (see also Figure 4). Moreover, it is highly unlikely that our observers accurately imaged the successive letters in the strings sequentially on the fovea. Kowler and Steinman measured the saccades made by two experienced observers when counting 10 to 19 identical vertical lines separated horizontally by gaps of 7.4 – 14.2 min arc. For lines separated by 7.4 to 8.2 min arc, one observer made saccades that ranged in amplitude from approximately 7 to 45 min arc; the saccades of the other observer ranged from less than 5 to approximately 20 min arc. Both observers frequently lost their place while counting the vertical lines and, for the range of line separations examined, reported the correct number of lines on half or fewer of the trials. Our finding that observers often reported the incorrect number of letters in the long-string condition (Fig. 3) is consistent with this observation. As suggested above in the Introduction, observers may be less likely to lose their place in short letter strings because they can judge the number of
letters, and presumably their relative positions in the string, essentially instantaneously and effortlessly.\textsuperscript{24,25}

Liu and Arditi observed that normal observers frequently reported only 4 of the letters in strings of 5 upper case letters when the edge-to-edge letter-to-letter spacing was made very small.\textsuperscript{33} The frequency of these under-reporting errors dropped rapidly from approximately 80% to 20% as the separation between adjacent letters increased from 0.04 to 0.24 of the threshold letter size. Only rarely did the observers make the opposite error of reporting 5 letters in strings that were 4 letters in length. Based on the strong dependence of under-reporting errors on the letter separation, the authors attributed these errors to overlap between the retinal images of adjacent letters. The observers in our study often erred in reporting the correct number of letters for edge-to-edge separations of 0.5 and 1 letter width, well beyond the range of separations used by Liu and Arditi.\textsuperscript{33} In addition, both under- and over-reporting of the number of letters were common among our observers (Table 1). For these reasons, we conclude that our results can not be attributed to overlap between the images of adjacent letters.

It is possible that the observers used the angular extent subtended by each string as a cue to the number of letters, as the ratios of the extent for the different short and long strings presented within a single block of trials generally exceed the Weber fraction for length discrimination (2 - 5%, e.g., Helmholtz, 1925; Ono, 1967\textsuperscript{34,35}). For the three letter separations tested, the ratios of extent for the 4, 5, and 6 letter strings are greater than those between 10, 11, and 12 letter strings, which potentially could account for the higher percentage of errors in reporting the number of letters on long- compared to short-string trials. However, the ratios of angular extent for the short and long letter strings do not change appreciably with the letter separation; i.e., the angular extent of 6 and 4 letter strings are in the ratio of 1.60 for a letter separation of two spaces and
1.55 for a letter separation of 0.5 spaces. Similarly, the angular extent of 12 and 10 letter strings are in the ratio of 1.21 for letter separations of both two and 0.5 spaces. Nevertheless, the number-of-response errors increase as the letter separation decreases from two to 0.5 spaces, both for the short and long letter strings (Figure 3). Further, in addition to the angular extent of the letter strings, information about the string length on each trial was available also from the angular separation between the first and last letter of the string and the edges of the monitor screen. The ratios of these separations for the different string lengths are uniformly higher for long than for short letter strings, and are greatest for long strings when the letter separation is large. When the separation between the adjacent letters in the long strings was two spaces, the ratios of the distances to the monitor edge for strings of 10, 11, and 12 letters are essentially identical to the ratios of the angular extents for strings of 4, 5, and 6 letters separated by one space. Nevertheless, observers made approximately 4.5 times more number-of-response errors on long-string trials with a separation of two letter spaces than on short-string trials with a separation of one letter space. The observations in this paragraph suggest that the observers did not attempt to deduce the number of letters presented on each trial and that, for a given separation between letters, the more frequent errors for long compared to short strings in the number of reported letters is attributable primarily to the number of letters the in the string.

We expected that observers would make more errors when they viewed the letter strings at 30 or 40 deg in left gaze compared to straight ahead because of an increase in the variability of fixation in association with the development of endpoint nystagmus. Although we observed a trend for a greater number of miscalls and more frequent errors in reporting the number of letters in a string, these trends did not reach statistical significance. The likely reason for the observers’ overall similar psychophysical performance in left and straight-ahead gaze is that the variability
of horizontal fixation did not change significantly in left gaze for three of the five observers. The two observers whose horizontal fixation was less stable in left gaze also identified widely spaced letters in the long-string condition less accurately in left compared to straight-ahead gaze. It is possible that fixation would have been less steady and psychophysical performance would have been worse if the observers had been required to view the letters with gaze diverted further to one side.\textsuperscript{38}

A displacement of attention from the acuity target towards the flanking stimuli also has been suggested to contribute to crowding.\textsuperscript{1,5} Leat et al. sought to assess the influence of attention on crowding by varying the similarity of the flanking targets to one another and to the acuity target which, in their study, was a Landolt C or tumbling E.\textsuperscript{6} The results indicated that the manipulation of flanker characteristics generates no consistent change in the magnitude of foveal crowding. However, it may be difficult to tease apart the potentially separate influences of eye movements and attention on foveal crowding, as there is evidence to suggest that the locus of attention remains closely tied to the direction of gaze during large eye movements.\textsuperscript{39-41} A similar intimate relationship has been suggested to exist also between the direction of gaze and attention during small shifts in the position of fixation by some,\textsuperscript{42-44} but not all authors.\textsuperscript{45}

We conclude that both the greater magnitude of foveal crowding and more frequent errors in reporting the correct number of letters in long compared to short letter strings are attributable to the imprecision and inaccuracy of small normal eye movements. As surmised previously by others, the eye-movement contribution to crowding may be substantially greater in individuals whose eye-movement control is poor, such as in patients with nystagmus,\textsuperscript{11,12} amblyopia,\textsuperscript{1,5,9,10} and young children.\textsuperscript{8,15,32}

\textbf{Acknowledgments.}
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References.


Table 1. Percentages of trials on which the five observers reported too few vs. too many letters for different combinations of string length, letter spacing, and gaze direction.

<table>
<thead>
<tr>
<th>Letter Separation Error</th>
<th>Type of Error</th>
<th>Straight-ahead Gaze</th>
<th>Left Gaze</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Short strings</td>
<td>Long strings</td>
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<tr>
<td>0.5</td>
<td>too few</td>
<td>18.9%</td>
<td>40.7%</td>
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<td>4.4%</td>
<td>20.0%</td>
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<td>1</td>
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<td>2.2%</td>
<td>35.0%</td>
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<td>too many</td>
<td>1.1%</td>
<td>20.0%</td>
</tr>
<tr>
<td>2</td>
<td>too few</td>
<td>0.6%</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>too many</td>
<td>1.7%</td>
<td>13.3%</td>
</tr>
</tbody>
</table>

Table 2. Mean standard deviations (SDs) of horizontal and vertical eye position during fixation for five observers in straight-ahead and left gaze.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Straight-ahead Gaze</th>
<th>Left Gaze</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal SD</td>
<td>Vertical SD</td>
</tr>
<tr>
<td>JC</td>
<td>0.16 ± 0.05</td>
<td>0.24 ± 0.09</td>
</tr>
<tr>
<td>JH</td>
<td>0.17 ± 0.05</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>JS</td>
<td>0.13 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>NB</td>
<td>0.19 ± 0.03</td>
<td>0.10 ± 0.04</td>
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<tr>
<td>SA</td>
<td>0.17 ± 0.05</td>
<td>0.18 ± 0.11</td>
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Figure Legends.

Figure 1. Percent correct letter identification is plotted for 5 observers for 3 presentation conditions of foveal viewing: uncrowded (‘single’) letters, short-letter strings, and long-letter strings. The top, middle, and lower pairs of panels show data for edge-to-edge letter separations of 2, 1 and 0.5 letter spaces. The right and left columns present results for letter strings viewed in straight ahead and left gaze, respectively. Within each column, the same values are plotted for each observer in the three panels for the uncrowded condition. The black lines in each panel connect the mean values of percent correct for the 3 different presentation conditions.

Figure 2. Mean percent correct letter identification is plotted as a function of the edge-to-edge letter spacing for short- and long-letter strings. The values plotted for a separation of 5 letter widths are from the uncrowded condition. The top and bottom panels present results for letters viewed in straight-ahead and left gaze.

Figure 3. The percentages of trials on which the observers reported the correct numbers of letters in the short and long letter strings are plotted as a function of the edge-to-edge letter separation within the strings. Results are shown separately for straight-ahead (unfilled symbols) and left gaze (filled symbols).

Figure 4. Five-second recordings of horizontal (black, higher traces) and vertical (gray, lower traces) eye position during fixation in straight-ahead (top) and left gaze (bottom) are presented for observer JC. The placement of each trace with respect to the vertical axis is arbitrary. Upward deflections represent rightward and upward eye movement. A leftward endpoint nystagmus with an amplitude of approximately one third of a degree is visible in the lower panel.
Figure 1

Two graphs show the percent correct for different conditions: 0.5 Letter Spaces, 1 Letter Space, and 2 Letter Spaces. Each graph plots percent correct against condition (Single, Short, Long) for different subjects (NB, JS, JH, SA, JC) and an average. The data is presented in a line graph format with markers for each subject and a line representing the average.
Figure 2

Straight Ahead Gaze

Percent Correct vs. Separation (letter widths)

Left Gaze

Percent Correct vs. Separation (letter widths)
Figure 3

% Trials with Correct Number of Letters

Percent of Trials vs. Separation (letter widths)

- SA Short
- SA Long
- L Gaze Short
- L Gaze Long
Figure 4

JC: Straight Ahead Gaze

Eye Position (deg)

Time (s)

JC: Left Gaze

Eye Position (deg)

Time (s)
Contour interaction is an impairment of fine spatial tasks, such as visual acuity, that occurs in the presence of nearby flanking contours.\textsuperscript{1,2} In addition to contour interaction, inaccurate and imprecise eye movements and divided or misplaced attention have been suggested to degrade visual acuity when measured with letter charts in amblyopic eyes.\textsuperscript{1,3-6} For example, Flom et al. reported that amblyopic eyes exhibit shallower psychometric functions and poorer visual acuity using ‘S charts’, composed of 8 Landolt C targets surrounded on all sides by tumbling Es, than for individual Landolt Cs surrounded by flanking bars.\textsuperscript{1} Eyes with normal vision exhibit little or no difference in the psychometric function for these types of acuity targets.\textsuperscript{1,7} In the aggregate, the deleterious influences of contour interaction, eye movements and attention on object discrimination and recognition are referred to as crowding.\textsuperscript{5}

Additional evidence for an effect of eye movement and/or misplaced attention on the measurement of foveal visual acuity comes from comparisons between standard clinical and repeat letter acuity charts.\textsuperscript{8} Repeat letter charts were developed to eliminate the effect of inaccurate eye positioning on the assessment of visual resolution. Indeed, measured visual acuity typically is better using repeat letter charts compared to standard clinical charts in populations with abnormal eye movement control, such as observers with amblyopia,\textsuperscript{9,10} nystagmus,\textsuperscript{11,12} central field loss,\textsuperscript{13,14} and young children.\textsuperscript{8,15} In contrast, adults with normal vision exhibit only a very slight acuity improvement, on the order of 1 to 1.5 letters, on repeat compared to standard letter charts.\textsuperscript{9,11,14} Instead of an eye-movement effect, this small acuity improvement in adults could be attributable to probability summation that results from multiple concurrent views of the same letter.

In normal adult observers, the range of eye movements during foveal fixation is larger than the spacing between adjacent threshold-sized letters on an acuity chart.\textsuperscript{16-18} Further, the saccadic
eye movements between closely spaced targets within an array typically are neither accurate nor
precise.\textsuperscript{19,20} These observations suggest that, during the measurement of visual acuity, normal
adults may sometimes fixate on a letter other than the one they are attempting to read. It seems a
legitimate question to ask why these fixation errors don’t interfere with normal observers’ acuity,
when measured with standard clinical letter charts compared to repeat letter charts or isolated
letters. One reason may be that most modern clinical acuity charts include 5 or fewer letters of
the same angular size per line.\textsuperscript{21-23} Normal adults can quickly, confidently, and accurately judge
numerosity for up to approximately 5 items within a visual display;\textsuperscript{24,25} they may therefore be
able to identify the location of a letter they are attempting to read even when the fovea is directed
momentarily somewhere else. For displays that contain more than 5 items, observers are slower
to determine numerosity and more likely to misperceive the number of items.\textsuperscript{24,25} These
observations suggest that inaccurate fixation and/or misplaced attention within a line of acuity
letters may be more likely to produce miscalls if the number of letters on the line is increased.

The purpose of this study was to infer the role of eye movements and/or attention in normal
foveal crowding by comparing performance for short and long horizontal strings of letters with
the same letter-to-letter separation, which should therefore produce equivalent amounts of
contour interaction. We assessed foveal letter identification both in straight ahead gaze and while
the observers fixated in left lateral gaze, where fixation was expected to become more variable.
Objective eye-movement recordings indicated that this latter expectation was fulfilled only
partially.

\textbf{Materials and Methods.}

\textit{Observers.}
Five adult observers with normal or corrected-to-normal vision participated after granting voluntary written informed consent. Experimental procedures were reviewed and approved by the Ethics Committee of Anglia Ruskin University. Four of the observers were female students and one older adult, age range 21 – 62 years old, all of whom remained naïve as to the experimental hypotheses that were tested in the study. The fifth, non-naïve observer was author JS, who was 51 years old. All testing was performed monocularly, using the left eye. One of the observers (SA) was emmetropic. The other four observers had refractive corrections in the tested left eye of -1.75 sph (JC), -6.50/-1.50x100 (JH), -3.00/-0.50x150 (JS), and +1.75 sph (NB), which were provided during the experiments by ophthalmic trial lenses. The non-viewing right eye was occluded with an opaque patch.

Psychophysical Methods.

Observers viewed dark Sloan letters presented on a 19-inch Clinton Monoray monochrome monitor from an optical distance of 9.5 m, after reflection from two mirrors. The screen resolution was 1024 by 768 pixels and the frame rate was 120 Hz. At this viewing distance, the dimensions of the monitor screen corresponded to 2.33 by 1.75 deg. Background luminance was 110 cd/m² and letter contrast, calculated using the Weber formula, was -99%. A letter size corresponding to -0.2 logMAR (3.16 min arc) was used in all of the experimental conditions, as each observer identified approximately 75% of the letters of this size correctly in preliminary, uncrowded trials (see below). The observers viewed the letters foveally under two conditions of gaze, either straight-ahead or, for observers JC, JH, NB and SA, at 40 deg in left gaze. Subject JS could not comfortably sustain fixation at 40 deg left gaze and was tested at 30 deg left gaze instead. For logistical reasons, data collection began in left gaze only after testing in straight-ahead gaze was completed. Head position was maintained in each gaze position using a head and
chir rest. For the observers who required refractive correction, trial lenses were mounted on a flexible arm, which allowed them to be placed close to the eye and aligned with the visual axis in both straight-ahead and left gaze.

Random sequences of Sloan letters, with the stipulation that adjacent letters on the screen were never the same, were presented for an unlimited viewing duration in 3 types of trials. On each short-string trial, 4, 5 or 6 letters were presented at one time, with a horizontal edge-to-edge letter spacing of 0.5, 1 or 2 letter widths (i.e., 1.58, 3.16 or 6.32 min arc). On each long-string trial, a sequence of 10, 11 or 12 letters was presented, also with a horizontal edge-to-edge letter spacing of 0.5, 1 or 2 letter widths. The minimum separation between the edge of the monitor and the edges of the first and last letter in the longest letter strings was 3 letter spaces. For each direction of gaze, observers completed 108 short-string trials (36 each with 4, 5 and 6 letters) and 36 long-string trials (12 each with 10, 11 and 12 letters). The numbers of short- and long-string trials were chosen so that performance in the two conditions was based on the same total numbers of letters. Short- and long-string trials were presented in blocks of 36 and 12, respectively. Within a block of short- or long-string trials the letter-to-letter separation remained constant at 0.5, 1 or 2 letter widths and the strings with different numbers of letters were presented in a random order. Observers were instructed to read all of the letters in each string in sequence from left to right. Although the observers were informed that different numbers of letters would be presented on different trials, they were not told about the length of each letter string either prior to or after a trial. A single trial lasted between approximately 5 and 15 s and each block of 12 or 36 trials had a total duration of between 5 - 10 minutes. The experimenter used the computer keyboard to record the observers’ letter responses in order and subsequently compared the responses to the presented sequences of letters. Because crowding is reduced for
letters at the left and right ends of a line,\textsuperscript{26,27} performance was calculated by scoring only the interior 2, 3 or 4 letters for the trials with 4, 5, and 6 letters, respectively, and only the interior 8, 9 or 10 letters for the trials with 10, 11, and 12 letters. Letters had to be read in the correct order to be scored as correct.

For comparison with the short- and long-string trials, each observer first completed six blocks (one for each combination of letter separation and gaze direction) of 34 uncrowded trials. On each uncrowded trial, three letters were presented with an edge-to-edge spacing of 5 letter widths (i.e., 15.8 min arc), a distance well beyond the extent of foveal crowding.\textsuperscript{1,6,28} Because crowding was assumed to be absent in this condition, all 3 letters presented on each trial were scored. As above, the letters had to be read in the correct order to be scored as correct.

\textit{Eye Movement Recording.}

To evaluate the influence of gaze direction on fixational eye movements, the horizontal and vertical positions of each observer’s left eye were recorded at a sampling rate of 250 Hz using an EyeLink 1000 Eyetracker with remote camera. Eye movement recordings were obtained in a separate session from the psychophysical measurements. During each trial, the observer fixated for 20 s at the center of a 3 to 5 letter string, displayed at a distance of 1 m on a 19-inch Sony Trinitron monitor. Four recordings were made while the observer viewed in straight-ahead gaze and another four were made during foveal fixation at 40 deg (observers JC, JH, NB and SA) or 30 deg (observer JS) left gaze. For each direction of gaze, head position was maintained using a head and chin rest.

Subsequently, two 5-s intervals without blinks were selected from each fixation file for further analysis: (1) calculation of the standard deviations (SDs) of the horizontal and vertical eye positions during each interval and (2) counts of the number of fixational saccades. The eye
movement results for each observer were summarized by taking the mean horizontal and vertical SDs and the mean number of fixation saccades during the 8 separate fixation intervals (i.e., 4 fixation trials x 2 intervals per trial).

**Data Analysis.**

To perform statistical analyses, the observers’ percent correct letter identification for each experimental condition was converted to a z score, as between-observer differences in z scores for the different experimental conditions are more similar than the differences in percent correct. A three-way repeated-measures ANOVA assessed the effects of string length (single letters, short strings and long strings), letter separation (0.5, 1 and 2 letter widths), and gaze direction (straight-ahead and left gaze). A separate two-way repeated-measures ANOVA evaluated whether string length and direction of gaze affected the percentage of trials on which the observers reported the correct number of letters. A Huynh-Feldt correction was applied to statistical tests when a departure from sphericity occurred. Although the statistical analyses were performed using z scores, for ease of presentation the results were transformed back to percent correct letter identification when plotting Figures 1 – 3, below.

**Results.**

**Letter Identification.**

The average z scores for letter identification in the *uncrowded* condition were 0.64 in straight-ahead gaze and 0.43 in left gaze, corresponding to 73.8% and 66.5% correct, respectively. These percentages did not differ significantly according to the letter position in the three-letter array (range: 72.0% – 74.3% in straight-ahead gaze; 63.4% – 66.6% in left gaze), confirming the absence of contour interaction in this condition. When the edge-to-edge separation between adjacent letters was 2 letter spaces, performance in the short- and long-string
conditions did not differ from that in the uncrowded condition (Figure 1 top panels). However, letter identification was poorer when the separation was less than 2 letter spaces, as indicated by a significant effect of separation ($F_{df=2,8} = 16.95$, $p = 0.0013$). The ANOVA also revealed a significant 2-way interaction between letter separation and string length ($F_{df=4,16} = 10.53$, $p = 0.011$). Compared to the uncrowded condition, $z$ scores were lower for long letter strings when the separation was 1 letter space ($F_{df=1,16} = 13.19$, $p = 0.019$), and for both the long and short letter strings when the separation was 0.5 letter spaces (for long letter strings, $F_{df=1,16} = 61.81$, $p = 0.0006$; for short letter strings, $F_{df=1,16} = 29.08$, $p = 0.0039$). These effects are visible in the data collected both in straight-ahead and left gaze in the middle and lower panels of Figure 1. Figure 2 replots the percent correct letter identification in straight ahead and left gaze, averaged across subjects, as a function of the letter separation and shows clearly that the magnitude of crowding is greater for the long compared to short letter strings.

Neither the direction of gaze nor the interactions between gaze direction and letter separation or string length exhibited a significant effect on letter identification. However, the ANOVA revealed a significant 3-way interaction between direction of gaze, letter separation, and string-length ($F_{df=4,16} = 3.03$, $p = 0.049$). Means comparisons indicated that this interaction resulted from significantly better performance in straight-ahead compared to left gaze for long strings when the letter separation was 2 letter widths ($F_{df=1,16} = 13.56$, $p = 0.0020$).

In a second analysis, we compared the percentage of trials (again, converted to $z$ scores) on which the observers reported the correct numbers of letters in the short- and long-string conditions. As anticipated, a three-way repeated-measures ANOVA found that observers reported the correct number of letters less frequently on long-string than short-string trials ($F_{df=1,4} = 145.96$, $p = 0.0003$). Observers also reported the correct number of letters less often as the
separation between adjacent letters decreased from 2 to 0.5 letter widths ($F_{df=1,4} = 26.41, p = 0.0014$). These trends can be seen in the results for both straight-ahead and left gaze, which are plotted in Figure 3. Of particular interest is the observation that observers reported the correct number of letters on a significantly lower proportion of long- compared to short-string trials even with a separation of two letter widths ($F_{df=1,8} = 12.59, p = 0.0075$). Although the observers generally reported the correct number of letters less frequently in left lateral compared to straight-ahead gaze (Figure 3), this difference did not achieve statistical significance ($F_{df=1,4} = 6.05, p = 0.070$). More detailed information is presented in Table 1, which summarizes the percentage of trials on which the observers reported fewer or more than the correct number of letters for each of the experimental conditions. Overall, when the observers did not report the correct number of letters, they erred more often (~60:40) by reporting too few rather than too many letters, both for the short and long letter strings.

When the observers reported too few letters, the majority of the time they reported one letter too few (73% of errors for long strings; 97% of errors for short strings). Similarly, when the observers reported too many letters, on the majority of trials they reported one extra letter (88% of trials for long strings; 98% of trials for short strings). On the remainder of the trials when an incorrect number letters was reported, the observers either omitted or added 2 (13% of trials) or 3 letters (1.6% of trials), primarily on long-string trials.

Examination of the responses on trials when the observers reported the incorrect number of letters indicated that errors of omission or insertion occurred almost always at interior positions in the string. The modal locations of these errors were letter places 6 (omissions) and 8 (insertions) in the long strings (accumulated across strings of 10, 11 and 12 letters), and place 4 (omissions and insertions) in the short letter strings (accumulated across strings of 4, 5, and 6
letters). When the observers reported one or more extra letters within a string, they typically reported a pair of confusion letters for one letter within the string, such as both ‘N’ and ‘R’ for the occurrence of an ‘R’ or both ‘D’ and ‘C’ for the occurrence of an ‘O.’

Observers would be expected to make more errors in reporting the correct number of letters for long compared to short letter strings, simply because the long strings include more letters to report. However, the following analysis reveals that merely increasing the average number of letters in the string does not account for our results. Assume the probability of incorrectly reporting each letter, either by omitting the letter or reporting an additional letter, is the same regardless of the string length. Further, assume that this probability, which we will designate as $p_e$, depends on the separation between the adjacent letters in the string. For each letter separation, we can estimate the value of $p_e$ from the percentage of reporting errors made when reading short letter strings, $p_5$. Specifically, if each short letter string is assumed to comprise 5 letters, then

$$\left(1 - p_e\right)^5 = 1 - p_5$$

and the predicted percentage of errors when reading strings of 11 letters, $p_{11}$, is

$$p_{11} = 1 - (1 - p_e)^{11}.$$ 

For example, when the letter separation is 2 letters in straight-ahead gaze, summing the percentages of reporting too few and too many letters in the short-string condition yields $p_5 = 0.023$ (Table 1) and $\left(1 - p_5\right) = 0.977$. Based on this result, the predicted probability of reporting an incorrect number of letters in the analogous long-string condition, $p_{11}$, is 0.05. The observed probability of reporting the incorrect number of letters in this long-string condition was 0.15, which is significantly higher ($z = 3.55, p = 0.0004$) than the predicted value. The observed probabilities of reporting the incorrect numbers of letters in the long-string condition also is
significantly greater than the predicted probabilities (p < 0.0001) for the other 5 conditions of letter separation and gaze direction.

*Fixational Eye Movements.*

During fixation in straight-ahead gaze, the average standard deviations (SD) of both the horizontal and the vertical eye position measurements were approximately 0.16 deg (i.e., 9.5 min arc; Table 2). Although four of the five observers (all except JH) exhibited a small endpoint nystagmus when fixating in left gaze (Figure 4), only two of them exhibited a noticeable increase in the SD of horizontal eye position: for observer JS from 0.13 to 0.19 (± 0.02 SE) deg and for observer NB from 0.19 to 0.27 (±0.02 SE) deg. The SDs of vertical eye position were either unchanged in left compared to straight-ahead gaze or decreased (from 0.24 to 0.11 deg for observer JC). However, consistent with the observed endpoint nystagmus in left gaze, the average number of saccades during fixation in left gaze was significantly greater than the number of saccades during fixation in straight-ahead gaze (mean difference = 2.58 saccades/5 s, t_{df=4} = 3.10, p = 0.036).

We compared the change in correct letter identification between straight-ahead and left gaze in observers JS and NB, who showed an increase in the SD of horizontal eye position, to the change in performance of the other three observers. We focused on the change in z scores for long letter strings separated by two letter widths because, as reported above, this condition produced a significant gaze-dependent effect on crowding. The average change in z score from straight ahead to left gaze was 0.75 ± 0.08 for JS and NB, compared to 0.10 ± 0.19 for the other three observers.

**Discussion.**
In normal observers, contour interaction does not occur in the fovea for targets separated by more than 3 – 6 min arc, which corresponds approximately to the width of a high-contrast threshold acuity letter.\textsuperscript{1,2,7,29-31} On this basis, we conclude that only the immediately adjacent letters within each string contributed to contour interaction and that the magnitude of contour interaction was identical for the interior letters in the short- and long-string stimuli in our experiment. The greater magnitude of crowding that we observed for strings of 10, 11 and 12 letters than for strings of 4, 5 and 6 letters for a separation of 0.5 and 1 letter space (Figure 2) therefore can not be attributed to an increase in contour interaction.

Inaccurate and imprecise eye movements are a potential contributor to foveal crowding.\textsuperscript{1,5,8,32} The imprecision of normal fixation is large enough to encompass more than a single letter, even in the letter strings with a separation of two letter spaces between the adjacent letters\textsuperscript{16-18} (see also Figure 4). Moreover, it is highly unlikely that our observers accurately imaged the successive letters in the strings sequentially on the fovea. Kowler and Steinman\textsuperscript{20} measured the saccades made by two experienced observers when counting 10 to 19 identical vertical lines separated horizontally by gaps of 7.4 – 14.2 min arc. For lines separated by 7.4 to 8.2 min arc, one observer made saccades that ranged in amplitude from approximately 7 to 45 min arc; the saccades of the other observer ranged from less than 5 to approximately 20 min arc. Both observers frequently lost their place while counting the vertical lines and, for the range of line separations examined, reported the correct number of lines on half or fewer of the trials. Our finding that observers often reported the incorrect number of letters in the long-string condition (Fig. 3) is consistent with this observation. As suggested above in the Introduction, observers may be less likely to lose their place in short letter strings because they can judge the number of
letters, and presumably their relative positions in the string, essentially instantaneously and effortlessly.\textsuperscript{24,25}

Liu and Arditi observed that normal observers frequently reported only 4 of the letters in strings of 5 upper case letters when the edge-to-edge letter-to-letter spacing was made very small.\textsuperscript{33} The frequency of these under-reporting errors dropped rapidly from approximately 80\% to 20\% as the separation between adjacent letters increased from 0.04 to 0.24 of the threshold letter size. Only rarely did the observers make the opposite error of reporting 5 letters in strings that were 4 letters in length. Based on the strong dependence of under-reporting errors on the letter separation, the authors attributed these errors to overlap between the retinal images of adjacent letters. The observers in our study often erred in reporting the correct number of letters for edge-to-edge separations of 0.5 and 1 letter width, well beyond the range of separations used by Liu and Arditi.\textsuperscript{33} In addition, both under- and over-reporting of the number of letters were common among our observers (Table 1). For these reasons, we conclude that our results can not be attributed to overlap between the images of adjacent letters.

It is possible that the observers used the angular extent subtended by each string as a cue to the number of letters, as the ratios of the extent for the different short and long strings presented within a single block of trials generally exceed the Weber fraction for length discrimination (2 - 5\%, e.g., Helmholtz, 1925; Ono, 1967\textsuperscript{34,35}). For the three letter separations tested, the ratios of extent for the 4, 5, and 6 letter strings are greater than those between 10, 11, and 12 letter strings, which potentially could account for the higher percentage of errors in reporting the number of letters on long- compared to short-string trials. However, the ratios of angular extent for the short and long letter strings do not change appreciably with the letter separation; i.e., the angular extent of 6 and 4 letter strings are in the ratio of 1.60 for a letter separation of two spaces and
1.55 for a letter separation of 0.5 spaces. Similarly, the angular extent of 12 and 10 letter strings
are in the ratio of 1.21 for letter separations of both two and 0.5 spaces. Nevertheless, the
number-of-response errors increase as the letter separation decreases from two to 0.5 spaces,
both for the short and long letter strings (Figure 3). Further, in addition to the angular extent of
the letter strings, information about the string length on each trial was available also from the
angular separation between the first and last letter of the string and the edges of the monitor
screen. The ratios of these separations for the different string lengths are uniformly higher for
long than for short letter strings, and are greatest for long strings when the letter separation is
large. When the separation between the adjacent letters in the long strings was two spaces, the
ratios of the distances to the monitor edge for strings of 10, 11, and 12 letters are essentially
identical to the ratios of the angular extents for strings of 4, 5, and 6 letters separated by one
space. Nevertheless, observers made approximately 4.5 times more number-of-response errors
on long-string trials with a separation of two letter spaces than on short-string trials with a
separation of one letter space. The observations in this paragraph suggest that the observers did
not attempt to deduce the number of letters presented on each trial and that, for a given
separation between letters, the more frequent errors for long compared to short strings in the
number of reported letters is attributable primarily to the number of letters the in the string.

We expected that observers would make more errors when they viewed the letter strings at
30 or 40 deg in left gaze compared to straight ahead because of an increase in the variability of
fixation in association with the development of endpoint nystagmus.\textsuperscript{36-38} Although we observed a
trend for a greater number of miscalls and more frequent errors in reporting the number of letters
in a string, these trends did not reach statistical significance. The likely reason for the observers’
overall similar psychophysical performance in left and straight-ahead gaze is that the variability
of horizontal fixation did not change significantly in left gaze for three of the five observers. The
two observers whose horizontal fixation was less stable in left gaze also identified widely spaced
letters in the long-string condition less accurately in left compared to straight-ahead gaze. It is
possible that fixation would have been less steady and psychophysical performance would have
been worse if the observers had been required to view the letters with gaze diverted further to
one side.\textsuperscript{38}

A displacement of attention from the acuity target towards the flanking stimuli also has been
suggested to contribute to crowding.\textsuperscript{1,5} Leat et al. sought to assess the influence of attention on
crowding by varying the similarity of the flanking targets to one another and to the acuity target
which, in their study, was a Landolt C or tumbling E.\textsuperscript{6} The results indicated that the manipulation
of flanker characteristics generates no consistent change in the magnitude of foveal crowding.
However, it may be difficult to tease apart the potentially separate influences of eye movements
and attention on foveal crowding, as there is evidence to suggest that the locus of attention
remains closely tied to the direction of gaze during large eye movements.\textsuperscript{39-41} A similar intimate
relationship has been suggested to exist also between the direction of gaze and attention during
small shifts in the position of fixation by some,\textsuperscript{42-44} but not all authors.\textsuperscript{45}

We conclude that both the greater magnitude of foveal crowding and more frequent errors in
reporting the correct number of letters in long compared to short letter strings are attributable to
the imprecision and inaccuracy of small normal eye movements. As surmised previously by
others, the eye-movement contribution to crowding may be substantially greater in individuals
whose eye-movement control is poor, such as in patients with nystagmus,\textsuperscript{11,12} amblyopia,\textsuperscript{1,5,9,10}
and young children.\textsuperscript{8,15,32}

\textbf{Acknowledgments.}
This research was supported by a grant from the Evelyn Trust and a Leverhulme Visiting Professorship to Anglia Ruskin University. Portions of the data were presented at the annual meeting of the American Academy of Optometry in Seattle, WA in October, 2013.
References.


Table 1. Percentages of trials on which the five observers reported too few vs. too many letters for different combinations of string length, letter spacing, and gaze direction.

<table>
<thead>
<tr>
<th>Letter Separation</th>
<th>Type of Error</th>
<th>Straight-ahead Gaze</th>
<th>Left Gaze</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short strings</td>
<td>Long strings</td>
<td>Short strings</td>
</tr>
<tr>
<td>0.5</td>
<td>too few</td>
<td>18.9%</td>
<td>40.7%</td>
</tr>
<tr>
<td></td>
<td>too many</td>
<td>4.4%</td>
<td>20.0%</td>
</tr>
<tr>
<td>1</td>
<td>too few</td>
<td>2.2%</td>
<td>35.0%</td>
</tr>
<tr>
<td></td>
<td>too many</td>
<td>1.1%</td>
<td>20.0%</td>
</tr>
<tr>
<td>2</td>
<td>too few</td>
<td>0.6%</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>too many</td>
<td>1.7%</td>
<td>13.3%</td>
</tr>
</tbody>
</table>

Table 2. Mean standard deviations (SDs) of horizontal and vertical eye position during fixation for five observers in straight-ahead and left gaze.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Straight-ahead Gaze</th>
<th>Left Gaze</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal SD</td>
<td>Vertical SD</td>
</tr>
<tr>
<td>JC</td>
<td>0.16 ± 0.05</td>
<td>0.24 ± 0.09</td>
</tr>
<tr>
<td>JH</td>
<td>0.17 ± 0.05</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>JS</td>
<td>0.13 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>NB</td>
<td>0.19 ± 0.03</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>SA</td>
<td>0.17 ± 0.05</td>
<td>0.18 ± 0.11</td>
</tr>
</tbody>
</table>
Figure Legends.

Figure 1. Percent correct letter identification is plotted for 5 observers for 3 presentation conditions of foveal viewing: uncrowded (‘single’) letters, short-letter strings, and long-letter strings. The top, middle, and lower pairs of panels show data for edge-to-edge letter separations of 2, 1 and 0.5 letter spaces. The right and left columns present results for letter strings viewed in straight ahead and left gaze, respectively. Within each column, the same values are plotted for each observer in the three panels for the uncrowded condition. The black lines in each panel connect the mean values of percent correct for the 3 different presentation conditions.

Figure 2. Mean percent correct letter identification is plotted as a function of the edge-to-edge letter spacing for short- and long-letter strings. The values plotted for a separation of 5 letter widths are from the uncrowded condition. The top and bottom panels present results for letters viewed in straight-ahead and left gaze.

Figure 3. The percentages of trials on which the observers reported the correct numbers of letters in the short and long letter strings are plotted as a function of the edge-to-edge letter separation within the strings. Results are shown separately for straight-ahead (unfilled symbols) and left gaze (filled symbols).

Figure 4. Five-second recordings of horizontal (black, higher traces) and vertical (gray, lower traces) eye position during fixation in straight-ahead (top) and left gaze (bottom) are presented for observer JC. The placement of each trace with respect to the vertical axis is arbitrary. Upward deflections represent rightward and upward eye movement. A leftward endpoint nystagmus with an amplitude of approximately one third of a degree is visible in the lower panel.