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Reading Speed Benefits from Increased Vertical Word Spacing in Normal Peripheral Vision

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Abstract

Purpose—Crowding, the adverse spatial interaction due to proximity of adjacent targets, has been suggested as an explanation for slow reading in peripheral vision. The purposes of this study were to (1) demonstrate that crowding exists at the word level and (2) examine whether or not reading speed in central and peripheral vision can be enhanced with increased vertical word spacing.

Methods—Five normal observers read aloud sequences of six unrelated four-letter words presented on a computer monitor, one word at a time, using rapid serial visual presentation (RSVP). Reading speeds were calculated based on the RSVP exposure durations yielding 80% correct. Testing was conducted at the fovea and at 5° and 10° in the inferior visual field. Critical print size (CPS) for each observer and at each eccentricity was first determined by measuring reading speeds for four print sizes using unflanked words. We then presented words at 0.8× or 1.4× CPS, with each target word flanked by two other words, one above and one below the target word. Reading speeds were determined for vertical word spacings (baseline-to-baseline separation between two vertically separated words) ranging from 0.8× to 2× the standard single-spacing, as well as the unflanked condition.

Results—At the fovea, reading speed increased with vertical word spacing up to about 1.2× to 1.5× the standard spacing and remained constant and similar to the unflanked reading speed at larger vertical word spacings. In the periphery, reading speed also increased with vertical word spacing, but it remained below the unflanked reading speed for all spacings tested. At 2× the standard spacing, peripheral reading speed was still about 25% lower than the unflanked reading speed for both eccentricities and print sizes. Results from a control experiment showed that the greater reliance of peripheral reading speed on vertical word spacing was also found in the right visual field.

Conclusions—Increased vertical word spacing, which presumably decreases the adverse effect of crowding between adjacent lines of text, benefits reading speed. This benefit is greater in peripheral than central vision.

Keywords

crowding; reading; peripheral vision; low vision

Slow reading is one of the most common clinical complaints of people who acquire central vision loss later in life. The principal cause of central vision loss is age-related macular degeneration, which is also the leading cause of visual impairment in developed countries.^{1, 2} People with central vision loss must rely on their residual peripheral vision for their day-to-day activities, including reading. Unfortunately, reading is slower and more difficult in peripheral than central vision, even when print size is made large enough so that resolution is

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not a limiting factor^{3, 4} and when oculomotor demands are minimized with rapid serial visual presentation (RSVP).^{3–5} Because retaining the ability to read is the primary goal of patients with age-related macular degeneration who seek visual rehabilitation, the understanding of why reading is slower in peripheral vision is of utmost importance to the visual rehabilitation of these patients.

Various factors have been examined as potential explanations for slow reading in peripheral vision, including poor spatial resolution and poor eye-movement control. In this study, we focused on the factor of crowding. Crowding refers to the decreased visibility of a visual target in the presence of nearby objects.⁶ Even when targets are scaled in size, the spatial extent^{7–9} and intensity^{7, 10} of crowding are still greater in peripheral than central vision. Therefore, crowding has been suggested as a major factor contributing to slow reading in peripheral vision.

In relation to reading, crowding can exist between adjacent characters or between adjacent words. Previously, we examined whether increased letter spacing, which presumably decreases crowding between adjacent characters, improves reading speed in peripheral vision.¹¹ Contrary to the well-established finding that identification accuracy of single letters improves with increased letter spacing, reading speed does not benefit from increased letter spacing beyond the “standard” spacing, i.e., the conventional spacing between adjacent characters in printed text. These findings imply that if crowding contributes to slow reading in peripheral vision, then it is not due to the crowding effect that occurs between adjacent characters. Therefore, in this study, we turned to another source of crowding that may occur in text—crowding between adjacent words.^a

Whereas crowding between adjacent characters has been studied extensively,^{8–17} little is known about crowding at the word level. To our knowledge, only a handful of previous studies have provided some insight into this issue. The earliest studies that are relevant to the issue of word spacing and reading speed are probably those of Bentley¹⁸ and Paterson and Tinker,¹⁹ who examined the effect of line spacing (also known as *leading* in typography) on reading speed. In both studies, a fixed character size was used (10-or 12-point size), and line spacing was manipulated by adding between 1 and 9 points to the “set solid” condition. “Set solid” refers to the type set where the separation between the baselines^b of two vertically adjacent lines of text (baseline-to-baseline distance) is the same as the character size. Bentley¹⁸ and Paterson and Tinker¹⁹ showed that reading speed generally improved with additional spaces added to the “set solid” condition, up to a few points, and then either stayed about the same at the maximum reading speed or dropped below the maximum value. In more recent years, a series of studies has been conducted to examine the role of horizontal word spaces on reading eye movements and reading speed.^{20–24} When horizontal word spaces were removed from text, reading speed decreased, compared with that for normal text with spaces. The decrease in reading speed was approximately 50%,^{20, 21, 24} although smaller magnitudes of the effect were also reported.²¹ Arditi et al.¹⁵ also studied the effect of horizontal word spacing on reading speed, although their primary goal was to compare reading speeds for fixed and proportional letter spacing. Because a line of text printed with proportional letter spacing is shorter than one printed with fixed letter spacing, Arditi et al. included the following control condition. A line of text printed with proportional letter spacing was matched in line length with a line of text printed with fixed letter spacing by adding additional spaces between words. Their results showed that text with additional word spaces was read faster than text with normal spaces by approximately a factor of 2 for small print sizes (uppercase characters with height <0.3°). This

^aCrowding between adjacent words is unlikely to be the only factor that accounts for slow peripheral reading, because when RSVP is used to present words one at a time, maximum reading speeds in peripheral vision are still always lower than the foveal maximum reading speed, even when character sizes are scaled to account for the difference in resolution between the fovea and the periphery.^{3,4}

^bIn typography, the baseline is the imaginary line on which a line of text rests. The baseline is the point from which other elements of type are measured, including x-height and spacing between lines.

difference in reading speed became much smaller and even vanished for larger print sizes ($>0.3^\circ$ characters). Although none of the aforementioned studies directly or systematically addressed the effect of different word spacing on reading speed, their results all indicate that there may be some crowding between adjacent words and that increased word spacing may minimize the effect of crowding, thus leading to increased reading speed.

Given that the effect of crowding between adjacent letters has been shown to be greater in peripheral vision, it is likely that the effect of crowding between adjacent words is also greater in peripheral than central vision. If so, then by increasing word spacing, which presumably decreases crowding among individual words, reading speed should show a greater improvement in peripheral than in central vision. The purposes of this study, therefore, were two-fold: (1) to demonstrate that crowding does exist at the word level and (2) to examine the effect of increased word spacing on reading speed in central and peripheral vision.

With respect to normal reading, most words are surrounded by neighboring words in four directions: above, below, right, and left of a given word. To examine the effect of word spacing on reading, in this study we chose to examine the spacing effect in the vertical dimension. We used the RSVP paradigm to present target words one at a time on the display, so as to minimize the need to make eye movements during reading. Hence, a target word was presented with two flanking words, one above and one below the target word. For comparison, we also measured observers' reading speeds for unflanked words, i.e., in the absence of any between-word crowding. We chose to examine the vertical instead of horizontal spacing simply because of the horizontal dimension of the computer display, which limited the largest letter size and word spacing that we could test. Although a similar physical limitation also exists in the vertical dimension, the vertical dimension allowed larger values of letter size and word spacing to be tested. When applied to real-life reading (page reading), varying the vertical spacing between words is analogous to changing the spacing between adjacent lines. To ensure that any effect we obtained was attributable to the separation between words, but not the different strength in crowding when the target and the flanking words had different word length, we used words that had the same number of characters. We hypothesized that, in general, reading speed should improve with vertical word spacing, up to a *critical vertical word spacing*, at which reading speed reaches and stays constant at its maximum value. We further hypothesized that the critical vertical word spacing is greater in magnitude (even after scaling with respect to letter size) in peripheral than central vision, thus contributing to slow reading with ordinary text printed in standard spacing in peripheral vision.

METHODS

Stimuli

Oral reading speed was measured using sequences of unrelated words of the same word length (four- or five-letter words; see below for details). Each trial consisted of six words, presented sequentially, one word at a time, using the RSVP paradigm. Words were rendered in Courier, a fixed-width font, to ensure that the physical length of each word was identical for words with the same number of letters. They were presented as high-contrast (approximately 90%), black letters on a white background of 45 cd/m^2 . Stimuli were generated with an SGI O2 workstation (Silicon Graphics Inc., Mountain View, CA) and presented on a Sony color graphics display monitor (model GDM-17E21; refresh rate = 75 Hz). The temporal dynamics of the computer and the monitor were verified with a photodetector and an oscilloscope.

Words were extracted from a pool of unrelated words used for an earlier study.^{25, c} In this study, we used four- and five-letter words only. There were 830 four-letter words and 760 five-letter words in the word list. None of the observers reported difficulty in recognizing any of the words. Because of these finite numbers of words and the number of testing conditions, over the course of the experiment each word was presented more than once to each observer. To minimize the effect of familiarity, we “recycled” the words only after all words in the word list (of a certain word length) had been presented in a previous cycle. On average, each four-letter word was presented 8 or 9 times (for a total of about 7000 presentations of four-letter words), and each five-letter word was presented 6 or 7 times (for a total of about 5200 presentations of five-letter words) to each observer.

For the flanked conditions, each target word was flanked above and below by two different flanking words of the same length as the target word. On each trial, the target word was chosen randomly from those remaining in the word list that had not been presented as the target word (unless all the words had been shown at least once). The two flanking words were chosen from the entire list, including words that had been presented previously as target words, with the only constraint being that the flanking words could not be the same as the target word in the same trial.

Psychophysical Methods

The psychophysical methods for estimating reading speeds were identical to those used for measuring reading speeds in Chung et al.³ and Chung.¹¹ In brief, we determined the number of words identified correctly as a function of RSVP word exposure duration. Observers were instructed to read aloud all six target words of each sequence. A word was scored as being identified correctly as long as the observer said the word correctly, irrespective of its word order within the word sequence. For each testing condition, we used the method of constant stimuli to randomly present word sequences at six word-exposure durations that spanned a range of approximately 1 log unit. Eighteen word sequences were tested in each block of trials, three for each duration. Each condition was tested twice, in separate blocks of trials. When pooled across the two blocks of trials, a total of six word sequences (36 words) was tested for each duration. We then fit each set of data with a cumulative Gaussian curve to construct a psychometric function. From the best-fitting psychometric function, we derived the exposure duration that yielded 80% of the words read correctly. This duration was then converted into our criterion reading speed according to the following equation: reading speed (wpm) = 60/(word exposure duration yielding 80% correct), where wpm represents words per minute.

Eye-Movement Monitoring

An Eyelink eye tracker (SMI, Boston, MA) was used to monitor fixation of the observers during testing in peripheral vision. Although this device is a binocular eye tracker, we used eye position information from the right eye only for our analyses. Before the beginning of each block of trials, the vertical eye positions of the observers were calibrated. During a trial, if the observers' eye positions deviated below the fixation line by more than 1°, the trial was discarded and subsequently replaced. We chose 1° as the tolerance because the accuracy of Eyelink for measuring eye position was approximately 0.5°. Across all eccentricities and print sizes, an average of 3.7% of trials was discarded and replaced (range, 1.1% to 7.5% for different observers).

^cFor this pool of words, the 750 most common 10-letter words were chosen according to ordinary English usage, and the frequencies of words for other word lengths were matched to the relative frequencies of these 10-letter words.²⁶

Experimental Design

The two main factors of interest in this study were vertical word spacing and eccentricity. Because crowding is reported to be stronger when letter size is close to the acuity limit, we also examined print size as the third main factor.

We defined vertical word spacing as the baseline-to-baseline separation between vertically separated adjacent words and normalized it with respect to the standard (single) spacing between adjacent lines of text (see Fig. 1). Our measurement indicated that the standard single vertical word spacing for the Courier font in printed text measures $2.6\times$ the x-height (the height of a lowercase letter “x”) for a wide range of print sizes. In this study, we adopted this standard separation as the standard single spacing for words presented on our SGI workstation. Five vertical word spacings were tested for each combination of eccentricity and print size: 1.0, 1.25, 1.6, and $2\times$ the standard vertical word spacing, as well as the unflanked condition (i.e., a vertical word spacing of infinite separation). For the $2\times$ spacing, the distance between the target and its flanking word exceeded what Bouma¹² claimed to be the extent of crowding in the periphery (half the eccentricity), at least for letter-by-letter crowding. For instance, with the smaller print size ($0.8\times$ critical print size [CPS]), the average vertical word separation was 2.8° at 5° eccentricity and 6.6° at 10° eccentricity in the inferior visual field. These separations were even larger for the larger print size ($1.4\times$ CPS). Because our pilot data had indicated that at the fovea, reading speed at single spacing already closely approximated that of the unflanked condition, we tested an even smaller spacing ($0.8\times$) at the fovea only. Given that the standard spacing is proportional to the letter size, the same level of vertical word spacing has a smaller physical magnitude (in centimeters) when presented in the fovea than in the periphery.

The three retinal eccentricities tested were 0° (foveal), 5° , and 10° in the inferior visual field. We used the inferior visual field as the retinal locus for peripheral vision testing because the local variation in eccentricity of letters within a word is much smaller than when the word is presented in the left or right visual fields. In addition, the inferior visual field is the region commonly used in studies examining peripheral vision.^{3, 4, 11, 25, 27, 28} Consequently, use of the inferior visual field will facilitate comparison of our data with those in the literature. Observers were allowed to look directly at the words on the display during foveal testing. For peripheral testing, observers were instructed to fixate along a horizontal, thin red line above the words, at a distance equivalent to the designated eccentricity. Viewing distances were 200 cm for foveal testing and 30 cm for testing at 5° and 10° eccentricity.

We tested two print sizes, one smaller ($0.8\times$) and one larger ($1.4\times$) than the CPS. In general, reading speed increases with print sizes up to the CPS and then plateaus at the maximum reading speed for larger print sizes. We chose the two print sizes of $0.8\times$ and $1.4\times$ CPS because we wanted to include a small print size for which reading speed could be limited by print size and a larger print size for which reading speed should be independent of print size. To determine the CPS for each observer and at each eccentricity, we first measured RSVP reading speed for four print sizes at each eccentricity.¹¹ Stimuli used were single (i.e., unflanked), five-letter words. Five-letter words were used instead of four-letter words as in the main experiment because we wanted to minimize the number of times each four-letter word was presented to the observers. The four print sizes were chosen to span a range of 0.7 log units, similar to the range of print sizes tested in the study of Chung et al.³ We fit each set of data with a bilinear fit (on log-log axes), where the intersection of the two lines represents the CPS. The slope of the first line was constrained to be 2.32 (on log-log axes), after the empirical finding of Chung et al.,³ who found that the slope of the first line did not vary systematically with eccentricity, and averaged 2.32 across all curve fits. The slope of the second line was constrained to be 0. Curve fitting was accomplished with the use of Igor Pro software (WaveMetrics, Lake Oswego, OR), which uses a Levenberg-Marquardt iterative algorithm to minimize the error between the experimental data and the model fit. The experimental data were weighted by the inverse of

the standard error of the mean value of each threshold estimate during curve fitting. The value of the CPS was then used to determine the physical print sizes used for each observer in the main experiment.

In the main experiment, we examined the interplay of vertical word spacing, eccentricity, and print size on reading speed. Each observer attended two sessions for this part of the study. In the first session, three observers were tested with the smaller print size ($0.8\times$ CPS) in the first half of the session and the larger print size ($1.4\times$ CPS) in the second half of the session. The other two observers were tested in reverse order. For each print size, 16 conditions (six vertical word spacings at the fovea and five vertical word spacings each at 5° and 10° eccentricity) were tested. The three eccentricities were tested in an order that was unique for each observer. For each eccentricity, the various vertical word spacings were tested in random order. The 32 conditions (16 for each print size) were repeated, in reversed sequence, in the second session.

Observers

Seven native English speakers with normal vision aged between 16 and 27 years participated in this study (5 in the main experiment and 2 in the control experiment; see below). All had (corrected) acuity of 20/15 or better in both eyes and were either emmetropic or wore contact lenses to correct for their refractive errors. This study followed the tenets of the Declaration of Helsinki. Protocols of the study were approved by the institutional review board of the University of Houston. Written, informed consent was obtained from each observer (and in the case of the 16-year-old, from her parents) after the procedures of the experiment had been explained and before commencement of data collection. All observers had participated in an earlier study involving the use of peripheral vision in identifying single letters, but none had prior experience in reading in peripheral vision or reading with the RSVP paradigm. Consequently, the first two experimental sessions were used for practice. Data from these practice sessions are not included in this report.

Control Experiment

In the inferior visual field, the separation between words was along the meridian connecting the eccentric location to the fovea (i.e., radial to the fovea). For letter-by-letter crowding, the zone of crowding is reported to be elliptical in shape for peripheral vision, such that the extent of crowding is greater along the radial than the tangential dimension.⁸ We do not yet know the shape of the crowding zone for word-by-word crowding, but if the elliptical crowding zone also applies to word-by-word crowding in peripheral vision, then the optimal horizontal word spacing to minimize word crowding in peripheral vision could be smaller than that for vertical word spacing. Also, when the larger print size ($1.4\times$ CPS) was presented at $2\times$ the vertical word spacing, the upper flanking word was very close to the fixation line, which might cause potential distraction to the observers. Therefore, to ensure that the results we obtained were not specific to use of the inferior visual field, we tested two new observers at 10° eccentricity in the inferior and right visual fields using the same experimental paradigm as in the main experiment. As a control measurement, these two observers were tested at the fovea as well. As in the main experiment, we first determined the CPS at each retinal location, and then we measured reading speed for the different vertical word spacings for a print size of $1.4\times$ CPS.

RESULTS

Reading speed, plotted as a function of print size for the three eccentricities and for each observer who participated in the main experiment, is shown in Fig. 2. To estimate the CPS, the bilinear fit (described in Methods) was used to fit each data-set. The intersection of the two lines represents the estimated CPS. Averaged across the five observers, the mean CPSs were 0.09° at the fovea (SD, 0.03° ; range, 0.07° to 0.14°), 0.69° at 5° eccentricity (SD, 0.13° ; range,

0.46° to 0.78°), and 1.59° at 10° eccentricity (SD, 0.11°; range, 1.41° to 1.69°). These values are very similar to those reported in Chung,¹¹ in which the same font (Courier) was used to measure sentence reading speed at the same three eccentricities used in the current study.

Data from the main experiment are summarized in Figs. 3 (0.8× CPS) and 4 (1.4× CPS), wherein reading speed is plotted as a function of vertical word spacing for the three eccentricities. As expected, reading speeds were higher at the fovea and lower in the periphery. Here, reading speeds obtained at 5° and 10° eccentricity were similar, especially for the larger (1.4× CPS) print size, a result that has been reported when sequences of unrelated words, instead of meaningful sentences, are used.^{3, 4} A comparison between Figs. 3 and 4 also reveals that reading speeds are higher for the larger (1.4× CPS) than the smaller (0.8× CPS) print size. With respect to the effect of vertical word spacing, reading speeds are highest for the unflanked condition, which is equivalent to having an infinite vertical word spacing, and at least in peripheral vision, decrease as vertical word spacing is reduced. The important point, however, is that the reading speed versus vertical word spacing curves do not retain the same shape as eccentricity changes, indicating an interaction effect between eccentricity and vertical word spacing on reading speed. These effects are more clearly illustrated in Fig. 5, where the group average data are presented for the two print sizes separately.

The described effects are supported by the results of a repeated-measures analysis of variance (ANOVA) performed on all data pooled across different conditions and observers, with the exclusion of the 0.8× spacing condition that was tested at the fovea only because of the unbalanced data set. The results of analysis confirm that reading speeds are affected by the main effects of retinal eccentricity ($F_{df=2,8} = 51.6$, Gessler-Greenhouse adjusted $p = 0.002$), print size ($F_{df=1,4} = 33.7$, $p = 0.004$), and vertical word spacing ($F_{df=4,16} = 8.95$, Gessler-Greenhouse adjusted $p = 0.025$). In addition, reading speeds are also influenced by an interaction effect between retinal eccentricity and vertical word spacing ($F_{df=8,32} = 13.9$, Gessler-Greenhouse adjusted $p = 0.001$). This interaction effect is clearly illustrated in Fig. 5, where in the fovea, reading speed in the presence of flanking words approaches the optimal unflanked reading speed at a vertical word spacing slightly greater than the single spacing. In the periphery, however, reading speeds in the presence of flanking words are still much lower than the optimal unflanked reading speeds, even at 2× the standard spacing.

Fig. 6 presents normalized reading speeds (reading speeds for the flanked conditions normalized to the unflanked reading speed) as a function of vertical word spacing for the three eccentricities. These normalized data facilitate a quantitative comparison of flanked and unflanked reading speeds at different vertical word spacings for the three eccentricities. There are a few points that are worth noting. First, after normalization, data for the two peripheral eccentricities more or less collapse into one single function. Second, as mentioned earlier, it is clear that at the fovea, reading speeds for the flanked conditions reach that of the unflanked condition at a vertical word spacing slightly greater than the single spacing. In contrast, at both 5° and 10° eccentricity, reading speeds obtained with flanking words never reached that of the unflanked reading speed for the range of vertical word spacings tested. Indeed, at the largest vertical word spacing (2× standard), reading speeds were still approximately 25% slower than the unflanked reading speed.

Control Experiment

The results of the control experiment comparing performance at 10° inferior and right visual fields are summarized in Fig. 7. Consistent with the results in the main experiment, foveal reading speeds for these two observers showed only minimal dependence on vertical word spacing—maximum reading speeds were reached at a vertical word spacing of approximately the standard spacing (see bottom panel). Also consistent with the results in the main experiment, there was a strong dependence of reading speed on vertical word spacing at 10°

inferior visual field (filled square symbols). The important point, however, is that reading speed at 10° right visual field (unfilled square symbols) also showed a sizeable dependence on vertical word spacing, implying that our results of a larger benefit of peripheral reading speed on vertical word spacing is not restricted to just the inferior visual field. Note that when reading speeds are normalized to their unflanked counterparts, the rate of change of normalized reading speed with vertical word spacing is similar between the inferior and right visual fields. Another noteworthy aspect of these data is that reading speeds were, in general, higher in the inferior than the right visual field. Indeed, the maximum reading speed was twice as high in the inferior than the right visual field (averaged between the two observers: 169 wpm at 10° inferior field vs. 86 wpm at 10° right field). This result is consistent with reports showing faster reading speeds in the inferior than the horizontal fields.^{29, 30}

Critical Vertical Word Spacing

Our hypothesis predicted that critical vertical word spacing would be greater in peripheral than central vision. To estimate the critical vertical word spacing in the fovea, we fit the normalized reading speed versus the logarithm of vertical word spacing data from the main experiment with a bilinear fit. The bilinear fit has been used to obtain the critical value of other important parameters in reading performance, such as print size^{3, 31} and letter spacing.¹¹ As in previous studies using the bilinear fit, we allowed the slope of the first line to vary freely while constraining that of the second line to have a slope of 0. Because we were interested in finding the vertical word spacing at which the flanked reading speed equaled the unflanked reading speed, we further constrained the maximum normalized reading speed to be 1. The best curve fits are given in Fig. 6. The slope of the first line (on semilogarithmic axes) was found to be 1.44 for the smaller (0.8× CPS) and 0.63 for the larger (1.4× CPS) print sizes. The critical vertical word spacings thus obtained were 1.2× and 1.5× the standard spacing for the smaller (0.8× CPS) and larger (1.4× CPS) print sizes, respectively. In other words, as long as vertical word spacing is > 1.5× the standard spacing, there is no additional advantage of using a larger spacing at the fovea.

For the 5° and 10° eccentricity data, it is clear from Fig. 6 that the range of vertical word spacings tested was not large enough to unambiguously identify the critical vertical word spacing. However, because normalized reading speeds showed a more or less linear relation with the logarithm of vertical word spacing at both 5° and 10° eccentricities and for both print sizes (Fig. 6), we attempted to estimate the critical vertical word spacing as follows. For each print size, we fit the normalized reading speed data for both eccentricities with a straight line and then derived from the fitted straight line the vertical word spacing at which the normalized reading speed was equal to 1. The best curve fits are given in Fig. 6. The slopes of these fitted lines (on semilogarithmic axes) were found to be 1.23 and 0.87 for the smaller (0.8× CPS) and the larger (1.4× CPS) print sizes, respectively. These fitted lines yield *estimated* critical vertical word spacings of between 3.2× and 3.9× the standard spacing.

Similar estimates for the control experiment data yielded estimated critical vertical word spacings of 2.3× and 2.2× at 10° inferior and right visual fields, respectively (Fig. 7). These values were smaller than those obtained in the main experiment and could have been due to the fact that there were only two observers in the control experiment and that there were individual differences. Despite the discrepancies in the absolute values of estimated critical vertical word spacing in Figs. 6 and 7 for the 10° inferior visual field, one point that is clear and consistent is that the critical vertical word spacing in peripheral vision is much larger than that in the fovea. Reading speeds did not reach their plateaus even at 2× the standard spacing.

DISCUSSION

The first purpose of this study was to demonstrate that crowding exists at the word level, i.e., between adjacent words. To do so, we adopted the method that is used traditionally to demonstrate the letter-by-letter crowding effect—comparing the performance measurement for recognizing a target with and without flanking objects. In this case, our target and flanking objects were words, instead of single letters, and our performance measurement was reading speed. The results show that in general, reading speeds are higher for the unflanked conditions than for the flanked conditions. This is the classical crowding effect. Here, we demonstrated that crowding also occurs between adjacent words.

Previously, using single sentences as text material, Arditi et al.¹⁵ showed that foveal reading speed was higher when additional horizontal spacing was added between individual words. They found this improvement for small letter sizes (uppercase characters of height $<0.3^\circ$) but not for larger letter sizes. Here, by increasing the vertical separation between words, we found that the improvement in reading speed occurred for a small (below the CPS) as well as a large (above the CPS) print size. We found a qualitatively similar effect in the periphery, which was not examined in the study of Arditi et al. Although there are many methodological differences between the present study and that of Arditi et al., our data are not at odds with those of Arditi et al. Arditi et al. specified their print sizes with respect to the height of the uppercase characters. Their smallest characters were approximately equivalent to 0.2° lower-case characters (see their Fig. 1). In the current study, the average foveal CPS was 0.09° . In other words, the print sizes were approximately 0.072° for our smaller print size ($0.8\times$ CPS) and 0.13° for our larger print size ($1.4\times$ CPS), both of which were smaller than the smallest print size examined by Arditi et al. Consequently, it is not surprising that we found an advantage of increased word spacing (vertical spacing, in this case) on foveal reading speed for both small and large print sizes. As for why Arditi et al. did not find any benefit of increased word spacing on foveal reading speed for larger print sizes, one possible explanation is that they used a sentence reading task, which required observers to make eye movements. When print size is large and horizontal spacing is added between adjacent words, it may be difficult for observers to plan where the next “landing position” of the eyes should be, therefore offsetting the advantage of increased word spacing. The lack of an advantage of increased word spacing on foveal reading speed for large print sizes is also supported by the finding of Rayner et al.,²⁴ who reported no difference in reading speed between text with wide (three spaces between words) and normal (one space between words) spacing for a print size of about 0.3° .

How does the word-crowding effect compare between central and peripheral vision? Figs. 3 through 7 clearly show that even when print size and vertical word spacing are scaled in size in the periphery, the spatial extent of the word-crowding effect is still much greater at 5° and 10° eccentricity than at the fovea. Indeed, at the fovea, reading speed in the presence of flanking words reaches the unflanked reading speed at a vertical word spacing of $1\times$ to $1.5\times$ the standard spacing, values that are slightly higher than the standard spacing. The averaged foveal CPS of our observers was 0.09° . Based on our measurement that the standard single spacing is $2.6\times$ the x-height of text, the foveal word-crowding zone measured herein corresponds to 0.23° to 0.35° . Previous studies for letter-by-letter crowding have reported a foveal crowding zone of between 0 (no crowding at the fovea)³² to 0.5° .¹⁷ Clearly, our foveal data are consistent with those studies, even though the tasks were different. At 5° and 10° eccentricity, we were unable to measure empirically the vertical word spacing at which reading speed equaled the unflanked reading speed, but our estimates, based on the trend of the data obtained, indicated a critical vertical word spacing of $3\times$ to $4\times$ the standard spacing (a lower value of $2.2\times$ was obtained for both 10° eccentricity inferior and right visual fields in the control experiment). These values, based on the averaged CPS of 0.69° at 5° eccentricity and 1.59° at 10° eccentricity, correspond to a word-crowding zone of at least 5.4° at 5° eccentricity and 12.4° at 10° eccentricity.

(assuming a critical spacing of $3\times$ the standard spacing). These results are consistent with previous studies reporting a greater spatial extent of crowding in peripheral than central vision for letter-by-letter crowding.⁷⁻⁹ However, previous studies using single letters as targets and simple contours or other letters as flankers all reported a crowding zone in peripheral vision between $0.1\times$ and $0.5\times$ times the eccentricity (for a detailed summary, refer to Chung et al.¹⁷). For instance, at 10° eccentricity, the expected crowding zone would be 5° . Here, the crowding zone for word-by-word crowding is definitely larger. Also, for letter-by-letter crowding, the zone of crowding is reported to be elliptical in peripheral vision, such that the extent of crowding is greater along the meridian connecting the zone to the fovea (i.e., radial to the fovea) than the one tangential to the fovea.⁸ Based on our results showing a similar rate of change of normalized reading speed as a function of vertical word spacing in the inferior and right visual fields (Fig. 7), we speculate that for word-by-word crowding, the extent of crowding may be similar along the radial (inferior visual field) and tangential (right visual field) dimensions.

The second purpose of this study was to examine the effect of increased vertical word spacing on reading speed in central and peripheral vision. Using sequences of unrelated words, we found that reading speed improved with vertical word spacing in both central and peripheral vision; however, for the same level of vertical word spacing, the improvement was greater in peripheral than in central vision.

In an attempt to estimate the critical vertical word spacing in the fovea as well as at 5° and 10° eccentricity, we fit the normalized reading speed versus vertical word spacing data, for data that did not show an asymptote, with a straight line (on semilogarithmic axes). The slopes of these lines at the fovea were 1.44 for $0.8\times$ CPS and 0.63 for $1.4\times$ CPS; corresponding values were 1.23 and 0.87 in the periphery. Here, the slope represents the rate of change in reading speed with vertical word spacing. The fact that the slopes were generally steeper for smaller than larger print sizes implies that smaller print size is more susceptible to the degrading effect of decreased vertical word spacing, or the effect of crowding. This is consistent with some reports that crowding is a near-resolution phenomenon.¹⁵

By varying the amount of leading between lines of text, Bentley¹⁸ and Paterson and Tinker¹⁹ found that reading speed improved with a leading of between 2 and 8 points. Tinker reported a “safety zone” (the limits within which satisfactory legibility is assured) of between 1 and 4 points of leading for a variety of print sizes and line lengths. According to Fig. 7.2 in Tinker’s book,³³ a 2-point leading for a few print sizes corresponds to a baseline-to-baseline vertical separation of approximately $2.6\times$ to $3\times$ the x-height. Based on our measurement that the standard single line spacing for Courier font in printed text is $2.6\times$ the x-height (see Methods), the results of those earlier studies suggest that reading speed would benefit from a line spacing corresponding to the standard single spacing, or a value slightly greater than the single spacing, a result that resonates with our foveal data.

In the main experiment, when reading speed was assessed for the larger print size ($1.4\times$ CPS) at $2\times$ the standard spacing in the inferior visual field, the upper flanking word was close to the fixation line. This could potentially cause a distraction to the observers who were fixating on the fixation line. However, because data for the smaller print size ($0.8\times$ CPS) showed a trend identical to that for $1.4\times$ CPS and the upper flanking word for the smaller print size was not close to the fixation line, we are confident that the effect of vertical word spacing on reading speed in the inferior visual field was not an artifact due to the close proximity of the upper flanking word to the fixation line. Also, results from the control experiment conducted in the right visual field showed a similar dependence of reading speed on vertical word spacing, supporting our conclusion that there is a larger benefit of increased vertical word spacing on reading speed in the periphery than in the fovea.

A few caveats should be kept in mind when evaluating our interpretation. First, we measured reading speed for sequences of unrelated words. Clearly, sequences of unrelated words do not carry any meaning in the sequence, in clear distinction from sentence reading. However, given the need to standardize the word-by-word crowding effect in the study and the fact that reading performance for unrelated words is less variable than that for sentence reading,^{34–36} we deemed it appropriate to use unrelated words in this study. The use of unrelated words instead of meaningful sentences yields lower maximum reading speeds, especially at the fovea. For instance, using meaningful sentences, we previously obtained an RSVP maximum reading speed of 807 wpm in the fovea and of approximately 250 wpm at 10° inferior visual field.³ These reading speeds are higher than those found in the main experiment in the present study (approximately 320 wpm at the fovea and 160 wpm at 10° inferior visual field). Another consequence of using sequences of unrelated words is that reading speeds are similar between 5° and 10° eccentricity, contrary to the progressive reduction in reading speed with eccentricity when meaningful sentences are used.³ This effect has been demonstrated previously when reading speeds were directly compared between meaningful sentences and sequences of random words with the same observers.^{3, 4} Second, we used the RSVP paradigm to present words, which clearly differs from conventional page reading. Third, our findings, obtained in young adults with healthy retinas, may not directly apply to people with central vision loss whose retinas may be compromised by disease processes and who may in fact have more practice in using the peripheral retina. Given these caveats and the limitation of our setup, which did not allow us to empirically determine the critical vertical word spacing in peripheral vision, we are currently conducting another study examining the effect of line spacing on reading speed for printed text with meaningful passages in patients with central vision loss. Results of the new study will provide direct insight in guiding text design and page layout for reading material for patients with central vision loss. Nevertheless, the present study is the first to demonstrate and quantify the crowding effect that exists between adjacent words and to show that an increased vertical word spacing benefits reading more in peripheral than central vision.

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References

1. Leat SJ, Rumney NJ. The experience of a university-based low vision clinic. *Ophthalmol Physiol Opt* 1990;10:8–15.
2. Elliott DB, Trukolo-Ilic M, Strong JG, Pace R, Plotkin A, Bevers P. Demographic characteristics of the vision-disabled elderly. *Invest Ophthalmol Vis Sci* 1997;38:2566–75. [PubMed: 9375576]
3. Chung STL, Mansfield JS, Legge GE. Psychophysics of reading, XVIII: the effect of print size on reading speed in normal peripheral vision. *Vision Res* 1998;38:2949–62. [PubMed: 9797990]
4. Latham K, Whitaker D. A comparison of word recognition and reading performance in foveal and peripheral vision. *Vision Res* 1996;36:2665–74. [PubMed: 8917753]
5. Rubin GS, Turano K. Low vision reading with sequential word presentation. *Vision Res* 1994;34:1723–33. [PubMed: 7941378]
6. Cline, D.; Hofstetter, HW.; Griffin, JR. *Dictionary of Visual Science*. Vol. 4. Boston: Butterworth-Heinemann; 1997.
7. Jacobs RJ. Visual resolution and contour interaction in the fovea and periphery. *Vision Res* 1979;19:1187–95. [PubMed: 550578]
8. Toet A, Levi DM. The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Res* 1992;32:1349–57. [PubMed: 1455707]

9. Latham K, Whitaker D. Relative roles of resolution and spatial interference in foveal and peripheral vision. *Ophthalmol Physiol Opt* 1996;16:49–57.
10. Loomis JM. Lateral masking in foveal and eccentric vision. *Vision Res* 1978;18:335–8. [PubMed: 664307]
11. Chung STL. The effect of letter spacing on reading speed in central and peripheral vision. *Invest Ophthalmol Vis Sci* 2002;43:1270–6. [PubMed: 11923275]
12. Bouma H. Interaction effects in parafoveal letter recognition. *Nature* 1970;226:177–8. [PubMed: 5437004]
13. Townsend JT, Taylor SG, Brown DR. Lateral masking for letters with unlimited viewing time. *Percept Psychophys* 1971;10:375–8.
14. Whittaker, S.; Rohrkaste, F.; Higgins, K. Noninvasive Assessment of the Visual System, 1989 Technical Digest Series. Vol. 7. Washington, DC: Optical Society of America; 1989. Optimum letter spacing for word recognition in central and peripheral vision; p. 56–9.
15. Arditi A, Knoblauch K, Grunwald I. Reading with fixed and variable character pitch. *J Opt Soc Am A* 1990;7:2011–5. [PubMed: 2231111]
16. Liu L, Arditi A. Apparent string shortening concomitant with letter crowding. *Vision Res* 2000;40:1059–67. [PubMed: 10738065]
17. Chung STL, Levi DM, Legge GE. Spatial-frequency and contrast properties of crowding. *Vision Res* 2001;41:1833–50. [PubMed: 11369047]
18. Bentley M. Leading and legibility. *Psychol Monogr* 1921;30:48–61.
19. Paterson DG, Tinker MA. Studies of typographical factors influencing speed of reading, VIII: space between lines or leading. *Am J Psychol* 1932;16:388–97.
20. Spragins AB, Lefton LA, Fisher DF. Eye movements while reading and searching spatially transformed text: a developmental examination. *Mem Cognit* 1976;4:36–42.
21. Epelboim J, Booth JR, Steinman RM. Reading unspaced text: implications for theories of reading eye movements. *Vision Res* 1994;34:1735–66. [PubMed: 7941379]
22. Rayner K, Pollatsek A. Reading unspaced text is not easy: comments on the implications of Epelboim et al. 's (1994) study for models of eye movement control in reading. *Vision Res* 1996;36:461–70. [PubMed: 8746235]
23. Epelboim J, Booth JR, Steinman RM. Much ado about nothing: the place of space in text. *Vision Res* 1996;36:465–70.
24. Rayner K, Fischer MH, Pollatsek A. Unspaced text interferes with both word identification and eye movement control. *Vision Res* 1998;38:1129–44. [PubMed: 9666972]
25. Legge GE, Mansfield JS, Chung STL. Psychophysics of reading, XX: linking letter recognition to reading speed in central and peripheral vision. *Vision Res* 2001;41:725–43. [PubMed: 11248262]
26. Kilgarriff A. Putting frequencies in the dictionary. *Int J Lexicogr* 1997;10:135–55.
27. Chaparro A, Young RSL. Reading with rods: the superiority of central vision for rapid reading. *Invest Ophthalmol Vis Sci* 1993;34:2341–7. [PubMed: 8505215]
28. Higgins KE, Arditi A, Knoblauch K. Detection and identification of mirror-image letter pairs in central and peripheral vision. *Vision Res* 1996;36:331–7. [PubMed: 8594832]
29. Cummings RW, Rubin GS. Reading speed and saccadic eye movements with an artificial paracentral scotoma. *Invest Ophthalmol Vis Sci* 1992;33(suppl):1418.
30. Petre KL, Hazel CA, Fine EM, Rubin GS. Reading with eccentric fixation is faster in inferior visual field than in left visual field. *Optom Vis Sci* 2000;77:34–9. [PubMed: 10654856]
31. Mansfield JS, Legge GE, Bane MC. Psychophysics of reading, XV: font effects in normal and low vision. *Invest Ophthalmol Vis Sci* 1996;37:1492–501. [PubMed: 8675391]
32. Strasburger H, Harvey LO Jr, Rentschler I. Contrast thresholds for identification of numeric characters in direct and eccentric view. *Percept Psychophys* 1991;49:495–508. [PubMed: 1857623]
33. Tinker, MA. Legibility of Print. Ames, IA: Iowa State University Press; 1963.
34. Bailey IL, Lovie JE. The design and use of a new near-vision chart. *Am J Optom Physiol Opt* 1980;57:378–87. [PubMed: 7406006]
35. Chung, STL. MS thesis. Melbourne, Australia: University of Melbourne; 1991. An investigation of the effects of magnification and field of view of optical magnifiers on reading performance.

36. Bullimore MA, Bailey IL. Reading and eye movements in age-related maculopathy. *Optom Vis Sci* 1995;72:125–38. [PubMed: 7753526]

		leaf	leaf	leaf	leaf	leaf
bike	leaf	leaf	leaf	leaf	leaf	leaf
	bike	bike	bike	bike	bike	bike
	hill	hill	hill	hill	hill	hill
<i>unflanked</i>	<i>0.8x</i>	<i>1x (standard)</i>	<i>1.25x</i>	<i>1.6x</i>	<i>2x</i>	

FIGURE 1.

Samples of the target word “bike” as rendered in the unflanked condition (leftmost) as well as conditions when it was flanked by two words, “leaf” and “hill,” for five vertical word spacings. The 0.8× vertical word spacing was tested in the fovea only. Values of vertical word spacing are given below the samples.

FIGURE 2.

Reading speed (wpm) plotted as a function of print size (deg) for the five observers at three eccentricities. Straight lines through the data points represent bilinear fits for estimating the critical print size (see text for details). Error bars represent ± 1 SEM.

FIGURE 3.

Reading speed (wpm) plotted as a function of vertical word spacing (multiples of standard spacing) for five observers at three eccentricities. Print size was $0.8\times$ critical print size, derived for each observer separately (see Fig. 2). Error bars are ± 1 SEM.

FIGURE 4.

Reading speed (wpm) plotted as a function of vertical word spacing as in Fig. 3, with the exception that the print size was 1.4× critical print size.

FIGURE 5.

Group average data showing how reading speed changes as a function of vertical word spacing for three eccentricities and two print sizes. Error bars are ± 1 SEM.

FIGURE 6.

Normalized reading speed, averaged across all observers, plotted as a function of vertical word spacing. Normalized reading speed refers to reading speed for the flanked condition normalized to that for the unflanked condition for the same eccentricity and print size. Error bars represent ± 1 SEM. Straight lines drawn through foveal data points represent the bilinear fits for estimating critical vertical word spacing, whereas the single line drawn through data points for 5° and 10° eccentricities represent a single line fitted to the data pooled across these two eccentricities. We estimated the critical vertical word spacing for 5° and 10° eccentricity by solving the equation of this line for a y value of 1.

FIGURE 7.

Reading speed (wpm) plotted as a function of vertical word spacing for two observers in the control experiment in the top panels. Data were obtained at the fovea (filled circles), 10° inferior (filled squares), and 10° right (unfilled squares) visual fields. The bottom panel plots averaged reading speeds, normalized to the unflanked reading speed, for each retinal eccentricity. Straight lines drawn through data points in the bottom panel represent the bilinear fit for foveal data and the single line fit, for peripheral data.