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Increased word spacing improves performance for reading scrolling text with central vision loss

Hannah Harvey[1], Stephen J. Anderson[2] and Robin Walker[1]

[1]Department of Psychology, Royal Holloway University of London, Egham Hill, Egham, TW20 0EX

[2]School of Life and Health Sciences, Aston University, Birmingham, B4 7ET

Correspondence: Hannah Harvey, Royal Holloway (hannahvharvey@gmail.com)

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Abstract

Significance: Scrolling text can be an effective reading aid for those with central vision loss. Our results suggest that increased inter-word spacing with scrolling text may further improve the reading experience of this population. This conclusion may be of particular interest to low vision aid developers and visual rehabilitation practitioners.

Purpose: The dynamic, horizontally scrolling text format has been shown to improve reading performance in individuals with central visual loss. Here, we sought to determine whether reading performance with scrolling text can be further improved by modulating inter-word spacing to reduce the effects of visual crowding: a factor known to impact negatively on reading with peripheral vision.

Methods: The effects of inter-word spacing on reading performance (accuracy, memory recall and speed) was assessed for eccentrically-viewed single sentences of scrolling text. Separate experiments were used to determine whether performance measures were affected by any confound between inter-word spacing and text presentation rate in words per minute (wpm). Normally-sighted participants were employed, with a central vision loss implemented using a gaze-contingent scotoma of 8^o diameter. In both experiments, participants read sentences that were presented with an inter-word spacing of one, two or three characters.

Results: Reading accuracy and memory recall were significantly enhanced with triple-character inter-word word spacing (both measures $P \leq 0.01$). These basic findings were independent of the text presentation rate (in wpm).

Conclusions: We attribute the improvements in reading performance with increased inter-word spacing to a reduction in the deleterious effects of visual crowding. We conclude that increased inter-word spacing may enhance reading experience and ability when using horizontally scrolling text with a central vision loss.

Introduction

Horizontally scrolling text has been shown to be a useful technique for reducing the level of reading difficulty and discomfort typically experienced by individuals with central vision loss.[1–5] Most commonly seen in rolling news tickers, this text format can be applied as a reading aid for individuals with macular dysfunction, either manually using CCTV (Closed-Circuit Television) aids[6] or via mobile apps such as the MD_evReader.[2] There are several reasons why this is the case. First, scrolling text allows readers to limit active oculomotor navigation of the text, a factor known to be a significant challenge for people without central vision.[7] Second, because scrolling text is presented as a single line, it not only removes the difficulty associated with navigation of multi-lined text with a central scotoma,[8] but also negates the deleterious effects of inter-line crowding.[9] Crowding refers here to the phenomenon in which identification of a target word is significantly impaired by the presence of nearby words.[10–12] Third, visual acuity for dynamic stimuli may be superior to that for static stimuli at some eccentricities when presented at a reasonable rate.[13] Finally, scrolling text may allow individuals without central vision to reduce their fixational instability[14] by holding fixation in an eccentric location so that the text can move through an optimal part of their remaining visual field (*i.e. their preferred retinal locus [PRL]);* this is similar to a viewing technique (‘*steady-eye strategy*’) which has been advocated by some low-vision practitioners to improve reading performance.[15]

Although reading a single line of drifting text cannot involve the influence of inter-line crowding, it may be adversely affected by inter-word crowding. The latter may impact significantly on reading performance with peripheral vision. Sufficient word spacing is naturally required for the delineation of word boundaries;[16] increased overall reading times and increased difficulty with word identification arise when typical word spacing information is removed.[17] However, due to the negative effects of visual crowding,[18–20] which are known to worsen as retinal eccentricity increases,[21] standard inter-word spacing (of a single-character space) may be insufficient to allow identification of individual words within a passage of eccentrically-viewed text.

Blackmore-Wright, Georgeson and Anderson[9] demonstrated the benefits of reduced visual crowding for reading with central vision loss, reporting that increased word and line spacing within multi-line passages of static text improves reading performance in individuals with macular disease. They assessed reading speed with single, double or triple word/line spacing, and observed the fastest reading speeds for text with double line and double word spacing. The effects of horizontal word crowding on reading performance with scrolling text is not known.

Furthermore, the effects of crowding in peripheral vision may be greater for dynamic text than static text. Reading scrolling text involves leftward pursuit tracking of words in place of periods of fixation typically seen in normal reading,[22–24] with rightward saccades made between words as usual. Studies of attentional deployment during periods of pursuit have shown that the effects of crowding may be increased for stimuli positioned behind the direction of pursuit.[25] This is broadly comparable to the situation for upcoming words with scrolling text (see Figure 1), suggesting that word crowding in peripheral vision may be more problematic with scrolling text than static text. If this is the case, reading performance with horizontally scrolling text may be enhanced by increasing inter-word spacing.

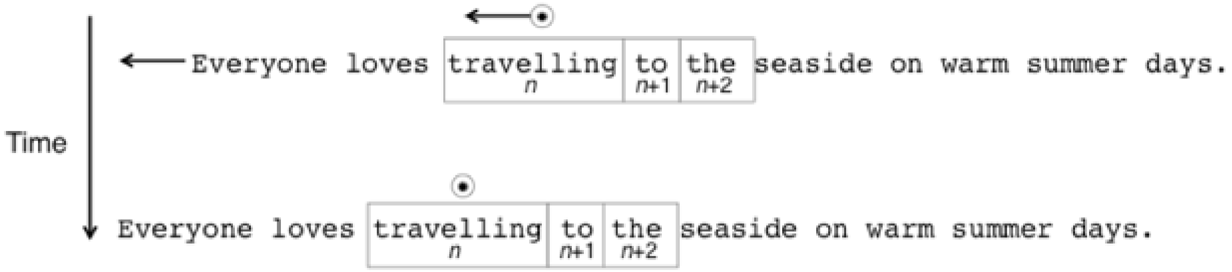

Figure 1. *Processing of upcoming words in the parafoveal area (e.g. word n + 1 and word n + 2) may be disrupted by increased crowding of text positioned behind the direction of movement.*

The aim of the present study was to investigate the effects of inter-word spacing on reading performance for scrolling text under conditions of central vision loss. The latter was achieved using a gaze-contingent central scotoma of 8^{o} diameter. Our study followed the general approach of Blackmore-Wright et al.[9] in that we compared single-, double- and triple-character inter-word spacing when reading eccentrically-viewed text. The measures of visual performance included reading accuracy (i.e. reading error rate), sentence recall, and reading speed (in words per minute, wpm).

Methods

Twelve students were recruited for each experiment (Expt. 1: 8 females, group mean age 19.5 years; Expt. 2: 11 females; group mean age 24.1 years). No participants took part in both studies. A-priori power calculations based on the effect size for inter-word spacing recorded by Blackmore-Wright et al.[9] were performed using G*Power software,[26] indicating that this sample size should provide adequate statistical power to detect this effect of interest. All participants were native English speakers from Royal Holloway, University of London, with no reading or language impairments. All had self-reported normal or corrected-to-normal vision, received course credit for their participation, and all gave prior informed consent as approved by departmental ethical review at Royal Holloway. This study adhered to the tenets of the Declaration of Helsinki.

Participants were required to read text under conditions of a simulated central vision loss, which was imposed as a gaze-contingent circular scotoma of 8^{o} diameter, as described below. The main manipulation of interest was inter-word spacing, set to one, two or three characters. Two experiments were employed to assess the effects on reading performance of any potential confound between text drift rate and inter-word spacing.

In both experiments, text was presented as a single scrolling line that moved smoothly across the screen from right to left, at a fixed speed on each trial. The fixed speeds were set differently in Experiments 1 and 2, constituting the only major difference between these studies. In Experiment 1, text was scrolled in every trial at a fixed speed of two pixels per screen refresh (6.7 ^{o}/s; which equates to approximately 9.1 characters/s). The increased inter-word spacing necessarily reduced text scrolling speed, with single, double and triple spacing conditions yielding display speeds of approximately 109, 91 and 78 wpm, respectively. In order to ensure that the slowing display speed with increased word spacing was not a confound in our results, the text in Experiment 2 was scrolled at a speed of approximately 91 wpm for all three spacing conditions, with the pixel-scrolling rate modified across conditions to compensate for the delayed rate of presentation produced by wider inter-word spacing. Single-spaced text was therefore scrolled at 3.8 ^{o}/s, double-spaced text at 4.6 ^{o}/s, and triple-spaced text at 5.1 ^{o}/s.

Stimuli were displayed on a computer monitor (refresh rate 100 Hz) as black text (24pt Courier font) on a white background. The Courier font has been identified as suitable for reading with central vision loss,[27,28] and is a fixed-width font with each character (including inter-word spaces) of the same horizontal extent. The character extent (x-height) in this study was 0.6^{o}, four times the letter acuity threshold at 4^{o} eccentricity,[29] and larger than the expected critical print size (CPS), assuming a CPS acuity ratio of 2:1.[30] Viewing distance was maintained at 70 cm using a table-mounted head restraint, which also served to stabilise head position. Note that a chinrest was not used as jaw movements made with vocalisations could potentially disrupt eye-tracking measures. Participants were advised to adopt a vertical PRL as this improves performance when reading horizontally scrolling with a central vision loss.[3] A horizontal guide-line positioned 4^{o} above the text was used to aid adherence to the advised PRL (see Figure 2).

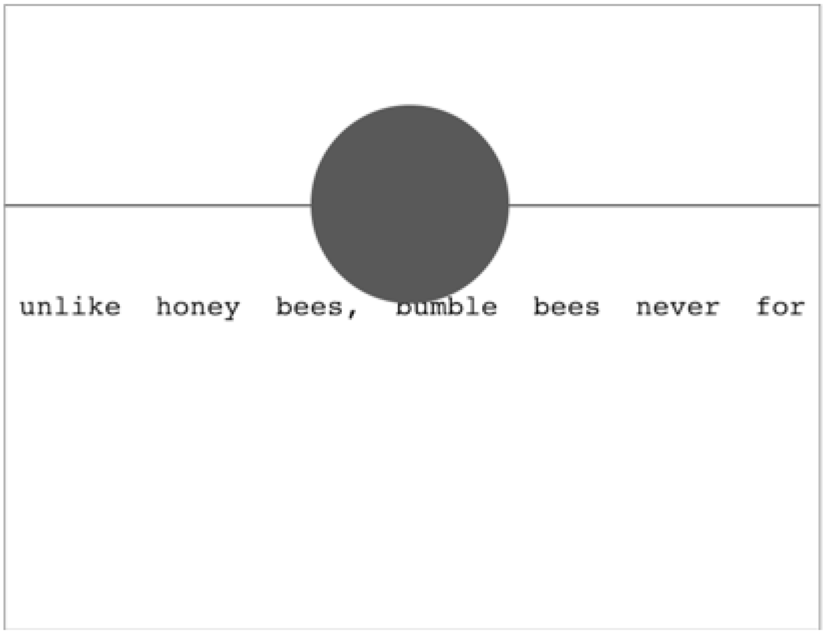

Figure 2. *Schematic of scrolling text presentation protocol. The horizontal line (positioned 4^o above the top of the text display area) was used to encourage participants to adhere to the eccentric viewing strategy (upper vertical PRL).*

A set of 290 similarly constructed sentences of average length 11.0 words (SD 1.2) was employed across both experiments. All sentences were based on the MNRead corpus.[31] The average number of characters in each word was 5.3 (SD 0.6). Sentences were randomly allocated into blocks which were allocated to each of the inter-word spacing conditions, with this allocation counterbalanced across participants so that all sentences appeared equally in each spacing condition. Inter-word spacing was set uniformly across a sentence as one, two or three character spaces.

During reading, monocular (right-eye) eye movements were recorded using an EyeLink 1000 video-based eye tracker at a sample rate of 1000 Hz. Except when a blink was detected, eye position was used to re-draw a scotoma every 10 ms based on the last sample location. If a blink was detected, the scotoma was redrawn continuously in the same position until the blink ended. The scotoma was developed and displayed as a homogenously filled grey circle following recommendations made by Aguilar and Castet[32] to address issues of pupil size changes (e.g. due to blinks) that are detrimental for gaze-contingent scotoma paradigms. Prior to each trial, a standard Eyelink drift-checking procedure was performed in the absence of the gaze-contingent scotoma using a gaze-fixation target positioned 4° above the location where the text would subsequently appear. This required the participant to adopt the correct eccentric fixation location prior to reading. Following this, as an additional means of ensuring gaze position accuracy, a gaze-contingent landmark (0.8° black square) was presented in the same spatial location as the drift-checking target, requiring stable fixation in this region for at least 40ms before the trial would begin. The importance of minimising head movements was stressed to participants before and during each experimental block of trials. On rare occasion (< 5% of trials), however, recalibration was required as one or the other verification stages indicated a loss of position accuracy.

The Experiment Builder software (SR Research, Ontario, Ca), with custom Python code, was used to present the stimuli. Prior to an experimental block, a practice block was completed to allow participants to (re-) familiarise themselves with the eccentric reading task – the practice block was drawn from a pool of unused sentences. Presentation of each spacing condition was randomised for each participant. Participants were asked to read aloud each presented sentence, and recall the sentences aloud at the conclusion of each trial. An auditory recording of the session was made for later scoring. Reading accuracy was determined from the number of errors made while reading each sentence. Errors were identified as omissions (e.g. *She could not sleep in the same room as the big [**scary**] clown*), substitutions (e.g. *We like feeding carrots to the rabbits [**horses**] that live in that field*) or insertions (e.g. *My sister was going to play [**by**] the piano but it was broken)*. This procedure allowed measures of reading speed, accuracy and memory to be analysed (using R 3.4.4[33]). Statistical analysis of the effects of inter-word spacing was completed using a within-subjects one-way ANOVA. Multiple comparisons were corrected using Bonferroni's method, and effect sizes are reported as generalised eta squared (η_G^2) or Cohen's *d* where appropriate.

Results

Accuracy

All participants in both experiments made some reading errors. Averaged across participants and all experimental trials in Experiment 1, an average of 26.25 errors (SD 20.57) were made by each participant. The average number of errors made per sentence by each participant was 1.25 (SD 2.16). In Experiment 2, an average of 24.31 errors (SD 19.05) were made by each participant. The average number of errors made per sentence by each participant was 0.65 (SD 0.49).

In both experiments, reading accuracy was modulated by spacing condition (Exp 1 $F_{2, 22} = 14.63$, $P = .04$, $\eta_G^2 = 0.16$; Exp 2 $F_{2, 22} = 17.95$, $P < .001$, $\eta_G^2 = 0.36$). In Experiment 1, participants made an average of 0.72 errors per sentence (SD 0.75) for triple-character spacing, compared with 1.16 errors (SD 0.85) for double-character and 1.83 errors (SD 1.44) for single-character spacing (Figure 3a). Pairwise comparisons showed that single and double inter-word spacing conditions were not significantly different ($P = .06$, $d = 0. 52$), but that reading with triple-character inter-word spacing produced significantly fewer errors than both single- ($P = .01$, $d = 0.96$) and double-character spacing ($P = .01$, $d = 0.54$). The pattern of results was similar for Experiment 2, where an average of 0.28 errors were made per sentence (SD 0.20) for triple-character spacing, compared with 0.69 errors (SD 0.29) for double- and 0.99 errors (SD 0.61) for single-character spacing (Figure 3b). Pairwise comparisons showed that single and double inter-word spacing conditions were not significantly different ($P = .23$, $d = 0.64$), but that reading with triple-character inter-word spacing produced significantly fewer errors than both single- ($P < .001$, $d = 1.57$) and double-character spacing ($P \leq .05$, $d = 1.65$). In summary, both experiments show that increasing inter-word spacing from one to three characters significantly enhances accuracy for reading eccentrically-viewed scrolling text.

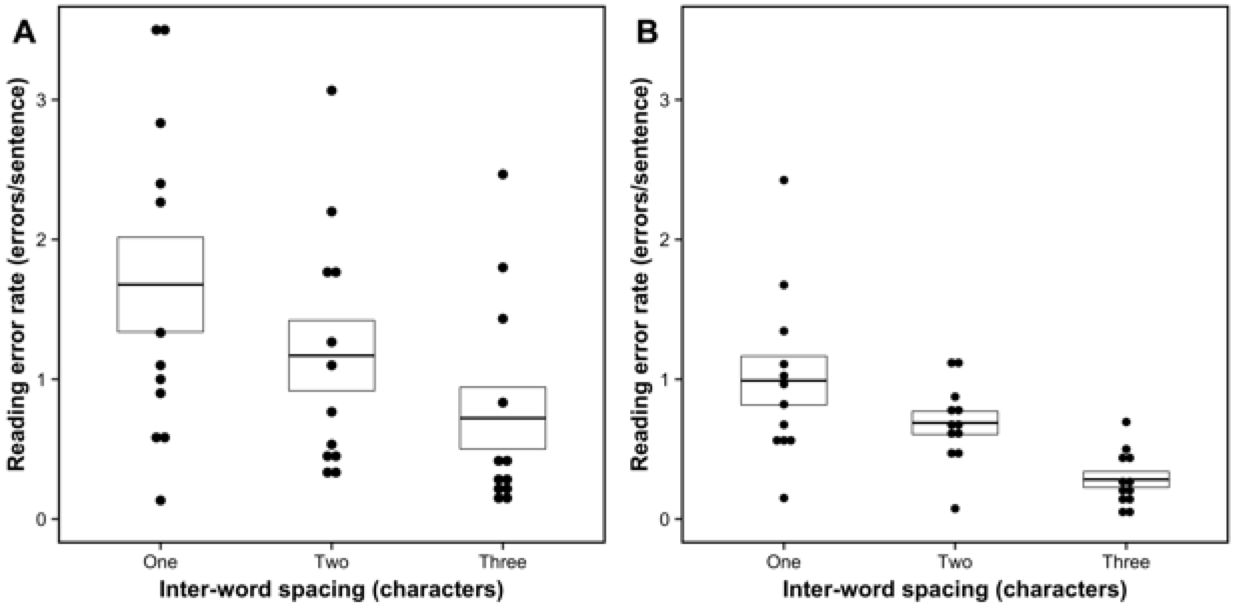

Figure 3. *Average number of reading errors made per sentence for inter-word spacing of one, two or three characters in Experiment 1 (panel a) and Experiment 2 (panel b). Individual dots show individual each participant's performance, and the subdivided box shows group mean and 95% confidence intervals.*

Memory

Memory was defined as the proportion of sentences correctly recalled at the end of each trial. Averaged across all conditions and all participants, the proportion of sentences correctly recalled was 73.53% in Experiment 1 and 80.75% in Experiment 2. In Experiment 1, 48.33% (SD 34.86) of sentences were correctly recalled with single-character inter-word spacing. This compares with 80.58% (SD 24.43) for double-character and 91.67% (SD 19.46) for triple-character spacing. In Experiment 2, memory scores across spacing conditions were 75.91% (SD 5.74) for single-character spacing, 80.89% (SD 5.31) for double-character spacing, and 85.44% (SD 4.93) for triple-character spacing. As for reading accuracy, there was an effect of spacing condition on recall in both Experiment 1 ($F_{2,\ 22}$ =13.30, P < .001, $\eta_G^2 = 0.34$) and Experiment 2 ($F_{2,\ 22}$ =11.98, P < .001, $\eta_G^2 = 0.37$). For Experiment 1, pairwise comparisons revealed significantly greater recall for both double- (P < .01, d = 1.07) and triple-character (P < .001, d = 1.53) inter-word spacing compared with single-character spacing (Figure 4a). For Experiment 2, pairwise comparisons revealed greater recall for triple-character compared with single-character spacing (P < .001, d = 1.78) alone (Figure 4b). Note that there were numerical trends in Experiment 2 towards better recall with triple- compared with double-character spacing, and with double- compared with single-character spacing, but these comparisons did not reach statistical significance (double vs. triple *P* = .13, *d* = 0.89; single vs. double *P* = .09, *d* = 0.90). In summary, both experiments show that, when reading scrolling text, increasing inter-word spacing from one to three characters significantly increases the proportion of sentences correctly recalled.

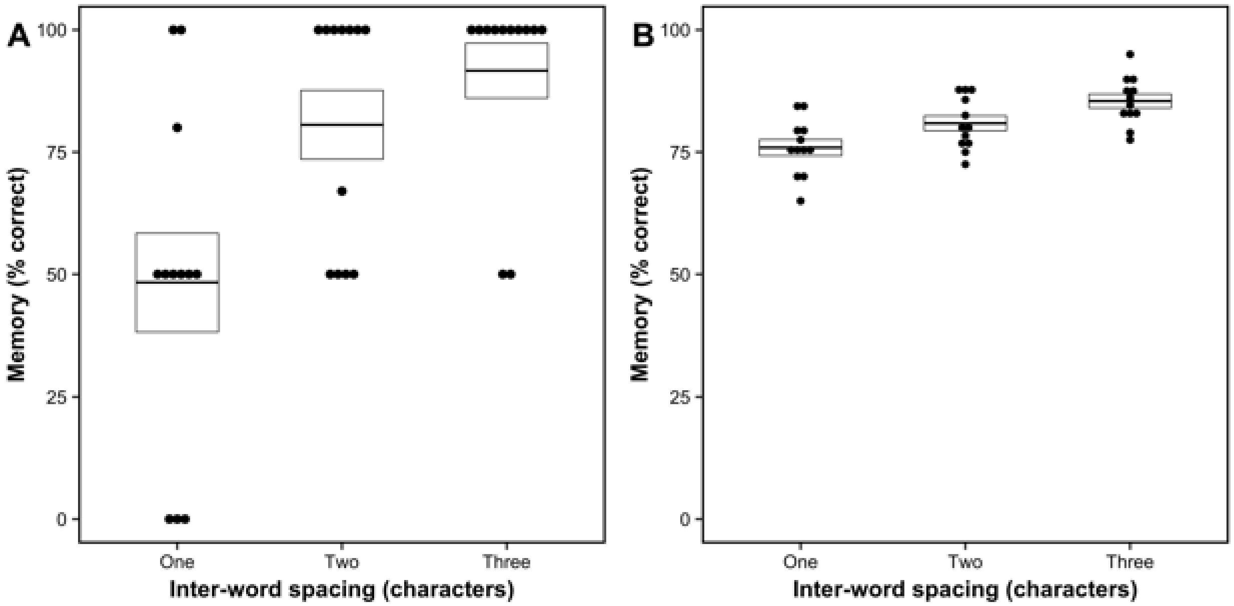

Figure 4. *Percentage of sentences correctly recalled, averaged across all participants for single-, double- and triple-character inter-word spaces in Experiment 1 (panel a) and Experiment 2 (panel b). Individual dots show each participant's performance, and the subdivided box shows group mean and 95% confidence intervals. Note that three participants failed to report any sentences correctly in Expt. 1 (single spacing condition). This result is unlikely to reflect a lack of familiarity with the task, as it was the first set of trials for only one of the three non-scoring participants.*

Reading Speed

Reading speed is reported here as the number of words read per minute (wpm), where the time taken to read each sentence was recorded as the temporal interval between screen sentence onset and the final vocalisation of the sentence. Substantial differences between Experiments 1 and 2 were expected for this measure because of the different ways in which text display speeds were set. In Experiment 1, the physical text display speed was matched across the three spacing conditions (to 6.7^{o}/s), resulting in effectively slower presentation speeds in words per minute for more widely spaced text. In Experiment 2, the physical text display speed was adjusted such that the presentation speed in words per minute (approx. 91 wpm) was the same for each spacing condition (see *Methods*).

In Experiment 1 reading speed was fastest in the single-character spacing condition (86.63 wpm, SD 7.86), and increasingly slower in the double (76.94, SD 3.56) and triple spacing (71.16, SD 3.12) conditions (see Figure 5a). The decrease in reading speed with increasing inter-word spacing was significant ($F_{2, 22} = 39.03$, $P < .001$, $\eta_G^2 = 0.62$). All comparisons between spacing conditions were significant ($P < .05$, $d > 1.5$).

By contrast, reading speeds in Experiment 2 were, as expected, similar across all three spacing conditions: 84.25 wpm (SD 26.56) with single-character spacing, 86.93 wpm (SD 25.38) with double-character spacing, and 88.33 wpm (SD 21.71) with triple-character spacing (see Figure 5b). There was no significant effect of spacing condition on average reading speed ($P = .74$). This supports the assertion that improved reading performance with increased inter-word spacing in Experiment 1 cannot be attributed to text display speed alone.

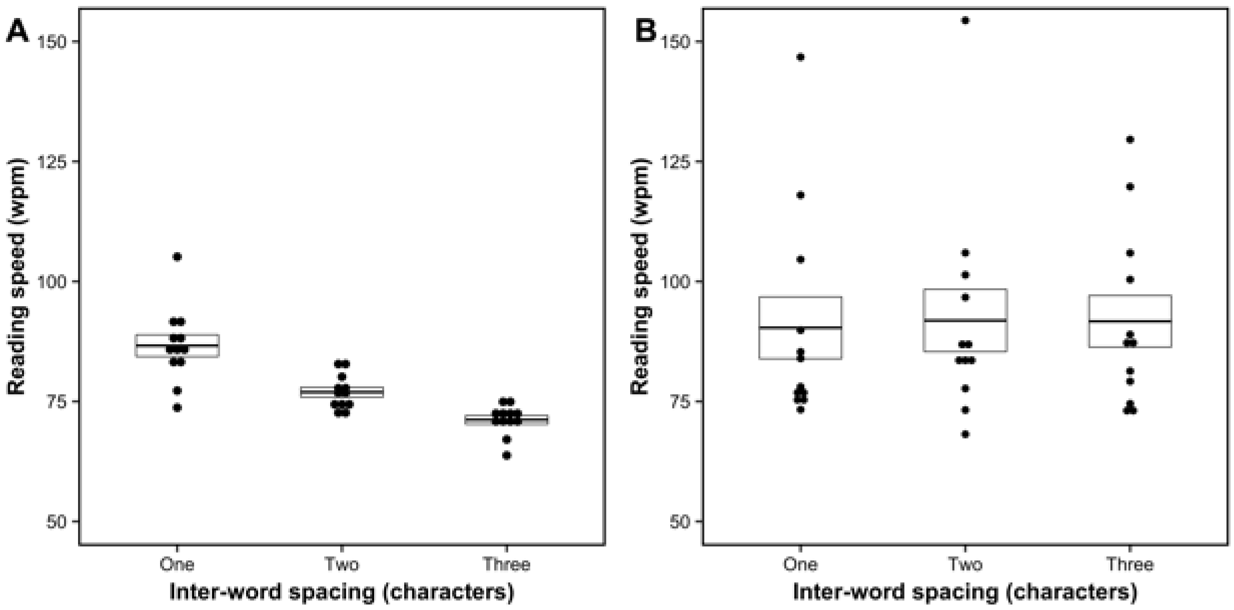

Figure 5. *Reading speed (words per minute) averaged across all participants for single-, double- and triple-character inter-word spaces in Experiment 1 (panel a) and Experiment 2 (panel b). Individual dots show individual each participant's performance, and the subdivided box shows group mean and 95% confidence intervals.*

Eye movements

A density heat map of fixations, weighted by fixation duration and averaged across all participants, is presented in Figure 6. Data are shown for for single-, double- and triple-character inter-word spaces for Experiment 1 (panel a) and Experiment 2 (panel b). The horizontal broken line, located 4^o above the text, indicates the 'ideal' viewing position for leaving the text unobscured by the artificial scotoma. Note that the distribution of eye fixations remained broadly similar with different word spacings.

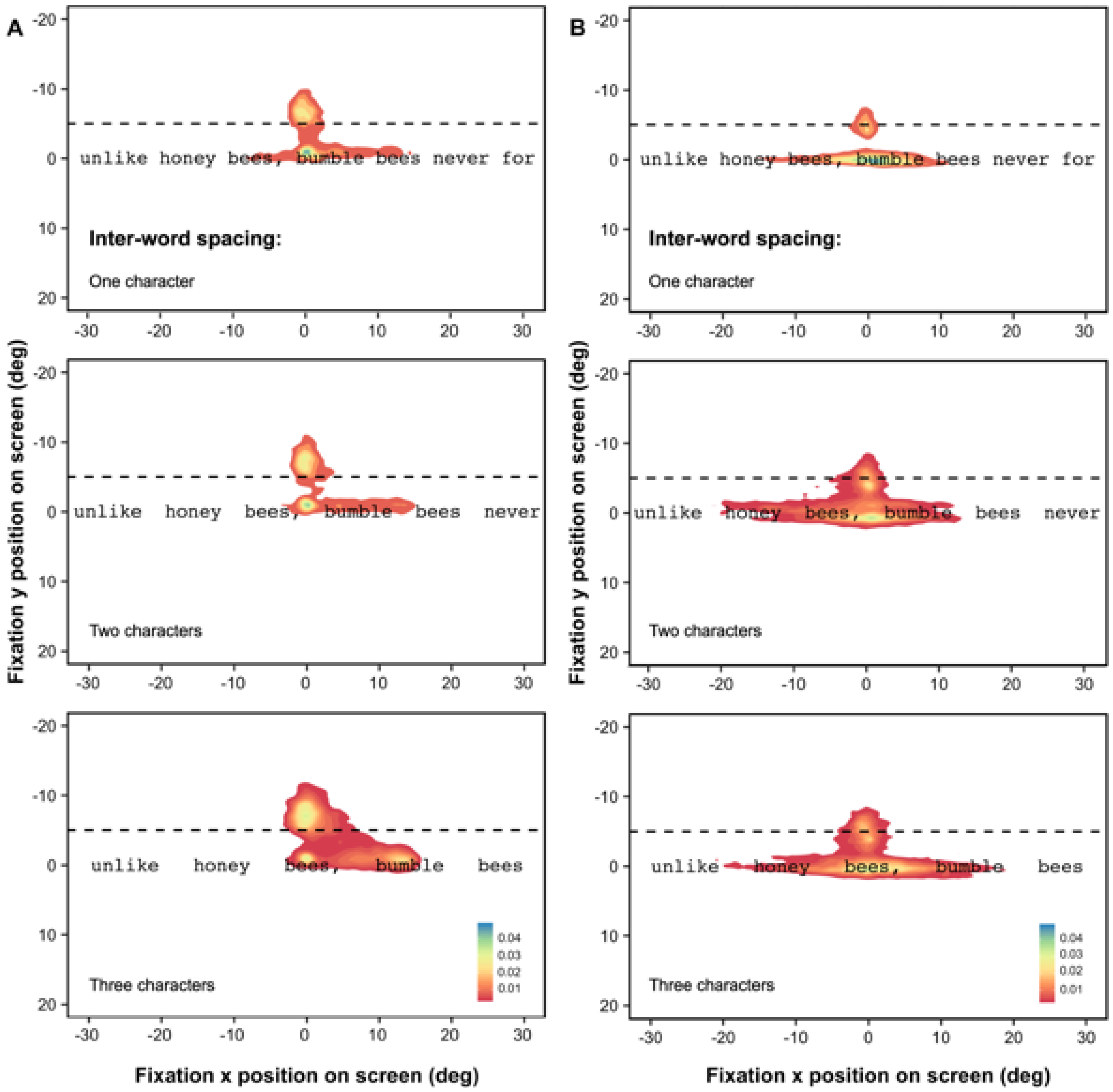

Figure 6. *Density heat map of fixations, weighted by fixation duration, averaged across all participants for single-, double- and triple-character inter-word spaces in Experiment 1 (panels a) and Experiment 2 (panels b). Densities are calculated using the nonparametric kernel density estimation technique, and brighter colours are associated with higher proportion of fixation time. Screen position is given in degrees of a visual angle, and coordinates (0,0) is the centre of the screen. The horizontal broken line, located 4° above the text, indicates the 'ideal' viewing position for leaving the text unobscured by the gaze-controlled scotoma.*

As can be seen from the heat maps, participants did not maintain the ideal viewing position throughout the experiments – on average, participants spent approximately one third of their viewing time with an ideal fixation location (mean 30% in both experiments, with a SE of 5% in Experiment 1 and 4% in Experiment 2). We note that one participant in Experiment 1 and two participants in Expeirment 2 were able to adhere to the ideal viewing strategy for approximately two-thirds of their viewing time. However, there was no evidence that these few participants achieved any better reading performance. There was also no evidence for any systematic differences in adherence to this viewing strategy across the three spacing conditions.

Discussion

We investigated the impact of inter-word spacing on performance for reading single lines of horizontally scrolling text in peripheral vision. To ensure that peripheral vision was used for reading, we employed a gaze-contingent central scotoma that covered the entire macular area. We show that reading accuracy (Figure 3) and memory recall (Figure 4) were significantly enhanced with increased inter-word spacing, with the largest improvements observed for triple-character spacing. Our experimental protocol affirmed that these findings were independent of the text presentation speed in words per minute. Given these results, and in general agreement with previous studies,[9,18–20] we attribute the observed improvements in reading performance with increased inter-word spacing to a reduction in visual crowding (cf[9]).

An improvement in reading performance with increased word spacing has been demonstrated in individuals with macular disease, where, for normal contrast static text, double-character inter-word spacing yielded superior reading performance than either single- or triple-character spacing.[9] In the present study reading performance, in terms of accuracy and memory recall, was better with triple-character word spacing than either single- or double-character spacing, a result that may reflect the increased crowding effect reported with dynamic stimuli.[25,34] The replication of the improvement across two measures of reading performance and two different experimental protocols demonstrates the reliability of this effect.

It is possible that inter-word separation beyond triple-character spacing may further enhance reading performance. However, given the known trade-off between the beneficial effects of reducing visual crowding and the detrimental consequences of stimuli being shifted into an area of poorer visual acuity,[21,29,35] it is likely that excessive inter-word spacing (i.e. more than three characters) may be counterproductive, although this remains to be tested. Similarly, although it would also be possible to investigate intra-word (letter) spacing to further reduce visual crowding, evidence from studies with static text suggests that this could disrupt the perception of the word form required for efficient lexical identification.[27]

Dynamic scrolling text necessarily imposes a limit on maximum reading speed as it restricts text availability – words can only be read at the rate at which they appear. With the protocol employed here in Experiment 1, a maximum reading speed of 109 wpm was achievable with single-character word spacing, reducing to 78 wpm for triple-character spacing (see Methods). This reduction may, in part, account for the measured change in reading speed when moving from single- to triple-character inter-word spacing (see Figure 5a). Nonetheless, although reading speed declined, enhanced word spacing allowed significant improvements in reading accuracy and memory recall. These improvements were replicated in Experiment 2, where using matched display speeds across spacing conditions we confirmed that there was no confound between our reading performance measures and text display speed. This experiment further demonstrated that the observed improvements in reading speed could be maintained at a reasonable reading rate of around 90 words per minute.[4,36]

Scrolling text, which can be achieved with a range of electronic devices, has proven to be an effective reading format for people with central vision loss.[1–5] Based on the results reported here, we suggest that increased inter-word spacing with scrolling text may further improve the overall reading experience of visually compromised individuals. This conclusion may be of particular use to developers of low vision aids and visual rehabilitation practitioners. Some caution may be appropriate in generalising the results here with regard to the retinal area employed for eccentric viewing. In this study we used an 8° wide central scotoma, in line with several reading studies of this kind.[32,37–47] For smaller areas of central vision loss, increased inter-word spacing may be less important as visual crowding is less severe in the region immediately surrounding the fovea.[21]

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