Binocular advantages for parafoveal processing in reading

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Abstract

During reading, binocular visual input results in superior performance and is particularly important in the pre-processing of parafoveal text prior to direct fixation. It is not yet clear whether binocular vision in the parafovea is necessary for accurate saccadic targeting, or for efficient pre-processing of upcoming text, prior to direct fixation. In the present sentence reading experiment, we used a dichoptic gaze-contingent moving window paradigm in order to establish 1) how much parafoveal binocular input is necessary for fluent reading and 2) which aspect of parafoveal processing is more reliant on binocular vision. Eye movement measures revealed that reading was disrupted unless word *N+1* was entirely binocular in the parafovea, though no additional benefit was observed when word *N+2* was also binocular. Additionally, while fixation durations and reading times were clearly affected by the manipulation, similarly pronounced changes in binocular saccadic parameters such as accuracy, speed, amplitude and velocity were not observed. We concluded that the disruption to reading caused by presenting monocular text to the right of fixation cannot be attributed to difficulties in targeting binocular saccacdes, but instead results from a decreased efficiency in the pre-processing of parafoveal text. These results provide further demonstration for the importance of binocular vision during written text processing.

Keywords: *reading, binocular vision, eye movements, parafoveal processing*

1. Introduction

Reading is a complex psychological task, involving rapid movements of both eyes in the same direction (saccades) from one word to the next, or, occasionally, backwards to previously encountered text (see Rayner, 1998, 2009 for reviews). During reading, as well as other visually demanding tasks, binocular coordination ensures that a stable, unified percept of the text is maintained across eye movements in order for visual processing to proceed without disruptions caused by diplopia (Blythe et al., 2006; Blythe et al., 2010; Jainta, Hoormann, Kloke, & Jaschinski, 2010; Liversedge et al., 2006a; Liversedge et al., 2006b; Nuthmann & Kliegl, 2009; Nuthmann, Beveridge & Shillcock, 2014; Vernet & Kapoula, 2009). Recent finding have also indicated that binocular vision provides clear advantages for reading, such as shorter overall fixation and sentence reading times and an increased efficiency of word processing (Heller & Radach, 1998; Jainta, Blythe, & Liversedge, 2014; Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986).

Several studies have investigated the mechanisms behind these differences in monocular and binocular reading performance. For example, Johansson, Pansell, Ygge and Seimyr (2014) conducted a study where sentences were presented binocularly or monocularly with three levels of contrast: 40%, 20% and 10%. They found that while reduced contrast resulted in increased fixation durations in both presentation conditions, the effect was more adverse in the monocular condition at lower contrast. That is, the binocular advantage increased with reduced contrast. Other research findings suggest that binocular advantages cannot be entirely attributed to changes in the visual quality of the text that result from switching from binocular to monocular presentation, such as reductions in contrast. Rather, these advantages may occur as a result of reduced efficiency in the word identification system when visual presentation is monocular relative to binocular (Jainta, Nikolova, & Liversedge, 2017).

Some studies have also shown that binocular vision influences not only the speed with which words are identified in foveal vision, but also the efficiency with which readers process upcoming, parafoveal text, prior to direct fixation. For example, Nikolova, Jainta, Blythe and Liversedge (2017) compared sentence reading performance in three different dichoptic gaze-contingent moving-window presentation conditions: 1) when only the fixated word (word *N*) was monocular and all other text was binocular; 2) when only words to the left of fixation (word *N-1* and beyond) were monocular and all other text was binocular; and 3) when only words to the right of fixation (word *N+1* and beyond) were monocular and all other text was binocular. We found that reading performance was largely unaffected in the first two conditions, but a considerable disruption to reading was observed when text to the right of fixation was monocular, even if the fixated word itself was binocular. We concluded that, during reading, binocular vision plays an important role for parafoveal pre-processing in reading. It is not yet clear, however, which particular aspects of parafoveal pre-processing benefit from binocular vision. Our main objectives in the present experiment were: 1) to quantify the spatial extent of parafoveal binocular visual input which is needed for uninterrupted reading; and 2) to establish whether binocular parafoveal visual input to the right of fixation is necessary for accurate saccadic targeting to, or for efficient pre-processing of, text to the right of fixation, or both.

Over the past 40 years, a large number of studies has investigated parafoveal pre-processing in reading using different gaze-contingent presentation techniques (McConkie & Rayner, 1975, 1976; Rayner, 1975), which allow the experimenter to manipulate in real-time the amount and/or type of printed information which is available around the point of fixation, contingent on fixation position. Using the gaze-contingent moving window paradigm, researchers have shown that in languages which are read from left to right, the perceptual span (the amount of useful information that can be extracted during a single fixation) extends from about 3-4 characters to the left of fixation (approximately the beginning of the fixated word) to about 13-14 characters to the right of fixation (approximately 2 words to the right of the fixated word; Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner, 1986; Rayner, Castelhano, & Yang, 2009; Schotter, Angele, & Rayner, 2012). The fact that readers require this information in order to process text efficiently is an indication that, during natural sentence reading, gaze location and attention do not necessarily coincide: a reader may be fixating on one word but processing and planning a saccade towards an upcoming word. This is also a core theoretical assumption of the most influential models of eye movement control during reading (E-Z Reader, Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; SWIFT, Engbert, Nuthmann, Richter, & Kliegl, 2005).

Importantly, readers undoubtedly benefit from this ability to attend to and pre-process parafoveal text prior to direct fixation. This has been demonstrated by a large number of studies using the gaze-contingent boundary paradigm (Rayner, 1975), in which an invisible boundary is placed in a sentence, usually in the blank space before a target word. The target word is then manipulated in some way (e.g., masked, misspelled, substituted with a different word, etc.). This experimentally manipulated preview of the target is available for the reader up to the point where they reach the pre-target word, but as soon as their eyes cross the invisible boundary, a display change is triggered and the correct version of the target word is presented. Thus, any manipulation of the target word is only ever available in parafoveal vision, as readers are not typically able to detect the display change (though see Slattery, Angele, & Rayner, 2011; Angele, Slattery, & Rayner, 2016). This experimental technique is among the most widely used in reading research and it has been extensively employed to study parafoveal pre-processing in reading (Rayner, 2014; Schotter et al., 2012; Vasilev & Angele, 2017).

One of the most robust and uncontroversial findings to have emerged from gaze-contingent boundary studies is that of a *preview benefit* effect, or shortened fixation times on a word for which valid preview information was available in the parafovea, prior to direct fixation (Rayner, 1998, 2009; Rayner, White, Kambe, Miller, & Liversedge, 2003; Vasilev & Angele, 2016). The critical importance of parafoveal pre-processing was compellingly demonstrated in a series of disappearing text studies (Liversedge, Rayner, White, Vergilino-Perez, Findlay, & Kentridge, 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, White & Liversedge, 2006). The authors found that if the fixated word (henceforth referred to as word *N*) was masked or disappeared 60 ms after fixation onset, reading proceeded without interruption, whereas if the word to the right of the fixated word (henceforth referred to as word *N+1*) disappeared during fixation on word *N*, reading performance was considerably disrupted. These findings suggest that during reading, while word identification processes are more efficient inside foveal vision than outside it (Bouma, 1973; Lee, Legge, & Ortiz, 2003), parafoveal pre-processing, to a very large degree, plays a critical role in fluent reading.

One important but under-investigated factor that contributes to a reader's ability to efficiently pre-process parafoveal text is the availability of binocular visual input to the right of fixation. In fact, Nikolova et al.'s (2017) findings are reminiscent of the abovementioned disappearing text studies, in that a significant cost to reading was observed when parafoveal text was presented monocularly. But while it is apparent that removing binocular visual input to the right of fixation hinders fluent reading, the underlying mechanisms of that effect are not well understood. In order to explore them, it is necessary first of all to consider the ways in which parafoveal text informs normal sentence reading. Research has suggested that parafoveal text to the right of fixation in reading is used for two main purposes with respect to eye movement control: to guide *where* the eyes move, and *when* the eyes move. The *where* decision relates to saccadic targeting: while a reader is fixating on word *N* (and processing it in foveal vision), they are able to direct their attention to upcoming text and accurately target their next saccade to a word in the parafovea (typically, but not always, word N+1). Evidence for this comes from the fact that readers of English – as well as other languages where individual word units are visually salient – make use of word length information and inter-word spacing cues in the parafovea (Inhoff, Liu, Starr & Wang, 1998; Morris, Rayner, & Pollatsek, 1990; Paterson & Jordan, 2010; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner, Fischer, & Pollatsek, 1998). This coarse, low spatial frequency, visual information is used to guide the eyes towards the preferred viewing location (PVL, Rayner, 1979) – slightly to the left of the centre of a word.

While parafoveal information is undoubtedly used for optimal saccadic targeting, it can also be used to guide *when* the eyes move by aiding word recognition processes. Readers can integrate information obtained from parafoveal previews with information obtained during direct fixation (Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1975). For example, they can extract orthographic (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; White, Johnson, Liversedge, & Rayner, 2008) and phonological (Ashby & Rayner, 2004; Liu, Inhoff, Ye, & Wu, 2002; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992) information from the parafovea in order to aid lexical identification during direct fixation. Recent findings have also indicated that syntactic context can also influence parafoveal word recognition by generating grammatical expectations for upcoming words (Brothers & Traxler, 2016). There is also some evidence to suggest that readers may be able to access semantic information in the parafovea. For example, Schotter and Jia (2016) and Veldre and Andrews (2016) recently observed a benefit from previews that were visually dissimilar from the target word, but were semantically related and plausible from the preceding sentence context. Since parafoveal information in reading can be used both to facilitate non-lexical saccadic targeting processes (e.g. the time required to select the next target) and to aid word recognition processes, it is now important to establish which of these two functions is reliant on binocular visual input in order to operate efficiently. A disruption in either – or both – could potentially explain the effects observed by Nikolova et al. (2017). If monocular visual input to the right of fixation causes increased difficulty for saccadic targeting processes, or if it reduces the efficiency of pre-processing of parafoveal text for the purposes of word recognition, then an overall disruption to reading would be observed, and that disruption might be accompanied with a disruption in saccade parameters.

We developed a version of the dichoptic gaze-contingent moving window technique introduced by Nikolova et al. (2017) and applied it to the investigation of parafoveal pre-processing during sentence reading. We created three gaze-contingent conditions for parafoveal text. In each of these conditions, the fixated word was always entirely binocular, but the amount of binocular text to the right of the fixated word varied on a fixation-by-fixation basis: 1) one binocular character, 2) one binocular word, or 3) two binocular words. We compared the different binocular moving window conditions with entirely binocular and entirely monocular control presentations.

To reiterate, our first objective was to determine the spatial extent of the parafoveal region in which a binocular input is necessary for undisrupted reading, by identifying the experimental condition in which reading behaviours reach asymptote performance (when compared against the full binocular condition). We predicted that increasing the amount of binocular information to the right of fixation available for parafoveal pre-processing would improve reading performance, similar to previous findings (Jainta et al., 2014, 2017; Nikolova et al., 2017).

Our second objective was to determine whether saccadic targeting, or lexical processing, or both, were the primary mechanism via which binocular vision might influence reading performance. In one case, if the disruption to fluent reading from monocular parafoveal input were caused by the reduced efficiency of word identification processes then, under conditions of insufficient binocular parafoveal input, we would expect to observe an early effect on local-level measures of word processing (e.g., first fixation duration, gaze duration). Processes related to the identification of words are the primary "engine" that drives the eyes forward, according to the most influential computational models of eye movement control in reading (Engbert et al., 2005; Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003).

These effects on word processing, when summed across all of the words in a sentence, would also be expected to contribute to an overall increase in sentence reading times.

Alternatively, if the disruption to reading associated with monocular parafoveal input were primarily caused by oculomotor factors related to saccadic targeting, then we would expect to see these effects in measures of saccadic targeting accuracy. Such disruptions might result from the fact that visual acuity in the parafovea is considerably reduced compared to foveal vision (Rayner, 1998), and relying on one parafoveal visual input instead of two (monocular vs. binocular reading) may prove an additional source of difficulty for accurately selecting potential parafoveal saccadic targets (e.g., specific landing positions within words). Indeed, it has been demonstrated that, during reading, dynamic adjustments in saccadic targeting can occur and can vary as a function of parafoveal pre-processing (Liu, Reichle, & Li, 2014). If this were the case, then restricting binocular input to the right of fixation would affect saccadic landing positions, as well as affecting other key characteristics of saccades such as duration, amplitude and peak velocity (Leigh & Zee, 2006).

Finally, it is important to note that these two sets of predictions are not mutually exclusive. Indeed, parafoveal information is crucial to fluent reading because it influences the decision of both where and when to move the eyes (McConkie, Kerr, Reddix, & Zola, 1988). It may be the case, therefore, that binocular vision provides advantages for both word processing and saccadic targeting. Thus, restricting parafoveal binocular visual input would be expected to influence both word processing measures and saccadic targeting measures.

2. Method

2.1. Participants

Participants were 20 native English speakers from the University of Southampton (6 males, 14 females; average age = 21.2 years, range = 18-27 years). Participants took part in the experiment in exchange for Psychology course credits or payment at the rate of £6 per hour. All participants had normal or corrected to normal vision (with soft contact lenses) and no diagnosed visual or reading difficulties. To confirm that participants had normal vision, prior to the experiment we tested their visual acuity both binocularly and separately for each eye using a Landolt-C acuity chart. Stereoacuity was tested using a Titmus Stereotest. There were no substantial differences in acuity between the two eyes (best-corrected acuity in each eye in decimal units was 1.0 or better at 4m). Additionally, all participants had functional stereopsis (minimal stereoacuity of 40 seconds of arc). Heterophoria was measured with a Maddox Rod test at near (33 cm). The average horizontal deviation across all participants was 1.50 prism dioptres (SD = 1.71), and only six participants had a vertical deviation, with an average of 1.28 prism dioptres (SD = 0.48). Participants were naïve to the purpose of the experiment.

2.2. Apparatus

Binocular eye movements were measured using two Fourward Technologies Dual Purkinje Image (DPI) eye trackers, which recorded the position of both eyes every millisecond (sampling rate of 1000 Hz, spatial resolution < 1 min arc). Dichoptic presentation of the stimuli was achieved through use of Cambridge Research Systems FE1 shutter goggles, which blocked the visual input received by each eye alternatively every 8.33 ms (in synchrony with a 120 Hz refresh rate of the display monitor). The shutter goggles were interfaced with the eye trackers, a Pentium 4 computer and a Philips 21B582BH 21 inch monitor. The monitor was situated at a viewing distance of 100 cm. To minimize head movements, participants leaned against two cushioned forehead rests and bit on an individually prepared bite bar.

2.3. Materials and design

Sixty sentences with neutral content were presented, as well as YES/NO comprehension questions after 25% of trials (see examples in Table 1). Sentences were presented in 14 point red uppercase/lowercase Courier New font on black background in order to minimise dichoptic cross-talk (i.e., the "bleed-through" of visual input to the occluded eye; see also Jaschinski, Jainta, & Schurer, 2006). At the specified viewing distance, each letter subtended 0.25 deg of visual angle. On average, each sentence contained 76.63 (range = 72-86) characters. There were 12 words in each sentence, and words were between four and eight characters long (mean word length = 5.68 characters). We divided the sentences into five blocks and presented each block of twelve sentences in one of five dichoptic gaze-contingent presentation conditions: (1) all words in the sentence were binocular (full binocular control); (2) the fixated word (word *N*) and two words to the right of fixation (word *N+1* and word *N+2*) were binocular, but all other words were monocular (two-word window); (3) word *N* and word *N+1* were binocular, but all other words to the right of fixation were monocular (one-word window); (4) word *N* and the first character of word *N+1* were binocular, but other characters in word *N+1* and all other words to the right of fixation were monocular (one-character window); (5) all words in the sentence were monocular (full monocular control). A Latin Square design was used and the presentation order of blocks in different conditions was counterbalanced such that, across all participants, every sentence appeared in each condition, but no sentence was repeated for any individual participant, and each participant saw the blocks in a different order. Monocular presentations were counterbalanced across the left and right eye. It is important to point out that while we refer to the first control presentation condition above as binocular, it did not resemble typical binocular viewing where the two eyes perceive visual input simultaneously. While the same input was presented to both eyes in the binocular condition, due to the use of the shutter goggles each eye saw the stimulus alternatively, rather than simultaneously.

2.4. Procedure

The experimental procedure was approved by the University of Southampton Ethics and Research Governance Office and followed the conventions of the Declaration of Helsinki. Informed written consent was obtained from each participant prior to the start of the experiment.

After participants had agreed to take part in the experiment, tests of visual acuity and stereo-acuity were administered. We used a monocular calibration procedure to calibrate the eye-trackers (the left eye was occluded during calibration of the right eye, and vice versa). Participants were instructed to look at each of nine points on a 3x3 grid in a set sequence from the top left to the bottom right. Horizontal separation of the calibration points was 10 deg, and the vertical separation was 2 deg, relative to screen centre. Afterwards, the calibration was checked for accuracy and repeated if the Euclidian distance between the recorded eye position and the actual position of each validation point on the screen exceeded 0.06 deg of visual angle. Once both eyes had been calibrated successfully, participants completed five practice trials in order to get accustomed to the task and the experimental setup. At the end of the practice trials, a full calibration/validation run was completed once again and the experiment began.

Each trial consisted of the following sequence of events. A fixation circle appeared on the centre of the screen for 1500 ms. Afterwards, another circle appeared on the left-hand side of the screen, marking the beginning of each sentence. Participants were required to fixate this circle. After 1000 ms, the fixation circle disappeared and a sentence was presented. Once the participant had finished reading the sentence, they pressed a button on a button box to initiate the presentation of the following sentence. Comprehension questions were presented after 25% of the sentences and participants used the button box to make a YES/NO response. Calibration was checked for accuracy after every four sentences and the eye trackers were recalibrated if necessary. A full calibration/validation run was performed before each new block of 12 sentences was presented. Participants were given a break halfway through the experiment, as well as additional breaks whenever required. The entire procedure lasted for approximately 45-60 minutes.

2.5. Data Analyses

Custom-designed software was used for the data analyses. Fixations and saccades were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995) or artefacts due to blinks. We excluded trials with track loss, fixations longer than 1200 ms or shorter than 80 ms, as well as the first and the last fixation on each trial (<2% of fixations).

From the separate signals of the two eyes, we calculated the horizontal and vertical conjugate eye components [(left eye + right eye)/2] and the horizontal and vertical disconjugate eye components [left eye – right eye]. For all the analyses of fixation disparity and vergence drift we only analysed fixations where the measured fixation disparity fell within 2.5 standard deviations of the mean for each participant in each condition (<1% of fixations were excluded). Thus, we were able to exclude any atypically large fixation disparities (e.g., bigger than 2 deg), which may have occurred as a result of tracker error. At the same time, basing the exclusion criteria around the performance of each participant in each condition, we retained the typically larger fixation disparities observed in monocular reading due to increased divergence of the occluded eye.

We computed Linear Mixed-effect Models (LMMs) using the *lmer* function from package lme4 (version 1.1-11, Bates, Maechler, Bolker, & Walker, 2014) in R, an open-source programming language and environment for statistical computation (R Development Core Team, 2012). We used the lmerTest package to compute *p*-values (Kuznetsova, Brockhoff, & Christensen, 2016). Values for first fixation duration and gaze duration were log-transformed prior to running the models, due to the skewed right tails of their distributions. We report regression coefficients (*b*s), which estimate the effect size relative to the intercept, as well as standard errors (*SE*s) and *t*-values. Given the number of participants and observations per participant, the *t*-distribution will approximate the *z*-distribution; therefore we consider as statistically significant those cases where $|t| > 1.96$ (Baayen, Davidson & Bates, 2008). For binary dependent variables such as regression probability we used generalised linear mixed models (*glmer* function from package lme4) and report the Wald *z* and its associated *p*-value.

3. Results

3.1. The spatial extent of the binocular advantage in parafoveal preview

First, we consider results that are relevant to our first objective: to determine the spatial extent of binocular input to the right of fixation that is needed in order for reading behaviour to reach asymptote. We examine both global reading performance across the entire sentences, as well as local measures of word processing.

3.1.1. Global analyses

Response accuracy to the comprehension questions was uniformly high (M = 97%, range = 89% - 100 %). Descriptive statistics for all fixation time measures are presented in Table 2. As expected, we found sentence reading times were longer in the full monocular control condition than the full binocular control condition (b = 225.67, SE = 75.16, t = 3.01, p = .008). This is in line with previous findings (Jainta et al., 2014, 2017; Jainta & Jaschinski, 2012; Nikolova et al., 2017), suggesting that reading is most efficient when binocular input is available throughout the sentence and least efficient during monocular presentation. Importantly, however, sentence reading times were not significantly different than those in the full binocular control condition either when word *N+1* was binocular (b = -75.72, SE = 56.06, t = -1.35, p = .19), or when both word *N+1* and word *N+2* were binocular (b = -105.55, SE = 63.52, t = -1.66, p = .12). The critical difference was observed when parafoveal binocular input was only available for the first character of word *N+1*. In that condition, sentence reading times were significantly longer than in the full binocular control condition (b = 138.13, SE = 60.57, t = 2.28, p = .03). In other words, participants were slower to read sentences where parafoveal binocular input was restricted to the first character of word *N+1*, but reading times were similar to the binocular control condition when the whole of word *N+1* was binocular (see *Figure 1*). [1]

3.1.2. Local analyses

Next, we considered two local measures of word processing: first fixation duration (FFD; the duration of the initial, first-pass fixation on a word) and gaze duration (GD; the sum of first-pass fixations on the word before the eyes move onto another word in the sentence). We did not have a target word in each sentence; rather, these local measures were calculated for each word in the sentence. We wished to examine in more detail the locus of the effect of monocular parafoveal preview on overall sentence reading times, given that monocular preview did not affect the overall pattern of inspection, to determine whether this did indeed result from reduced efficiency of word processing.

We found that FFDs were inflated in the full monocular condition relative to the full binocular condition ($b = 0.08$, $SE = 0.02$, $t = 5.36$, $p < .001$), and were also longer in the one-character window condition ($b = 0.05$, $SE = 0.01$, $t = 3.85$, $p < .001$). There was no significant difference in FFD between binocular reading and the other two moving window conditions (one-word window *N+1*: $b = -0.02$, $SE = 0.01$, $t = -1.46$, $p = .12$; two-words window: $b = -0.02$, $SE = 0.02$, $t = -1.29$, $p = .13$). Once again, the latter two conditions were not significantly different from each other, indicating no additional

[1] We also investigated regression probability and number of fixations made per sentence. We observed no significant differences in regression probability between the full binocular and monocular control conditions, or between the full binocular control condition and the three moving window conditions. Similarly, with the number of fixations made per sentence, we found no differences across conditions. There were also no differences in first-pass skipping rates across conditions. It seems, therefore, that although cognitive processing of the text was slower when parafoveal preview was monocular, this did not cause the reader to alter their overall pattern of inspection of the text.

benefit of binocular input for word *N+2*, as well as word *N+1*.; thus, FFD in the one-word window condition was not significantly different from FFD in the binocular control condition.

For GD, the pattern of results was similar to that for FFD. GDs in the full monocular condition were about 35 ms longer than those in the full binocular condition (b = 0.07, SE = 0.02, t = 3.58, p < .01). In addition, there was a marginally significant 16ms increase in GD in the one-character window condition relative to the full binocular baseline (b = 0.04, SE = 0.02, t = 1.92, p = .07). Again, there were no significant differences in GD between the one-word window and two-word window conditions and the binocular baseline (ts < 1).

3.2. The locus of the binocular advantage in parafoveal preview

Recall that our second objective was to determine whether disruptions to reading from monocular parafoveal input could be attributed to targeting of binocular saccades towards a monocular parafoveal input, or to a disruption of word identification processes for parafoveal text. The analyses reported in Section 3.1 clearly demonstrated that insufficient binocular parafoveal preview was available then disruption to word-level processing occurred, as indexed by reading time measures. It remains possible, however, that saccadic targeting might also be disrupted by monocular parafoveal preview.

3.2.1. Binocular saccadic programming

For the next part of the analysis, we only considered progressive saccades. Observed descriptive values for saccade landing positions, amplitudes, durations, and peak velocities can be found in Table 3. Firstly, we measured the accuracy of saccades by analysing the landing position of each eye separately as a function of presentation condition, target word length and launch site distance. Mean landing positions are plotted in *Figure 2*. On average, the right eye tended to land less than half a character space (0.11 deg) further to the right than the left eye ($b = 0.35$, $SE = .11$, $t = 3.12$, $p < .001$). We did not, however, find this pattern to be different across presentation conditions. In other words, there was no significant influence of presentation condition on the relative landing positions of the two eyes (all ps > .18). In fact, the most reliable predictors of saccadic landing positions were target word length ($b = -0.16$, $SE = .02$, t = 8.79, $p < .001$) and launch site distance ($b = -1.37$, $SE = 0.50$, $t = 2.77$, $p = .006$). These results suggest that participants tended to target a position about 0.04 deg further to the left of the centre of a word if it was long, and about 0.34 deg further to the left of the word centre if the launch site was more distant.

Next, we analysed saccade amplitude (reported in degrees of visual angle), duration (reported in ms), and peak velocity (reported in deg/sec). We found that the right eye's saccade amplitude exceeded the left eye's saccade amplitude, and the difference was statistically reliable ($b = 0.04$, $SE = 0.02$, $t = 2.17$, $p = .01$). Additionally, we observed a small effect of condition on overall saccade length and duration. In the one-character window condition, saccade amplitude for both eyes was slightly reduced ($b = -0.07$, $SE = 0.03$, $t = -2.10$, $p = .04$) and saccades were marginally shorter in duration ($b = -1.23$, $SE = 0.63$, $t = -1.95$, $p = .07$) relative to the full binocular control condition. In the one-word window condition, saccade amplitude was reduced ($b = -0.06$, $SE = 0.03$, $t = -2.63$, $p = .01$), but there were no significant differences in duration ($t < 1$) relative to the full binocular condition. No other presentation conditions influenced either saccade duration or saccade length (all ts < 1). Critically, we did not find any interactions between eye (left vs. right) and condition in any of the reported analyses on saccade amplitude. Thus, manipulation of monocular parafoveal preview did not influence the binocular coordination of saccades in terms of either amplitude or duration.

Finally, we analysed saccade peak velocity. This was computed by taking the derivative of the position response recorded by the eye trackers using a Savitzky-Golay 2-point central difference algorithm with the *savitzkyGolay* function from the prospectr package in R (Stevens & Ramirez-Lopez, 2014). The peak velocity of the left-eye and right-eye saccades were quantified as the maximum value within each movement. We computed a linear mixed-effect model with the peak velocity of all forward saccades as a dependent variable and tracked eye (left or right) and presentation condition as fixed effects. We found that, across all presentation conditions, the right eye's peak velocity was approximately 89 deg/sec higher than the left eye's peak velocity (b = 88.78, SE = 1.48, t = 59.97, p < .001). Once again, this effect did not vary as a function of condition, suggesting that the amount of binocular input available in the parafovea did not influence the programming of saccades. Instead, regardless of presentation condition, in all forward saccades the abducting eye (right) made faster movements than the adducting eye (left).

4. Discussion

In the present experiment, we investigated the extent to which parafoveal pre-processing requires a binocular visual input in order to operate efficiently. Below we discuss our findings with relation to our two key objectives: 1) to determine the spatial extent of parafoveal binocular input that is needed for reading behaviours to reach asymptote; and 2) to determine whether binocular parafoveal advantages can be attributed to enhanced saccadic targeting processes, a facilitation in the efficient extraction of information from upcoming text for the purposes of word recognition, or both. Our results demonstrated that while our experimental manipulation clearly influenced reading time measures, reflecting a reduced efficiency in word processing, there was no such influence on measures of binocular saccadic programming. We now discuss these results in relation to both our objectives.

In terms of the spatial extent of parafoveal binocular input that is necessary for fluent reading, our results indicated that reading performance reached asymptote when word *N+1* was entirely binocular in the parafovea. In fact, we found that no benefit to processing speed was obtained by presenting just the first character of word *N+1* binocularly.

These results have clear relevance for understanding the perceptual span during binocular and monocular reading. Previous research has shown that the perceptual span in English extends from about the beginning of the currently fixated word to about two words to the right of fixation. For example, Rayner et al. (2009) found that for skilled young adult readers, if only one word to the right of word *N* was available in a moving-window paradigm then reading speed was reduced, but if two words (word *N+1* and word *N+2*) were available then reading speed did not differ from that observed in the no-window condition. That is, readers benefitted from having about three words available during each fixation: the fixated word and two words to the right, for reading in English. We have now shown that, with respect to binocular visual input, only one word to the right of fixation needs to be presented to both eyes in order for reading to proceed uninterrupted. The fact that no additional benefit was obtained from a binocular preview of word *N+2* is likely an indication that the region within the perceptual span for which binocular visual input is crucial includes word *N* and word

N+1. In addition, our findings indicate that the first character of a word, while particularly important for lexical identification during both direct fixation and parafoveal pre-processing (Pagan et al., 2015; White et al., 2008), may not be sufficient to allow for binocular advantages to be obtained from parafoveal text.

As mentioned previously, our results indicated that it was word processing, rather than binocular saccadic targeting, which suffered when the spatial extent of parafoveal binocular input was reduced. To understand this effect, it is important to consider the widely accepted finding that, during normal reading, gaze location and attention do not always coincide. Previous work has shown that orthographic processing of words can begin prior to those words being directly fixated (Balota, Pollatsek & Rayner, 1985; Binder, Pollatsek & Rayner, 1999). In fact, according to Miellet and Sparrow (2004), parafoveal preview benefit can (at least to some extent) be attributed to partial activation of the target word's lexical entry prior to direct fixation. The degree of activation depends on the degree of similarity between preview and target. For instance, a visually identical preview can be expected to elicit maximal orthographic and phonological activation of the target word's lexical entry prior to direct fixation. In the current study, all previews were identical to the actual words in in terms of the content of the printed stimulus: we had no letter substitutions or letter masking. The only difference between a word and its parafoveal preview was whether all characters of the preview were binocular in the parafovea prior to direct fixation. Our results clearly indicated that a binocular advantage was only obtained from binocular preview of the whole of word *N+1*. Our findings suggest, therefore, that a monocular parafoveal preview is not sufficient to activate the target's lexical entry and facilitate processing upon direct fixation.

Existing evidence indicates that the binocular advantage to parafoveal pre-processing of words cannot be explained by changes in the visual quality of the preview. Our previous work has already demonstrated that a reduction in contrast is not what drives binocular advantages during foveal processing in reading (Jainta et al., 2017). Reducing the contrast of an entire sentence to an extent that resembles natural contrast reductions that arise from switching visual presentation from binocular to monocular does not influence reading performance or the speed of lexical access. Furthermore, it is only much more drastic visual degradation manipulations that can influence the ability to obtain a preview benefit (e.g. spatial frequency manipulations, Patterson, McGowan, & Jordan, 2014; contrast reduction manipulations below 40%, Jainta et al., 2017; Sheridan & Reingold, 2013). It is evident that such dramatic changes in visual quality do not occur when switching from binocular to monocular presentation (as can be easily demonstrated by covering one eye while reading this text). A more feasible explanation for the observed effects may be, therefore, that monocular parafoveal text poses a challenge for word identification processes prior to direct fixation by making the extraction of useful information from the perceptual span less efficient than during binocular reading.

This explanation is also supported by our analysis of saccadic parameters across conditions, which showed little influence of presentation condition on binocular characteristics of saccade amplitude, landing position, duration or peak velocity. That is, participants were able to target the PVL (slightly to the left of the word centre) in all presentation conditions. In fact, the most significant sources of influence on saccadic landing position were launch site distance and target word length, these effects being well-established within the literature (McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979). Furthermore, we replicated previous findings of muscle imbalance and transient divergence during binocular saccades in adults with normal vision, as reported by Collewijn, Erkelens, and Steinman (1988), Vernet and Kapoula (2009) and Yang and Kapoula (2003). Critically, however, our findings indicate that denying binocular visual input for the word to the right of fixation does not affect the physiological mechanisms responsible for maintaining typical binocular coordination. Instead, parafoveal monocular input appears to exert its influence on reading times by disrupting readers' ability to extract the information necessary for facilitating efficient word identification.

It is important to point out that the present study did not provide a manipulation of the orthographic nature of the preview of word *N+1*. Such a manipulation could be used in future work to establish whether reading times differ for accurate and inaccurate orthographic previews under monocular presentation conditions. If compared with an investigation of skipping rates in binocular and monocular reading given the lexical frequency of word *N+1,* an orthographic manipulation could help to further disentangle lexical and non-lexical processes that may play a part in the binocular advantage. For instance, it may be the case that a non-lexical process (for example, the time required to select the next word saccade target or programme the saccade) might result in longer reading times when there are monocular previews of word *N+1*, without affecting saccade metrics.

The findings of the present study are somewhat similar to results reported by Rayner et al. (2006) who found, in their disappearing text experiment, that participants targeted the PVL both when word *N+1* disappeared 60 ms after fixation onset on word *N*, and when it was masked with Xs. In the case of disappearing text, when word *N+1* had either no preview (disappearing condition) or an invalid preview (X mask), participants were still able to use visual information about the width of the blank space/mask and the surrounding word in order to target their saccades appropriately. They did not, however, have the opportunity to extract any linguistic cues from parafoveal preview that would have allowed for pre-processing of the word's cognitive representation, which resulted in an overall disruption to reading. In the present experiment, we showed that information about word *N+1* must be available to both eyes simultaneously in order for efficient word identification to take place.

5. Conclusions

We report a gaze-contingent dichoptic moving window experiment in which the spatial extent of parafoveal binocular information available to readers was varied on a fixation-by-fixation basis. We observed parafoveal binocular advantages when word *N+1* was entirely binocular, but all other text to the right of fixation was monocular. The disruption caused by presenting parafoveal text monocularly could not be counteracted if only the first character of word *N+1* was binocular, and no additional benefit in performance was observed when both word *N+1* and word *N+2* were binocular. Critically, we found these effects on fixation times but not on saccadic parameters. We conclude, therefore, that while a monocular visual presentation does not disrupt the ability to use parafoveal visual input for accurate saccadic targeting, it can prevent readers from efficiently extracting sufficient information during pre-processing to facilitate word recognition during subsequent direct fixation.

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Tables and Figures

Table 1.

Examples of sentences and comprehension questions used in the experiment.

Sentence	Alice waters those exotic white flowers every five days during warmer months.
Question	*Does Alice water the plants regularly in summer? (Yes/No)*
Sentence	That greedy mayor made plans without caring about people from remote areas.
Question	*Was the mayor considerate of people in remote areas? (Yes/No)*
Sentence	They could hardly hear Lilly’s soft voice behind that thick wooden door.
Question	*Did Lilly have a loud, booming voice? (Yes/No)*

Table 2.

Means and standard deviations for fixation durations and sentence reading time across conditions (in milliseconds).

	Binocular	Word N+2 Binocular	Word N+1 Binocular	1st char of Word N+1 Binocular	Monocular
First Fixation Duration	250	244	243	262	267
(SD)	*77*	*77*	*70*	*76*	*81*
Gaze Duration	296	295	304	311	323
(SD)	*129*	*139*	*143*	*147*	*145*
Sentence Reading Time	2476	2386	2332	2595	2617
(SD)	*696*	*669*	*637*	*636*	*698*

Table 3.

Mean values and standard deviations for saccade duration (ms), saccade amplitude (deg), peak velocity (deg/sec) and saccade landing position (characters).[2]

	Binocular	Word N+2 Binocular	Word N+1 Binocular	1st char of Word N+1 Binocular	Monocular
Saccade duration	45 *(8)*	45 *(9)*	45 *(8)*	44 *(7)*	46 *(9)*
Saccade amplitude(R)	1.57 *(0.65)*	1.58 *(0.66)*	1.55 *(0.62)*	1.53 *(0.61)*	1.62 *(0.68)*
Saccade amplitude (L)	1.51 *(0.63)*	1.52 *(0.65)*	1.50 *(0.65)*	1.46 *(0.60)*	1.56 *(0.67)*
Peak velocity (R)	324.68 *(117.67)*	332.23 *(117.02)*	328.10 *(120.30)*	328.17 *(117.52)*	329.73 *(119.20)*
Peak velocity (L)	236.27 *(81.10)*	238.01 *(83.22)*	236.44 *(81.61)*	243.31 *(80.94)*	244.56 *(85.29)*
Landing position (R)	2.47 *(1.34)*	2.51 *(1.40)*	2.41 *(1.34)*	2.42 *(1.32)*	2.40 *(1.35)*
Landing position (L)	2.19 *(1.31)*	2.38 *(1.37)*	2.35 *(1.36)*	2.31 *(1.32)*	2.25 *(1.37)*

[2] Because the right eye was the "leading" eye, and triggered the display change, the presented values are for cases where the right eye sees the entire sentence, and the left eye sees either the entire sentence, partial input or no input (in the monocular condition).

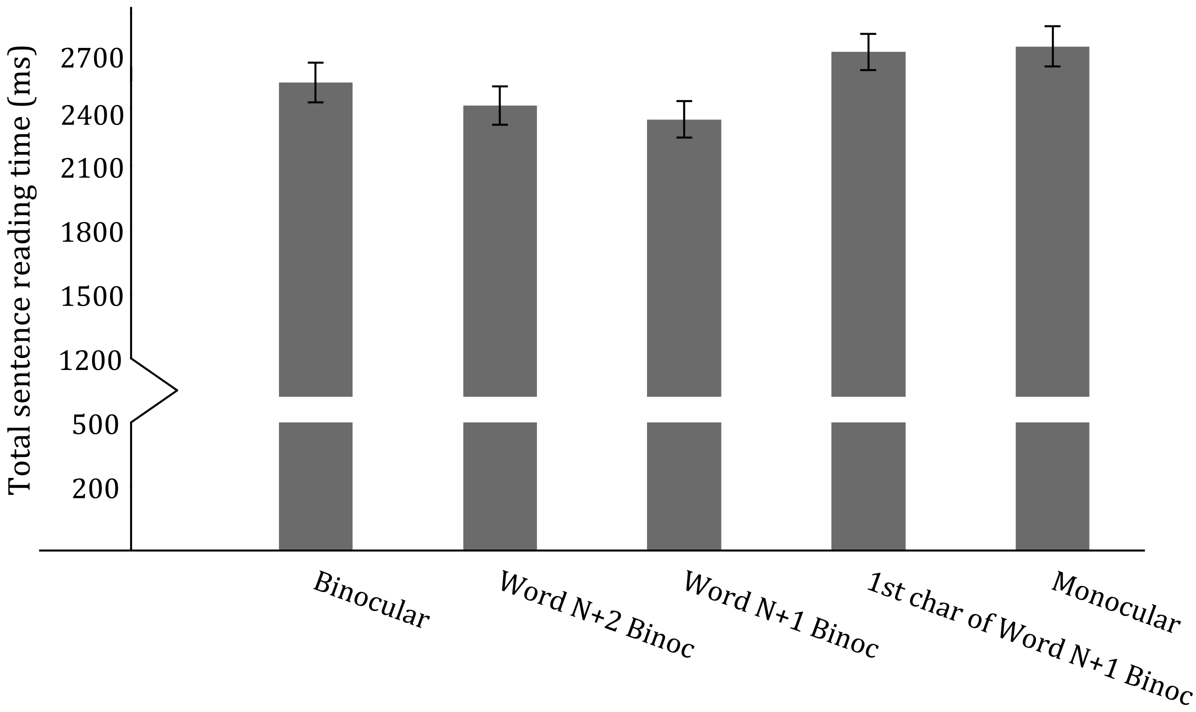

Figure 1. Mean total sentence reading time in the five different presentation conditions (the bars represent standard error).

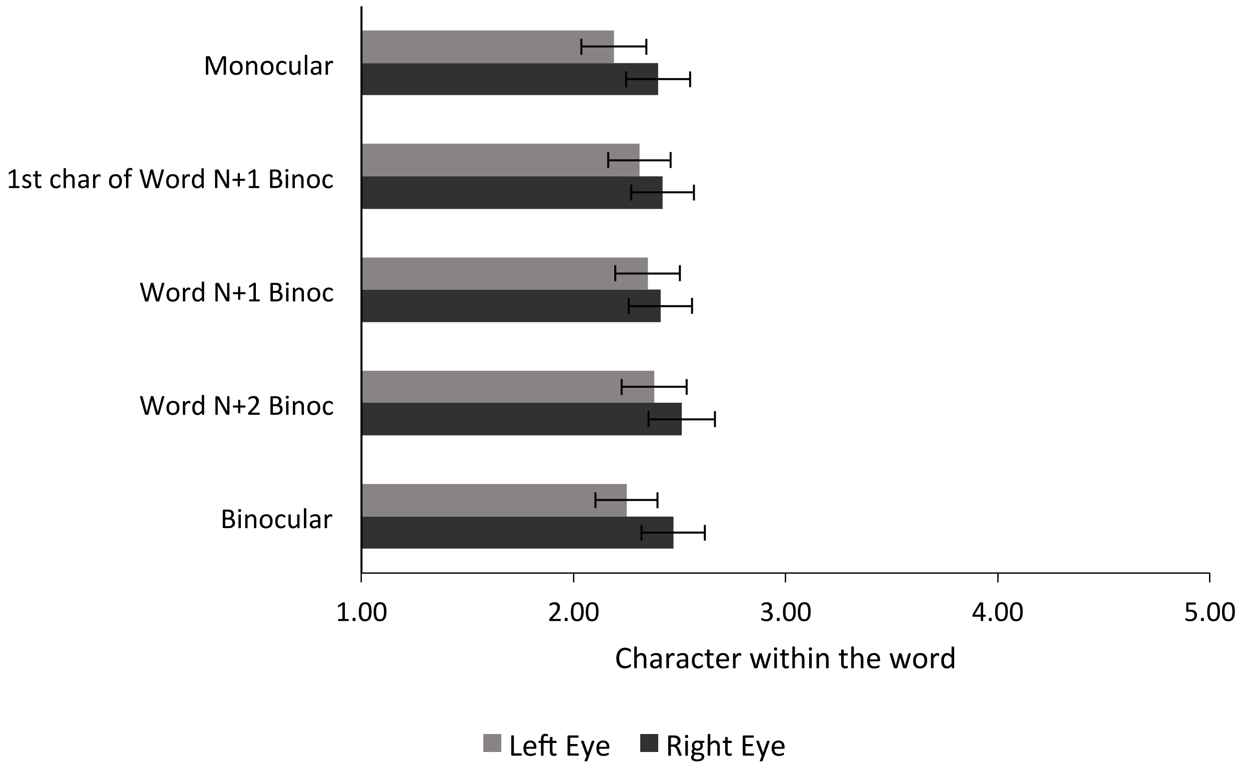

Figure 2. Mean landing positions of the left and right eye in all presentation conditions (in characters).