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Evidence for an eye-movement contribution to normal foveal crowding

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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 horizonal 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.

1   Contour interaction is an impairment of fine spatial tasks, such as visual acuity, that occurs in

2   the presence of nearby flanking contours.[1,2] In addition to contour interaction, inaccurate and

3   imprecise eye movements and divided or misplaced attention have been suggested to degrade

4   visual acuity when measured with letter charts in amblyopic eyes.[1,3-6] For example, Flom et al.

5   reported that amblyopic eyes exhibit shallower psychometric functions and poorer visual acuity

6   using 'S charts', composed of 8 Landolt C targets surrounded on all sides by tumbling Es, than

7   for individual Landolt Cs surrounded by flanking bars.[1] Eyes with normal vision exhibit little or

8   no difference in the psychometric function for these types of acuity targets.[1,7] In the aggregate,

9   the deleterious influences of contour interaction, eye movements and attention on object

10   discrimination and recognition are referred to as crowding.[5]

11   Additional evidence for an effect of eye movement and/or misplaced attention on the

12   measurement of foveal visual acuity comes from comparisons between standard clinical and

13   repeat letter acuity charts.[8] Repeat letter charts were developed to eliminate the effect of

14   inaccurate eye positioning on the assessment of visual resolution. Indeed, measured visual acuity

15   typically is better using repeat letter charts compared to standard clinical charts in populations

16   with abnormal eye movement control, such as observers with amblyopia,[9,10] nystagmus,[11,12]

17   central field loss,[13,14] and young children.[8,15] In contrast, adults with normal vision exhibit only a

18   very slight acuity improvement, on the order of 1 to 1.5 letters, on repeat compared to standard

19   letter charts.[9,11,14] Instead of an eye-movement effect, this small acuity improvement in adults

20   could be attributable to probability summation that results from multiple concurrent views of the

21   same letter.

22   In normal adult observers, the range of eye movements during foveal fixation is larger than

23   the spacing between adjacent threshold-sized letters on an acuity chart.[16-18] Further, the saccadic

24   eye movements between closely spaced targets within an array typically are neither accurate nor

25   precise.[19,20] These observations suggest that, during the measurement of visual acuity, normal

26   adults may sometimes fixate on a letter other than the one they are attempting to read. It seems a

27   legitimate question to ask why these fixation errors don't interfere with normal observers' acuity,

28   when measured with standard clinical letter charts compared to repeat letter charts or isolated

29   letters. One reason may be that most modern clinical acuity charts include 5 or fewer letters of

30   the same angular size per line.[21-23] Normal adults can quickly, confidently, and accurately judge

31   numerosity for up to approximately 5 items within a visual display;[24,25] they may therefore be

32   able to identify the location of a letter they are attempting to read even when the fovea is directed

33   momentarily somewhere else. For displays that contain more than 5 items, observers are slower

34   to determine numerosity and more likely to misperceive the number of items.[24,25] These

35   observations suggest that inaccurate fixation and/or misplaced attention within a line of acuity

36   letters may be more likely to produce miscalls if the number of letters on the line is increased.

37   The purpose of this study was to infer the role of eye movements and/or attention in normal

38   foveal crowding by comparing performance for short and long horizontal strings of letters with

39   the same letter-to-letter separation, which should therefore produce equivalent amounts of

40   contour interaction. We assessed foveal letter identification both in straight ahead gaze and while

41   the observers fixated in left lateral gaze, where fixation was expected to become more variable.

42   Objective eye-movement recordings indicated that this latter expectation was fulfilled only

43   partially.

44
45   **Materials and Methods.**

46   *Observers.*

47 Five adult observers with normal or corrected-to-normal vision participated after granting

48 voluntary written informed consent. Experimental procedures were reviewed and approved by

49 the Ethics Committee of Anglia Ruskin University. Four of the observers were female (3

50 students and one older adult, age range 21 – 62 years old), all of whom remained naïve as to the

51 experimental hypotheses that were tested in the study. The fifth, non-naïve observer was author

52 JS, who was 51 years old. All testing was performed monocularly, using the left eye. One of the

53 observers (SA) was emmetropic. The other four observers had refractive corrections in the tested

54 left eye of -1.75 sph (JC), -6.50/-1.50x100 (JH), -3.00/-0.50x150 (JS), and +1.75 sph (NB),

55 which were provided during the experiments by ophthalmic trial lenses. The non-viewing right

56 eye was occluded with an opaque patch.

57 *Psychophysical Methods.*

58 Observers viewed dark Sloan letters presented on a 19-inch Clinton Monoray monochrome

59 monitor from an optical distance of 9.5 m, after reflection from two mirrors. The screen

60 resolution was 1024 by 768 pixels and the frame rate was 120 Hz. At this viewing distance, the

61 dimensions of the monitor screen corresponded to 2.33 by 1.75 deg. Background luminance was

62 110 cd/m^2 and letter contrast, calculated using the Weber formula, was -99%. A letter size

63 corresponding to -0.2 logMAR (3.16 min arc) was used in all of the experimental conditions, as

64 each observer identified approximately 75% of the letters of this size correctly in preliminary,

65 *uncrowded* trials (see below). The observers viewed the letters foveally under two conditions of

66 gaze, either straight-ahead or, for observers JC, JH, NB and SA, at 40 deg in left gaze. Subject JS

67 could not comfortably sustain fixation at 40 deg left gaze and was tested at 30 deg left gaze

68 instead. For logistical reasons, data collection began in left gaze only after testing in straight-

69 ahead gaze was completed. Head position was maintained in each gaze position using a head and

70   chin rest. For the observers who required refractive correction, trial lenses were mounted on a

71   flexible arm, which allowed them to be placed close to the eye and aligned with the visual axis in

72   both straight-ahead and left gaze.

73   Random sequences of Sloan letters, with the stipulation that adjacent letters on the screen

74   were never the same, were presented for an unlimited viewing duration in 3 types of trials. On

75   each *short-string* trial, 4, 5 or 6 letters were presented at one time, with a horizontal edge-to-edge

76   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*

77   trial, a sequence of 10, 11 or 12 letters was presented, also with a horizontal edge-to-edge letter

78   spacing of 0.5, 1 or 2 letter widths. The minimum separation between the edge of the monitor

79   and the edges of the first and last letter in the longest letter strings was 3 letter spaces. For each

80   direction of gaze, observers completed 108 short-string trials (36 each with 4, 5 and 6 letters) and

81   36 long-string trials (12 each with 10, 11 and 12 letters). The numbers of short- and long-string

82   trials were chosen so that performance in the two conditions was based on the same total

83   numbers of letters. Short- and long-string trials were presented in blocks of 36 and 12,

84   respectively. Within a block of short- or long-string trials the letter-to-letter separation remained

85   constant at 0.5, 1 or 2 letter widths and the strings with different numbers of letters were

86   presented in a random order. Observers were instructed to read all of the letters in each string in

87   sequence from left to right. Although the observers were informed that different numbers of

88   letters would be presented on different trials, they were not told about the length of each letter

89   string either prior to or after a trial. A single trial lasted between approximately 5 and 15 s and

90   each block of 12 or 36 trials had a total duration of between 5 - 10 minutes. The experimenter

91   used the computer keyboard to record the observers' letter responses in order and subsequently

92   compared the responses to the presented sequences of letters. Because crowding is reduced for

93   letters at the left and right ends of a line,[26,27] performance was calculated by scoring only the

94   interior 2, 3 or 4 letters for the trials with 4, 5, and 6 letters, respectively, and only the interior 8,

95   9 or 10 letters for the trials with 10, 11, and 12 letters. Letters had to be read in the correct order

96   to be scored as correct.

97   For comparison with the short- and long-string trials, each observer first completed six

98   blocks (one for each combination of letter separation and gaze direction) of 34 *uncrowded* trials.

99   On each uncrowded trial, three letters were presented with an edge-to-edge spacing of 5 letter

100   widths (i.e., 15.8 min arc), a distance well beyond the extent of foveal crowding.[1,6,28] Because

101   crowding was assumed to be absent in this condition, all 3 letters presented on each trial were

102   scored. As above, the letters had to be read in the correct order to be scored as correct.

103   *Eye Movement Recording.*

104   To evaluate the influence of gaze direction on fixational eye movements, the horizontal and

105   vertical positions of each observer's left eye were recorded at a sampling rate of 250 Hz using an

106   EyeLink 1000 Eyetracker with remote camera. Eye movement recordings were obtained in a

107   separate session from the psychophysical measurements. During each trial, the observer fixated

108   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

109   Trinitron monitor. Four recordings were made while the observer viewed in straight-ahead gaze

110   and another four were made during foveal fixation at 40 deg (observers JC, JH, NB and SA) or

111   30 deg (observer JS) left gaze. For each direction of gaze, head position was maintained using a

112   head and chin rest.

113   Subsequently, two 5-s intervals without blinks were selected from each fixation file for

114   further analysis: (1) calculation of the standard deviations (SDs) of the horizontal and vertical

115   eye positions during each interval and (2) counts of the number of fixational saccades. The eye

116   movement results for each observer were summarized by taking the mean horizontal and vertical

117   SDs and the mean number of fixation saccades during the 8 separate fixation intervals (i.e., 4

118   fixation trials x 2 intervals per trial).

119   *Data Analysis.*

120   To perform statistical analyses, the observers' percent correct letter identification for each

121   experimental condition was converted to a z score, as between-observer differences in z scores

122   for the different experimental conditions are more similar than the differences in percent correct.

123   A three-way repeated-measures ANOVA assessed the effects of string length (single letters,

124   short strings and long strings), letter separation (0.5, 1 and 2 letter widths), and gaze direction

125   (straight-ahead and left gaze). A separate two-way repeated-measures ANOVA evaluated

126   whether string length and direction of gaze affected the percentage of trials on which the

127   observers reported the correct *number* of letters. A Huynh-Feldt correction was applied to

128   statistical tests when a departure from sphericity occurred. Although the statistical analyses were

129   performed using z scores, for ease of presentation the results were transformed back to percent

130   correct letter identification when plotting Figures 1 – 3, below.

131   **Results.**

132   *Letter Identification.*

133   The average z scores for letter identification in the *uncrowded* condition were 0.64 in

134   straight-ahead gaze and 0.43 in left gaze, corresponding to 73.8% and 66.5% correct,

135   respectively. These percentages did not differ significantly according to the letter position in the

136   three-letter array (range: 72.0% – 74.3% in straight-ahead gaze; 63.4% – 66.6% in left gaze),

137   confirming the absence of contour interaction in this condition. When the edge-to-edge

138   separation between adjacent letters was 2 letter spaces, performance in the short- and long-string

139   conditions did not differ from that in the uncrowded condition (Figure 1 top panels). However,

140   letter identification was poorer when the separation was less than 2 letter spaces, as indicated by

141   a significant effect of separation ($F_{df=2,8} = 16.95$, $p = 0.0013$). The ANOVA also revealed a

142   significant 2-way interaction between letter separation and string length ($F_{df=4,16} = 10.53$, $p =$

143   0.011). Compared to the uncrowded condition, z scores were lower for long letter strings when

144   the separation was 1 letter space ($F_{df=1,16} = 13.19$, $p = 0.019$), and for both the long and short

145   letter strings when the separation was 0.5 letter spaces (for long letter strings, $F_{df=1,16} = 61.81$, $p =$

146   0.0006; for short letter strings, $F_{df=1,16} = 29.08$, $p = 0.0039$). These effects are visible in the data

147   collected both in straight-ahead and left gaze in the middle and lower panels of Figure 1. Figure

148   2 replots the percent correct letter identification in straight ahead and left gaze, averaged across

149   subjects, as a function of the letter separation and shows clearly that the *magnitude* of crowding

150   is greater for the long compared to short letter strings.

151   Neither the direction of gaze nor the interactions between gaze direction and letter separation

152   or string length exhibited a significant effect on letter identification. However, the ANOVA

153   revealed a significant 3-way interaction between direction of gaze, letter separation, and string-

154   length ($F_{df=4,16} = 3.03$, $p = 0.049$). Means comparisons indicated that this interaction resulted

155   from significantly better performance in straight-ahead compared to left gaze for long strings

156   when the letter separation was 2 letter widths ($F_{df=1,16} = 13.56$, $p = 0.0020$).

157   In a second analysis, we compared the percentage of trials (again, converted to z scores) on

158   which the observers reported the correct numbers of letters in the short- and long-string

159   conditions. As anticipated, a three-way repeated-measures ANOVA found that observers

160   reported the correct number of letters less frequently on long-string than short-string trials ($F_{df=1,4}$

161    $= 145.96$, $p = 0.0003$). Observers also reported the correct number of letters less often as the

162   separation between adjacent letters decreased from 2 to 0.5 letter widths ($F_{df=1,4}$ = 26.41, p =

163   0.0014). These trends can be seen in the results for both straight-ahead and left gaze, which are

164   plotted in Figure 3. Of particular interest is the observation that observers reported the correct

165   number of letters on a significantly lower proportion of long- compared to short-string trials even

166   with a separation of two letter widths ($F_{df=1,8}$ = 12.59, p = 0.0075). Although the observers

167   generally reported the correct number of letters less frequently in left lateral compared to

168   straight-ahead gaze (Figure 3), this difference did not achieve statistical significance ($F_{df=1,4}$ =

169   6.05, p = 0.070). More detailed information is presented in Table 1, which summarizes the

170   percentage of trials on which the observers reported fewer or more than the correct number of

171   letters for each of the experimental conditions. Overall, when the observers did not report the

172   correct number of letters, they erred more often (~60:40) by reporting too few rather than too

173   many letters, both for the short and long letter strings.

174   When the observers reported too few letters, the majority of the time they reported one letter

175   too few (73% of errors for long strings; 97% of errors for short strings). Similarly, when the

176   observers reported too many letters, on the majority of trials they reported one extra letter (88%

177   of trials for long strings; 98% of trials for short strings). On the remainder of the trials when an

178   incorrect number letters was reported, the observers either omitted or added 2 (13% of trials) or 3

179   letters (1.6% of trials), primarily on long-string trials.

180   Examination of the responses on trials when the observers reported the incorrect number of

181   letters indicated that errors of omission or insertion occurred almost always at interior positions

182   in the string. The modal locations of these errors were letter places 6 (omissions) and 8

183   (insertions) in the long strings (accumulated across strings of 10, 11 and 12 letters), and place 4

184   (omissions and insertions) in the short letter strings (accumulated across strings of 4, 5, and 6

185   letters). When the observers reported one or more extra letters within a string, they typically

186   reported a pair of confusion letters for one letter within the string, such as both 'N' and 'R' for

187   the occurrence of an 'R' or both 'D' and 'C' for the occurrence of an 'O.'

188   Observers would be expected to make more errors in reporting the correct number of letters

189   for long compared to short letter strings, simply because the long strings include more letters to

190   report. However, the following analysis reveals that merely increasing the average number of

191   letters in the string does not account for our results. Assume the probability of incorrectly

192   reporting each letter, either by omitting the letter or reporting an additional letter, is the same

193   regardless of the string length. Further, assume that this probability, which we will designate as

194   p_e, depends on the separation between the adjacent letters in the string. For each letter separation,

195   we can estimate the value of p_e from the percentage of reporting errors made when reading short

196   letter strings, p_5. Specifically, if each short letter string is assumed to comprise 5 letters, then

197    $$(1 - p_e)^5 = 1 - p_5$$

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

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

200   For example, when the letter separation is 2 letters in straight-ahead gaze, summing the

201   percentages of reporting too few and too many letters in the short-string condition yields $p_5 =$

202   0.023 (Table 1) and $(1 - p_5) = 0.977$. Based on this result, the predicted probability of reporting

203   an incorrect number of letters in the analogous long-string condition, p_{11}, is 0.05. The observed

204   probability of reporting the incorrect number of letters in this long-string condition was 0.15,

205   which is significantly higher ($z = 3.55$, $p = 0.0004$) than the predicted value. The observed

206   probabilities of reporting the incorrect numbers of letters in the long-string condition also is

207   significantly greater than the predicted probabilities (p < 0.0001) for the other 5 conditions of

208   letter separation and gaze direction.

209   *Fixational Eye Movements.*

210   During fixation in straight-ahead gaze, the average standard deviations (SD) of both the

211   horizontal and the vertical eye position measurements were approximately 0.16 deg (i.e., 9.5 min

212   arc; Table 2). Although four of the five observers (all except JH) exhibited a small endpoint

213   nystagmus when fixating in left gaze (Figure 4), only two of them exhibited a noticeable increase

214   in the SD of horizontal eye position: for observer JS from 0.13 to 0.19 (± 0.02 SE) deg and for

215   observer NB from 0.19 to 0.27 (±0.02 SE) deg. The SDs of vertical eye position were either

216   unchanged in left compared to straight-ahead gaze or decreased (from 0.24 to 0.11 deg for

217   observer JC). However, consistent with the observed endpoint nystagmus in left gaze, the

218   average number of saccades during fixation in left gaze was significantly greater than the number

219   of saccades during fixation in straight-ahead gaze (mean difference = 2.58 saccades/5 s, $t_{df=4}$ =

220   3.10, p = 0.036).

221   We compared the *change* in correct letter identification between straight-ahead and left gaze

222   in observers JS and NB, who showed an increase in the SD of horizontal eye position, to the

223   change in performance of the other three observers. We focused on the change in z scores for

224   long letter strings separated by two letter widths because, as reported above, this condition

225   produced a significant gaze-dependent effect on crowding. The average change in z score from

226   straight ahead to left gaze was 0.75 ± 0.08 for JS and NB, compared to 0.10 ± 0.19 for the other

227   three observers.

228   **Discussion.**

229   In normal observers, contour interaction does not occur in the fovea for targets separated by

230   more than 3 – 6 min arc, which corresponds approximately to the width of a high-contrast

231   threshold acuity letter.[1,2,7,29-31] On this basis, we conclude that only the immediately adjacent

232   letters within each string contributed to contour interaction and that the magnitude of contour

233   interaction was identical for the interior letters in the short- and long-string stimuli in our

234   experiment. The greater magnitude of *crowding* that we observed for strings of 10, 11 and 12

235   letters than for strings of 4, 5 and 6 letters for a separation of 0.5 and 1 letter space (Figure 2)

236   therefore can not be attributed to an increase in contour interaction.

237   Inaccurate and imprecise eye movements are a potential contributor to foveal crowding.[1,5,8,32]

238   The imprecision of normal fixation is large enough to encompass more than a single letter, even

239   in the letter strings with a separation of two letter spaces between the adjacent letters[16-18] (see

240   also Figure 4). Moreover, it is highly unlikely that our observers accurately imaged the

241   successive letters in the strings sequentially on the fovea. Kowler and Steinman[20] measured the

242   saccades made by two experienced observers when counting 10 to 19 identical vertical lines

243   separated horizontally by gaps of 7.4 – 14.2 min arc. For lines separated by 7.4 to 8.2 min arc,

244   one observer made saccades that ranged in amplitude from approximately 7 to 45 min arc; the

245   saccades of the other observer ranged from less than 5 to approximately 20 min arc. Both

246   observers frequently lost their place while counting the vertical lines and, for the range of line

247   separations examined, reported the correct number of lines on half or fewer of the trials. Our

248   finding that observers often reported the incorrect number of letters in the long-string condition

249   (Fig. 3) is consistent with this observation. As suggested above in the Introduction, observers

250   may be less likely to lose their place in short letter strings because they can judge the number of

251 letters, and presumably their relative positions in the string, essentially instantaneously and

252 effortlessly.[24,25]

253   Liu and Arditi observed that normal observers frequently reported only 4 of the letters in

254 strings of 5 upper case letters when the edge-to-edge letter-to-letter spacing was made very

255 small.[33] The frequency of these under-reporting errors dropped rapidly from approximately 80%

256 to 20% as the separation between adjacent letters increased from 0.04 to 0.24 of the threshold

257 letter size. Only rarely did the observers make the opposite error of reporting 5 letters in strings

258 that were 4 letters in length. Based on the strong dependence of under-reporting errors on the

259 letter separation, the authors attributed these errors to overlap between the retinal images of

260 adjacent letters. The observers in our study often erred in reporting the correct number of letters

261 for edge-to-edge separations of 0.5 and 1 letter width, well beyond the range of separations used

262 by Liu and Arditi.[33] In addition, both under- and over-reporting of the number of letters were

263 common among our observers (Table 1). For these reasons, we conclude that our results can *not*

264 be attributed to overlap between the images of adjacent letters.

265   It is possible that the observers used the angular extent subtended by each string as a cue to

266 the number of letters, as the ratios of the extent for the different short and long strings presented

267 within a single block of trials generally exceed the Weber fraction for length discrimination (2 -

268 5%, e.g., Helmholtz, 1925; Ono, 1967 [34,35]). For the three letter separations tested, the ratios of

269 extent for the 4, 5, and 6 letter strings are greater than those between 10, 11, and 12 letter strings,

270 which potentially could account for the higher percentage of errors in reporting the number of

271 letters on long- compared to short-string trials. However, the ratios of angular extent for the

272 short and long letter strings do not change appreciably with the letter separation; i.e., the angular

273 extent of 6 and 4 letter strings are in the ratio of 1.60 for a letter separation of two spaces and

274   1.55 for a letter separation of 0.5 spaces. Similarly, the angular extent of 12 and 10 letter strings

275   are in the ratio of 1.21 for letter separations of both two and 0.5 spaces. Nevertheless, the

276   number-of-response errors increase as the letter separation decreases from two to 0.5 spaces,

277   both for the short and long letter strings (Figure 3). Further, in addition to the angular extent of

278   the letter strings, information about the string length on each trial was available also from the

279   angular separation between the first and last letter of the string and the edges of the monitor

280   screen. The ratios of these separations for the different string lengths are uniformly *higher* for

281   long than for short letter strings, and are greatest for long strings when the letter separation is

282   large. When the separation between the adjacent letters in the long strings was two spaces, the

283   ratios of the distances to the monitor edge for strings of 10, 11, and 12 letters are essentially

284   identical to the ratios of the angular extents for strings of 4, 5, and 6 letters separated by one

285   space. Nevertheless, observers made approximately 4.5 times more number-of-response errors

286   on long-string trials with a separation of two letter spaces than on short-string trials with a

287   separation of one letter space. The observations in this paragraph suggest that the observers did

288   not attempt to deduce the number of letters presented on each trial and that, for a given

289   separation between letters, the more frequent errors for long compared to short strings in the

290   number of reported letters is attributable primarily to the number of letters the in the string.

291   We expected that observers would make more errors when they viewed the letter strings at

292   30 or 40 deg in left gaze compared to straight ahead because of an increase in the variability of

293   fixation in association with the development of endpoint nystagmus.[36-38] Although we observed a

294   trend for a greater number of miscalls and more frequent errors in reporting the number of letters

295   in a string, these trends did not reach statistical significance. The likely reason for the observers'

296   overall similar psychophysical performance in left and straight-ahead gaze is that the variability

297   of horizontal fixation did not change significantly in left gaze for three of the five observers. The

298   two observers whose horizontal fixation was less stable in left gaze also identified widely spaced

299   letters in the long-string condition less accurately in left compared to straight-ahead gaze. It is

300   possible that fixation would have been less steady and psychophysical performance would have

301   been worse if the observers had been required to view the letters with gaze diverted further to

302   one side.[38]

303   A displacement of attention from the acuity target towards the flanking stimuli also has been

304   suggested to contribute to crowding.[1,5] Leat et al. sought to assess the influence of attention on

305   crowding by varying the similarity of the flanking targets to one another and to the acuity target

306   which, in their study, was a Landolt C or tumbling E.[6] The results indicated that the manipulation

307   of flanker characteristics generates no consistent change in the magnitude of foveal crowding.

308   However, it may be difficult to tease apart the potentially separate influences of eye movements

309   and attention on foveal crowding, as there is evidence to suggest that the locus of attention

310   remains closely tied to the direction of gaze during large eye movements.[39-41] A similar intimate

311   relationship has been suggested to exist also between the direction of gaze and attention during

312   small shifts in the position of fixation by some,[42-44] but not all authors.[45]

313   We conclude that both the greater magnitude of foveal crowding and more frequent errors in

314   reporting the correct number of letters in long compared to short letter strings are attributable to

315   the imprecision and inaccuracy of small normal eye movements. As surmised previously by

316   others, the eye-movement contribution to crowding may be substantially greater in individuals

317   whose eye-movement control is poor, such as in patients with nystagmus,[11,12] amblyopia,[1,5,9,10]

318   and young children.[8,15,32]

319   **Acknowledgments**.

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411

412 **Table 1**. Percentages of trials on which the five observers reported too few vs. too many letters

413 for different combinations of string length, letter spacing, and gaze direction.

414

Letter Separation	Type of Error	Straight-ahead Gaze		Left Gaze	
		Short strings	Long strings	Short strings	Long strings
0.5	too few	18.9%	40.7%	10.6%	45.0%
	too many	4.4%	20.0%	7.2%	30.0%
1	too few	2.2%	35.0%	1.7%	36.7%
	too many	1.1%	20.0%	4.4%	16.7%
2	too few	0.6%	1.7%	0.6%	15.0%
	too many	1.7%	13.3%	2.2%	13.3%

415
416
417
418 **Table 2**. Mean standard deviations (SDs) of horizontal and vertical eye position during fixation

419 for five observers in straight-ahead and left gaze.

420

	Straight-ahead Gaze		Left Gaze	
Observer	Horizontal SD	Vertical SD	Horizontal SD	Vertical SD
JC	0.16 ± 0.05	0.24 ± 0.09	0.14 ± 0.04	0.11 ± 0.02
JH	0.17 ± 0.05	0.17 ± 0.03	0.17 ± 0.04	0.15 ± 0.01
JS	0.13 ± 0.04	0.11 ± 0.04	0.19 ± 0.03	0.14 ± 0.06
NB	0.19 ± 0.03	0.10 ± 0.04	0.27 ± 0.04	0.13 ± 0.04
SA	0.17 ± 0.05	0.18 ± 0.11	0.13 ± 0.03	0.17 ± 0.03

421
422

423   **Figure Legends.**
424
425   *Figure 1*. Percent correct letter identification is plotted for 5 observers for 3 presentation

426   conditions of foveal viewing: uncrowded ('single') letters, short-letter strings, and long-letter

427   strings. The top, middle, and lower pairs of panels show data for edge-to-edge letter separations

428   of 2, 1 and 0.5 letter spaces. The right and left columns present results for letter strings viewed in

429   straight ahead and left gaze, respectively. Within each column, the same values are plotted for

430   each observer in the three panels for the uncrowded condition. The black lines in each panel

431   connect the mean values of percent correct for the 3 different presentation conditions.

432   *Figure 2*. Mean percent correct letter identification is plotted as a function of the edge-to-edge

433   letter spacing for short- and long-letter strings. The values plotted for a separation of 5 letter

434   widths are from the uncrowded condition. The top and bottom panels present results for letters

435   viewed in straight-ahead and left gaze.

436   *Figure 3*. The percentages of trials on which the observers reported the correct numbers of letters

437   in the short and long letter strings are plotted as a function of the edge-to-edge letter separation

438   within the strings. Results are shown separately for straight-ahead (unfilled symbols) and left

439   gaze (filled symbols).

440   *Figure 4*. Five-second recordings of horizontal (black, higher traces) and vertical (gray, lower

441   traces) eye position during fixation in straight-ahead (top) and left gaze (bottom) are presented

442   for observer JC. The placement of each trace with respect to the vertical axis is arbitrary. Upward

443   deflections represent rightward and upward eye movement. A leftward endpoint nystagmus with

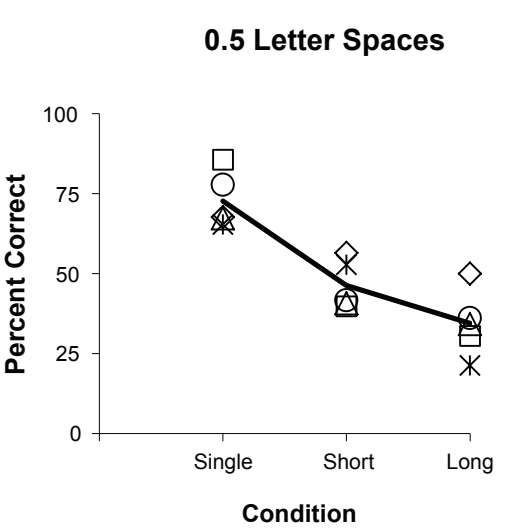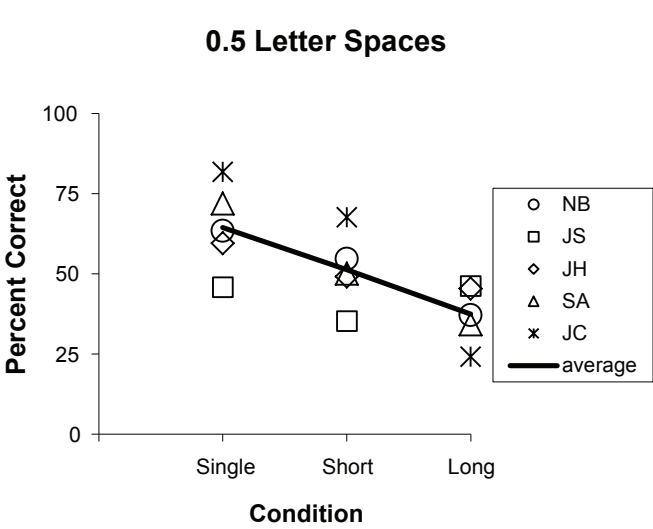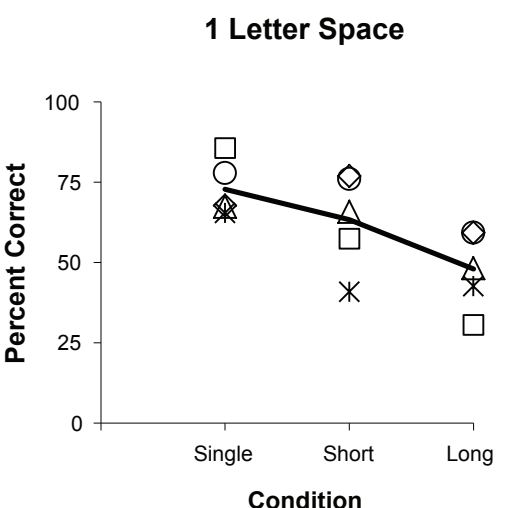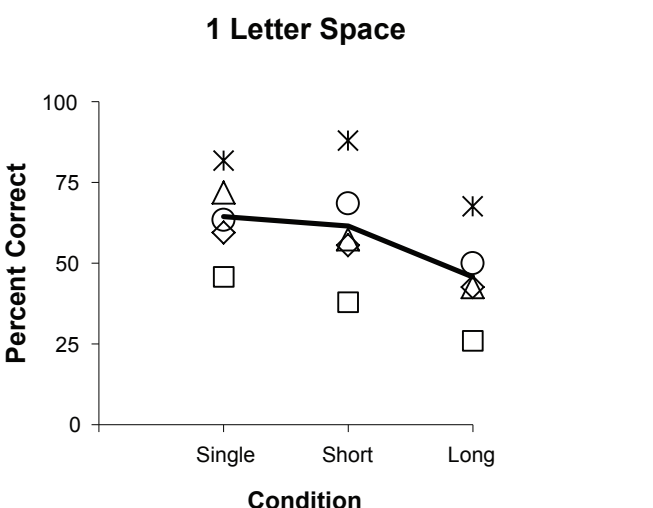444   an amplitude of approximately one third of a degree is visible in the lower panel.

445

Figure 1

Figure 2

Straight Ahead Gaze

Percent Correct vs Separation (letter widths)
Short Strings
Long Strings

Left Gaze

Percent Correct vs Separation (letter widths)
Short Strings
Long Strings
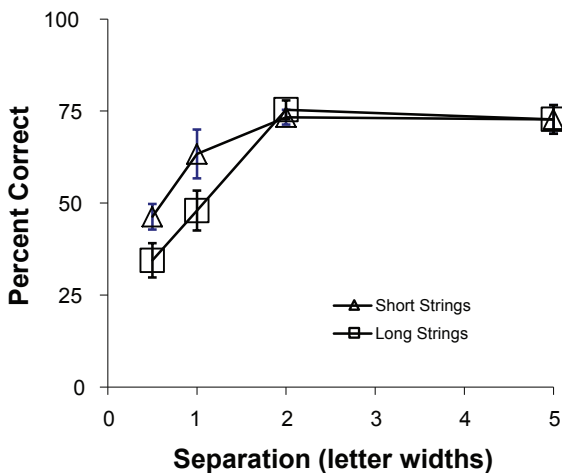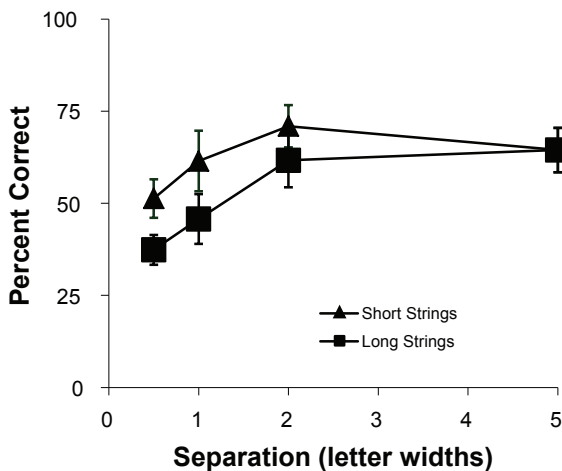
Figure 3

% Trials with Correct Number of Letters

Legend:
- SA Short
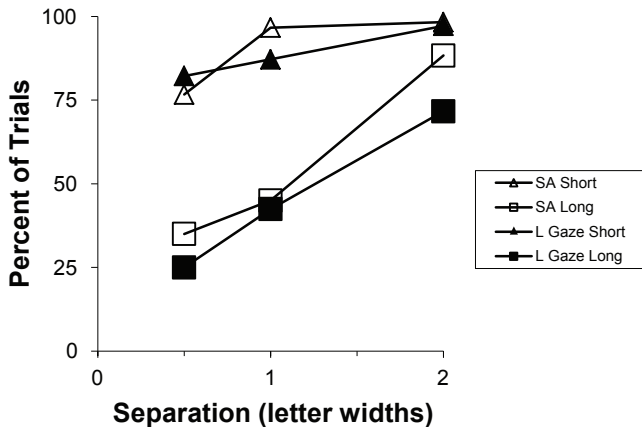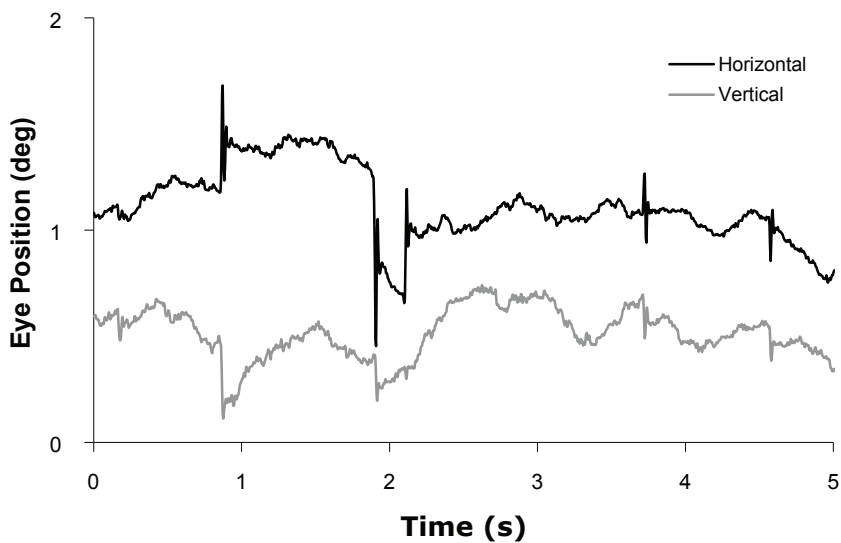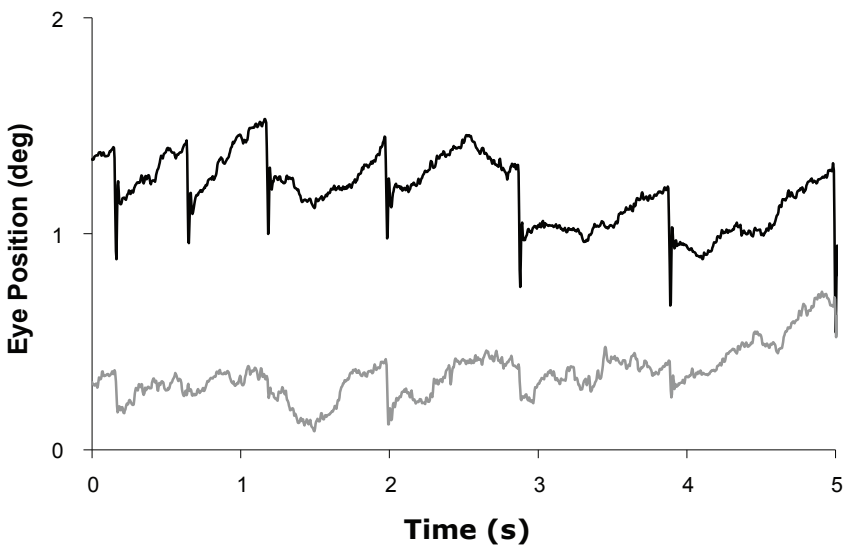- SA Long
- L Gaze Short
- L Gaze Long

Figure 4

JC: Straight Ahead Gaze

JC: Left Gaze

1   Contour interaction is an impairment of fine spatial tasks, such as visual acuity, that occurs in

2   the presence of nearby flanking contours.[1,2] In addition to contour interaction, inaccurate and

3   imprecise eye movements and divided or misplaced attention have been suggested to degrade

4   visual acuity when measured with letter charts in amblyopic eyes.[1,3-6] For example, Flom et al.

5   reported that amblyopic eyes exhibit shallower psychometric functions and poorer visual acuity

6   using 'S charts', composed of 8 Landolt C targets surrounded on all sides by tumbling Es, than

7   for individual Landolt Cs surrounded by flanking bars.[1] Eyes with normal vision exhibit little or

8   no difference in the psychometric function for these types of acuity targets.[1,7] In the aggregate,

9   the deleterious influences of contour interaction, eye movements and attention on object

10   discrimination and recognition are referred to as crowding.[5]

11   Additional evidence for an effect of eye movement and/or misplaced attention on the

12   measurement of foveal visual acuity comes from comparisons between standard clinical and

13   repeat letter acuity charts.[8] Repeat letter charts were developed to eliminate the effect of

14   inaccurate eye positioning on the assessment of visual resolution. Indeed, measured visual acuity

15   typically is better using repeat letter charts compared to standard clinical charts in populations

16   with abnormal eye movement control, such as observers with amblyopia,[9,10] nystagmus,[11,12]

17   central field loss,[13,14] and young children.[8,15] In contrast, adults with normal vision exhibit only a

18   very slight acuity improvement, on the order of 1 to 1.5 letters, on repeat compared to standard

19   letter charts.[9,11,14] Instead of an eye-movement effect, this small acuity improvement in adults

20   could be attributable to probability summation that results from multiple concurrent views of the

21   same letter.

22   In normal adult observers, the range of eye movements during foveal fixation is larger than

23   the spacing between adjacent threshold-sized letters on an acuity chart.[16-18] Further, the saccadic

24 eye movements between closely spaced targets within an array typically are neither accurate nor

25 precise.[19,20] These observations suggest that, during the measurement of visual acuity, normal

26 adults may sometimes fixate on a letter other than the one they are attempting to read. It seems a

27 legitimate question to ask why these fixation errors don't interfere with normal observers' acuity,

28 when measured with standard clinical letter charts compared to repeat letter charts or isolated

29 letters. One reason may be that most modern clinical acuity charts include 5 or fewer letters of

30 the same angular size per line.[21-23] Normal adults can quickly, confidently, and accurately judge

31 numerosity for up to approximately 5 items within a visual display;[24,25] they may therefore be

32 able to identify the location of a letter they are attempting to read even when the fovea is directed

33 momentarily somewhere else. For displays that contain more than 5 items, observers are slower

34 to determine numerosity and more likely to misperceive the number of items.[24,25] These

35 observations suggest that inaccurate fixation and/or misplaced attention within a line of acuity

36 letters may be more likely to produce miscalls if the number of letters on the line is increased.

37   The purpose of this study was to infer the role of eye movements and/or attention in normal

38 foveal crowding by comparing performance for short and long horizontal strings of letters with

39 the same letter-to-letter separation, which should therefore produce equivalent amounts of

40 contour interaction. We assessed foveal letter identification both in straight ahead gaze and while

41 the observers fixated in left lateral gaze, where fixation was expected to become more variable.

42 Objective eye-movement recordings indicated that this latter expectation was fulfilled only

43 partially.

44
45 **Materials and Methods.**

46 *Observers.*

47   Five adult observers with normal or corrected-to-normal vision participated after granting

48   voluntary written informed consent. Experimental procedures were reviewed and approved by

49   the Ethics Committee of Anglia Ruskin University. Four of the observers were female (3

50   students and one older adult, age range 21 – 62 years old), all of whom remained naïve as to the

51   experimental hypotheses that were tested in the study. The fifth, non-naïve observer was author

52   JS, who was 51 years old. All testing was performed monocularly, using the left eye. One of the

53   observers (SA) was emmetropic. The other four observers had refractive corrections in the tested

54   left eye of -1.75 sph (JC), -6.50/-1.50x100 (JH), -3.00/-0.50x150 (JS), and +1.75 sph (NB),

55   which were provided during the experiments by ophthalmic trial lenses. The non-viewing right

56   eye was occluded with an opaque patch.

57   *Psychophysical Methods.*

58   Observers viewed dark Sloan letters presented on a 19-inch Clinton Monoray monochrome

59   monitor from an optical distance of 9.5 m, after reflection from two mirrors. The screen

60   resolution was 1024 by 768 pixels and the frame rate was 120 Hz. At this viewing distance, the

61   dimensions of the monitor screen corresponded to 2.33 by 1.75 deg. Background luminance was

62   110 cd/m^2 and letter contrast, calculated using the Weber formula, was -99%. A letter size

63   corresponding to -0.2 logMAR (3.16 min arc) was used in all of the experimental conditions, as

64   each observer identified approximately 75% of the letters of this size correctly in preliminary,

65   *uncrowded* trials (see below). The observers viewed the letters foveally under two conditions of

66   gaze, either straight-ahead or, for observers JC, JH, NB and SA, at 40 deg in left gaze. Subject JS

67   could not comfortably sustain fixation at 40 deg left gaze and was tested at 30 deg left gaze

68   instead. For logistical reasons, data collection began in left gaze only after testing in straight-

69   ahead gaze was completed. Head position was maintained in each gaze position using a head and

70 | chin rest. For the observers who required refractive correction, trial lenses were mounted on a

71 | flexible arm, which allowed them to be placed close to the eye and aligned with the visual axis in

72 | both straight-ahead and left gaze.

73 | Random sequences of Sloan letters, with the stipulation that adjacent letters on the screen

74 | were never the same, were presented for an unlimited viewing duration in 3 types of trials. On

75 | each *short-string* trial, 4, 5 or 6 letters were presented at one time, with a horizontal edge-to-edge

76 | 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*

77 | trial, a sequence of 10, 11 or 12 letters was presented, also with a horizontal edge-to-edge letter

78 | spacing of 0.5, 1 or 2 letter widths. The minimum separation between the edge of the monitor

79 | and the edges of the first and last letter in the longest letter strings was 3 letter spaces. For each

80 | direction of gaze, observers completed 108 short-string trials (36 each with 4, 5 and 6 letters) and

81 | 36 long-string trials (12 each with 10, 11 and 12 letters). The numbers of short- and long-string

82 | trials were chosen so that performance in the two conditions was based on the same total

83 | numbers of letters. Short- and long-string trials were presented in blocks of 36 and 12,

84 | respectively. Within a block of short- or long-string trials the letter-to-letter separation remained

85 | constant at 0.5, 1 or 2 letter widths and the strings with different numbers of letters were

86 | presented in a random order. Observers were instructed to read all of the letters in each string in

87 | sequence from left to right. Although the observers were informed that different numbers of

88 | letters would be presented on different trials, they were not told about the length of each letter

89 | string either prior to or after a trial. A single trial lasted between approximately 5 and 15 s and

90 | each block of 12 or 36 trials had a total duration of between 5 - 10 minutes. The experimenter

91 | used the computer keyboard to record the observers' letter responses in order and subsequently

92 | compared the responses to the presented sequences of letters. Because crowding is reduced for

93 letters at the left and right ends of a line,[26,27] performance was calculated by scoring only the

94 interior 2, 3 or 4 letters for the trials with 4, 5, and 6 letters, respectively, and only the interior 8,

95 9 or 10 letters for the trials with 10, 11, and 12 letters. Letters had to be read in the correct order

96 to be scored as correct.

97   For comparison with the short- and long-string trials, each observer first completed six

98 blocks (one for each combination of letter separation and gaze direction) of 34 *uncrowded* trials.

99 On each uncrowded trial, three letters were presented with an edge-to-edge spacing of 5 letter

100 widths (i.e., 15.8 min arc), a distance well beyond the extent of foveal crowding.[1,6,28] Because

101 crowding was assumed to be absent in this condition, all 3 letters presented on each trial were

102 scored. As above, the letters had to be read in the correct order to be scored as correct.

103 *Eye Movement Recording.*

104   To evaluate the influence of gaze direction on fixational eye movements, the horizontal and

105 vertical positions of each observer's left eye were recorded at a sampling rate of 250 Hz using an

106 EyeLink 1000 Eyetracker with remote camera. Eye movement recordings were obtained in a

107 separate session from the psychophysical measurements. During each trial, the observer fixated

108 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

109 Trinitron monitor. Four recordings were made while the observer viewed in straight-ahead gaze

110 and another four were made during foveal fixation at 40 deg (observers JC, JH, NB and SA) or

111 30 deg (observer JS) left gaze. For each direction of gaze, head position was maintained using a

112 head and chin rest.

113   Subsequently, two 5-s intervals without blinks were selected from each fixation file for

114 further analysis: (1) calculation of the standard deviations (SDs) of the horizontal and vertical

115 eye positions during each interval and (2) counts of the number of fixational saccades. The eye

116   movement results for each observer were summarized by taking the mean horizontal and vertical

117   SDs and the mean number of fixation saccades during the 8 separate fixation intervals (i.e., 4

118   fixation trials x 2 intervals per trial).

119   *Data Analysis.*

120   To perform statistical analyses, the observers' percent correct letter identification for each

121   experimental condition was converted to a z score, as between-observer differences in z scores

122   for the different experimental conditions are more similar than the differences in percent correct.

123   A three-way repeated-measures ANOVA assessed the effects of string length (single letters,

124   short strings and long strings), letter separation (0.5, 1 and 2 letter widths), and gaze direction

125   (straight-ahead and left gaze). A separate two-way repeated-measures ANOVA evaluated

126   whether string length and direction of gaze affected the percentage of trials on which the

127   observers reported the correct *number* of letters. A Huynh-Feldt correction was applied to

128   statistical tests when a departure from sphericity occurred. Although the statistical analyses were

129   performed using z scores, for ease of presentation the results were transformed back to percent

130   correct letter identification when plotting Figures 1 – 3, below.

131   **Results.**

132   *Letter Identification.*

133   The average z scores for letter identification in the *uncrowded* condition were 0.64 in

134   straight-ahead gaze and 0.43 in left gaze, corresponding to 73.8% and 66.5% correct,

135   respectively. These percentages did not differ significantly according to the letter position in the

136   three-letter array (range: 72.0% – 74.3% in straight-ahead gaze; 63.4% – 66.6% in left gaze),

137   confirming the absence of contour interaction in this condition. When the edge-to-edge

138   separation between adjacent letters was 2 letter spaces, performance in the short- and long-string

139   conditions did not differ from that in the uncrowded condition (Figure 1 top panels). However,

140   letter identification was poorer when the separation was less than 2 letter spaces, as indicated by

141   a significant effect of separation ($F_{df=2,8}$ = 16.95, p = 0.0013). The ANOVA also revealed a

142   significant 2-way interaction between letter separation and string length ($F_{df=4,16}$ = 10.53, p =

143   0.011). Compared to the uncrowded condition, z scores were lower for long letter strings when

144   the separation was 1 letter space ($F_{df=1,16}$ = 13.19, p = 0.019), and for both the long and short

145   letter strings when the separation was 0.5 letter spaces (for long letter strings, $F_{df=1,16}$ = 61.81, p =

146   0.0006; for short letter strings, $F_{df=1,16}$ = 29.08, p = 0.0039). These effects are visible in the data

147   collected both in straight-ahead and left gaze in the middle and lower panels of Figure 1. Figure

148   2 replots the percent correct letter identification in straight ahead and left gaze, averaged across

149   subjects, as a function of the letter separation and shows clearly that the *magnitude* of crowding

150   is greater for the long compared to short letter strings.

151   Neither the direction of gaze nor the interactions between gaze direction and letter separation

152   or string length exhibited a significant effect on letter identification. However, the ANOVA

153   revealed a significant 3-way interaction between direction of gaze, letter separation, and string-

154   length ($F_{df=4,16}$ = 3.03, p = 0.049). Means comparisons indicated that this interaction resulted

155   from significantly better performance in straight-ahead compared to left gaze for long strings

156   when the letter separation was 2 letter widths ($F_{df=1,16}$ = 13.56, p = 0.0020).

157   In a second analysis, we compared the percentage of trials (again, converted to z scores) on

158   which the observers reported the correct numbers of letters in the short- and long-string

159   conditions. As anticipated, a three-way repeated-measures ANOVA found that observers

160   reported the correct number of letters less frequently on long-string than short-string trials ($F_{df=1,4}$

161   = 145.96, p = 0.0003). Observers also reported the correct number of letters less often as the

162   separation between adjacent letters decreased from 2 to 0.5 letter widths ($F_{df=1,4}$ = 26.41, p =

163   0.0014). These trends can be seen in the results for both straight-ahead and left gaze, which are

164   plotted in Figure 3. Of particular interest is the observation that observers reported the correct

165   number of letters on a significantly lower proportion of long- compared to short-string trials even

166   with a separation of two letter widths ($F_{df=1,8}$ = 12.59, p = 0.0075). Although the observers

167   generally reported the correct number of letters less frequently in left lateral compared to

168   straight-ahead gaze (Figure 3), this difference did not achieve statistical significance ($F_{df=1,4}$ =

169   6.05, p = 0.070). More detailed information is presented in Table 1, which summarizes the

170   percentage of trials on which the observers reported fewer or more than the correct number of

171   letters for each of the experimental conditions. Overall, when the observers did not report the

172   correct number of letters, they erred more often (~60:40) by reporting too few rather than too

173   many letters, both for the short and long letter strings.

174   When the observers reported too few letters, the majority of the time they reported one letter

175   too few (73% of errors for long strings; 97% of errors for short strings). Similarly, when the

176   observers reported too many letters, on the majority of trials they reported one extra letter (88%

177   of trials for long strings; 98% of trials for short strings). On the remainder of the trials when an

178   incorrect number letters was reported, the observers either omitted or added 2 (13% of trials) or 3

179   letters (1.6% of trials), primarily on long-string trials.

180   Examination of the responses on trials when the observers reported the incorrect number of

181   letters indicated that errors of omission or insertion occurred almost always at interior positions

182   in the string. The modal locations of these errors were letter places 6 (omissions) and 8

183   (insertions) in the long strings (accumulated across strings of 10, 11 and 12 letters), and place 4

184   (omissions and insertions) in the short letter strings (accumulated across strings of 4, 5, and 6

185   letters). When the observers reported one or more extra letters within a string, they typically

186   reported a pair of confusion letters for one letter within the string, such as both 'N' and 'R' for

187   the occurrence of an 'R' or both 'D' and 'C' for the occurrence of an 'O.'

188   Observers would be expected to make more errors in reporting the correct number of letters

189   for long compared to short letter strings, simply because the long strings include more letters to

190   report. However, the following analysis reveals that merely increasing the average number of

191   letters in the string does not account for our results. Assume the probability of incorrectly

192   reporting each letter, either by omitting the letter or reporting an additional letter, is the same

193   regardless of the string length. Further, assume that this probability, which we will designate as

194   p_e, depends on the separation between the adjacent letters in the string. For each letter separation,

195   we can estimate the value of p_e from the percentage of reporting errors made when reading short

196   letter strings, p_5. Specifically, if each short letter string is assumed to comprise 5 letters, then

197    $$(1 - p_e)^5 = 1 - p_5$$

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

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

200   For example, when the letter separation is 2 letters in straight-ahead gaze, summing the

201   percentages of reporting too few and too many letters in the short-string condition yields $p_5 =$

202   0.023 (Table 1) and $(1 - p_5) = 0.977$. Based on this result, the predicted probability of reporting

203   an incorrect number of letters in the analogous long-string condition, p_{11}, is 0.05. The observed

204   probability of reporting the incorrect number of letters in this long-string condition was 0.15,

205   which is significantly higher (z = 3.55, p = 0.0004) than the predicted value. The observed

206   probabilities of reporting the incorrect numbers of letters in the long-string condition also is

207   significantly greater than the predicted probabilities (p < 0.0001) for the other 5 conditions of

208   letter separation and gaze direction.

209   *Fixational Eye Movements.*

210   During fixation in straight-ahead gaze, the average standard deviations (SD) of both the

211   horizontal and the vertical eye position measurements were approximately 0.16 deg (i.e., 9.5 min

212   arc; Table 2). Although four of the five observers (all except JH) exhibited a small endpoint

213   nystagmus when fixating in left gaze (Figure 4), only two of them exhibited a noticeable increase

214   in the SD of horizontal eye position: for observer JS from 0.13 to 0.19 (± 0.02 SE) deg and for

215   observer NB from 0.19 to 0.27 (±0.02 SE) deg. The SDs of vertical eye position were either

216   unchanged in left compared to straight-ahead gaze or decreased (from 0.24 to 0.11 deg for

217   observer JC). However, consistent with the observed endpoint nystagmus in left gaze, the

218   average number of saccades during fixation in left gaze was significantly greater than the number

219   of saccades during fixation in straight-ahead gaze (mean difference = 2.58 saccades/5 s, $t_{df=4}$ =

220   3.10, p = 0.036).

221   We compared the *change* in correct letter identification between straight-ahead and left gaze

222   in observers JS and NB, who showed an increase in the SD of horizontal eye position, to the

223   change in performance of the other three observers. We focused on the change in z scores for

224   long letter strings separated by two letter widths because, as reported above, this condition

225   produced a significant gaze-dependent effect on crowding. The average change in z score from

226   straight ahead to left gaze was 0.75 ± 0.08 for JS and NB, compared to 0.10 ± 0.19 for the other

227   three observers.

228   **Discussion.**

229   In normal observers, contour interaction does not occur in the fovea for targets separated by

230   more than 3 – 6 min arc, which corresponds approximately to the width of a high-contrast

231   threshold acuity letter.[1,2,7,29-31] On this basis, we conclude that only the immediately adjacent

232   letters within each string contributed to contour interaction and that the magnitude of contour

233   interaction was identical for the interior letters in the short- and long-string stimuli in our

234   experiment. The greater magnitude of *crowding* that we observed for strings of 10, 11 and 12

235   letters than for strings of 4, 5 and 6 letters for a separation of 0.5 and 1 letter space (Figure 2)

236   therefore can not be attributed to an increase in contour interaction.

237   Inaccurate and imprecise eye movements are a potential contributor to foveal crowding.[1,5,8,32]

238   The imprecision of normal fixation is large enough to encompass more than a single letter, even

239   in the letter strings with a separation of two letter spaces between the adjacent letters[16-18] (see

240   also Figure 4). Moreover, it is highly unlikely that our observers accurately imaged the

241   successive letters in the strings sequentially on the fovea. Kowler and Steinman[20] measured the

242   saccades made by two experienced observers when counting 10 to 19 identical vertical lines

243   separated horizontally by gaps of 7.4 – 14.2 min arc. For lines separated by 7.4 to 8.2 min arc,

244   one observer made saccades that ranged in amplitude from approximately 7 to 45 min arc; the

245   saccades of the other observer ranged from less than 5 to approximately 20 min arc. Both

246   observers frequently lost their place while counting the vertical lines and, for the range of line

247   separations examined, reported the correct number of lines on half or fewer of the trials. Our

248   finding that observers often reported the incorrect number of letters in the long-string condition

249   (Fig. 3) is consistent with this observation. As suggested above in the Introduction, observers

250   may be less likely to lose their place in short letter strings because they can judge the number of

251   letters, and presumably their relative positions in the string, essentially instantaneously and

252   effortlessly.[24,25]

253   Liu and Arditi observed that normal observers frequently reported only 4 of the letters in

254   strings of 5 upper case letters when the edge-to-edge letter-to-letter spacing was made very

255   small.[33] The frequency of these under-reporting errors dropped rapidly from approximately 80%

256   to 20% as the separation between adjacent letters increased from 0.04 to 0.24 of the threshold

257   letter size. Only rarely did the observers make the opposite error of reporting 5 letters in strings

258   that were 4 letters in length. Based on the strong dependence of under-reporting errors on the

259   letter separation, the authors attributed these errors to overlap between the retinal images of

260   adjacent letters. The observers in our study often erred in reporting the correct number of letters

261   for edge-to-edge separations of 0.5 and 1 letter width, well beyond the range of separations used

262   by Liu and Arditi.[33] In addition, both under- and over-reporting of the number of letters were

263   common among our observers (Table 1). For these reasons, we conclude that our results can *not*

264   be attributed to overlap between the images of adjacent letters.

265   It is possible that the observers used the angular extent subtended by each string as a cue to

266   the number of letters, as the ratios of the extent for the different short and long strings presented

267   within a single block of trials generally exceed the Weber fraction for length discrimination (2 -

268   5%, e.g., Helmholtz, 1925; Ono, 1967 [34,35]). For the three letter separations tested, the ratios of

269   extent for the 4, 5, and 6 letter strings are greater than those between 10, 11, and 12 letter strings,

270   which potentially could account for the higher percentage of errors in reporting the number of

271   letters on long- compared to short-string trials. However, the ratios of angular extent for the

272   short and long letter strings do not change appreciably with the letter separation; i.e., the angular

273   extent of 6 and 4 letter strings are in the ratio of 1.60 for a letter separation of two spaces and

274 1.55 for a letter separation of 0.5 spaces. Similarly, the angular extent of 12 and 10 letter strings

275 are in the ratio of 1.21 for letter separations of both two and 0.5 spaces. Nevertheless, the

276 number-of-response errors increase as the letter separation decreases from two to 0.5 spaces,

277 both for the short and long letter strings (Figure 3). Further, in addition to the angular extent of

278 the letter strings, information about the string length on each trial was available also from the

279 angular separation between the first and last letter of the string and the edges of the monitor

280 screen. The ratios of these separations for the different string lengths are uniformly *higher* for

281 long than for short letter strings, and are greatest for long strings when the letter separation is

282 large. When the separation between the adjacent letters in the long strings was two spaces, the

283 ratios of the distances to the monitor edge for strings of 10, 11, and 12 letters are essentially

284 identical to the ratios of the angular extents for strings of 4, 5, and 6 letters separated by one

285 space. Nevertheless, observers made approximately 4.5 times more number-of-response errors

286 on long-string trials with a separation of two letter spaces than on short-string trials with a

287 separation of one letter space. The observations in this paragraph suggest that the observers did

288 not attempt to deduce the number of letters presented on each trial and that, for a given

289 separation between letters, the more frequent errors for long compared to short strings in the

290 number of reported letters is attributable primarily to the number of letters the in the string.

291 We expected that observers would make more errors when they viewed the letter strings at

292 30 or 40 deg in left gaze compared to straight ahead because of an increase in the variability of

293 fixation in association with the development of endpoint nystagmus.[36-38] Although we observed a

294 trend for a greater number of miscalls and more frequent errors in reporting the number of letters

295 in a string, these trends did not reach statistical significance. The likely reason for the observers'

296 overall similar psychophysical performance in left and straight-ahead gaze is that the variability

297   of horizontal fixation did not change significantly in left gaze for three of the five observers. The

298   two observers whose horizontal fixation was less stable in left gaze also identified widely spaced

299   letters in the long-string condition less accurately in left compared to straight-ahead gaze. It is

300   possible that fixation would have been less steady and psychophysical performance would have

301   been worse if the observers had been required to view the letters with gaze diverted further to

302   one side.[38]

303   A displacement of attention from the acuity target towards the flanking stimuli also has been

304   suggested to contribute to crowding.[1,5] Leat et al. sought to assess the influence of attention on

305   crowding by varying the similarity of the flanking targets to one another and to the acuity target

306   which, in their study, was a Landolt C or tumbling E.[6] The results indicated that the manipulation

307   of flanker characteristics generates no consistent change in the magnitude of foveal crowding.

308   However, it may be difficult to tease apart the potentially separate influences of eye movements

309   and attention on foveal crowding, as there is evidence to suggest that the locus of attention

310   remains closely tied to the direction of gaze during large eye movements.[39-41] A similar intimate

311   relationship has been suggested to exist also between the direction of gaze and attention during

312   small shifts in the position of fixation by some,[42-44] but not all authors.[45]

313   We conclude that both the greater magnitude of foveal crowding and more frequent errors in

314   reporting the correct number of letters in long compared to short letter strings are attributable to

315   the imprecision and inaccuracy of small normal eye movements. As surmised previously by

316   others, the eye-movement contribution to crowding may be substantially greater in individuals

317   whose eye-movement control is poor, such as in patients with nystagmus,[11,12] amblyopia,[1,5,9,10]

318   and young children.[8,15,32]

319   **Acknowledgments**.

323

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411

412   **Table 1**. Percentages of trials on which the five observers reported too few vs. too many letters

413   for different combinations of string length, letter spacing, and gaze direction.

414

Letter	Type of	Straight-ahead Gaze		Left Gaze	
Separation	Error	Short strings	Long strings	Short strings	Long strings
0.5	too few	18.9%	40.7%	10.6%	45.0%
	too many	4.4%	20.0%	7.2%	30.0%
1	too few	2.2%	35.0%	1.7%	36.7%
	too many	1.1%	20.0%	4.4%	16.7%
2	too few	0.6%	1.7%	0.6%	15.0%
	too many	1.7%	13.3%	2.2%	13.3%

415
416
417
418   **Table 2**. Mean standard deviations (SDs) of horizontal and vertical eye position during fixation

419   for five observers in straight-ahead and left gaze.

420

	Straight-ahead Gaze		Left Gaze	
Observer	Horizontal SD	Vertical SD	Horizontal SD	Vertical SD
JC	0.16 ± 0.05	0.24 ± 0.09	0.14 ± 0.04	0.11 ± 0.02
JH	0.17 ± 0.05	0.17 ± 0.03	0.17 ± 0.04	0.15 ± 0.01
JS	0.13 ± 0.04	0.11 ± 0.04	0.19 ± 0.03	0.14 ± 0.06
NB	0.19 ± 0.03	0.10 ± 0.04	0.27 ± 0.04	0.13 ± 0.04
SA	0.17 ± 0.05	0.18 ± 0.11	0.13 ± 0.03	0.17 ± 0.03

421
422

423 **Figure Legends.**
424
425 *Figure 1*. Percent correct letter identification is plotted for 5 observers for 3 presentation

426 conditions of foveal viewing: uncrowded ('single') letters, short-letter strings, and long-letter

427 strings. The top, middle, and lower pairs of panels show data for edge-to-edge letter separations

428 of 2, 1 and 0.5 letter spaces. The right and left columns present results for letter strings viewed in

429 straight ahead and left gaze, respectively. Within each column, the same values are plotted for

430 each observer in the three panels for the uncrowded condition. The black lines in each panel

431 connect the mean values of percent correct for the 3 different presentation conditions.

432 *Figure 2*. Mean percent correct letter identification is plotted as a function of the edge-to-edge

433 letter spacing for short- and long-letter strings. The values plotted for a separation of 5 letter

434 widths are from the uncrowded condition. The top and bottom panels present results for letters

435 viewed in straight-ahead and left gaze.

436 *Figure 3*. The percentages of trials on which the observers reported the correct numbers of letters

437 in the short and long letter strings are plotted as a function of the edge-to-edge letter separation

438 within the strings. Results are shown separately for straight-ahead (unfilled symbols) and left

439 gaze (filled symbols).

440 *Figure 4*. Five-second recordings of horizontal (black, higher traces) and vertical (gray, lower

441 traces) eye position during fixation in straight-ahead (top) and left gaze (bottom) are presented

442 for observer JC. The placement of each trace with respect to the vertical axis is arbitrary. Upward

443 deflections represent rightward and upward eye movement. A leftward endpoint nystagmus with

444 an amplitude of approximately one third of a degree is visible in the lower panel.

445