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Title	Using a dichoptic moving window presentation technique to investigate binocular advantages during reading
Type	Article
URL	<a href="https://clock.uclan.ac.uk/22338/">https://clock.uclan.ac.uk/22338/</a>
DOI	<a href="https://doi.org/10.1037/xhp0000296">https://doi.org/10.1037/xhp0000296</a>
Date	2017
Citation	Nikolova, Mirela, Jainta, Stephanie, Blythe, Hazel I. and Liversedge, Simon Paul (2017) Using a dichoptic moving window presentation technique to investigate binocular advantages during reading. <i>Journal of Experimental Psychology: Human Perception and Performance</i> , 43 (2). pp. 265-280. ISSN 0096-1523
Creators	Nikolova, Mirela, Jainta, Stephanie, Blythe, Hazel I. and Liversedge, Simon Paul

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<https://doi.org/10.1037/xhp0000296>

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Using a dichoptic moving window presentation technique to investigate binocular advantages during reading

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## Abstract

Reading comes with a clear binocular advantage, expressed in shorter fixation times and fewer regressions in binocular relative to monocular visual presentations. Little is known, however, about whether the cost associated with monocular viewing derives primarily from the encoding of foveal information or in obtaining a preview benefit from upcoming parafoveal text. In the present sentence reading eye tracking experiment, we used a novel dichoptic binocular gaze-contingent moving window technique to selectively manipulate the amount of text made available to the reader both binocularly and monocularly in the fovea and parafovea on a fixation-by-fixation basis. This technique allowed us to quantify disruption to reading caused by prevention of binocular fusion during direct fixation of words and parafoveal pre-processing of upcoming text. Sentences were presented (1) binocularly; (2) monocularly; (3) with monocular text to the left of fixation (4) with monocular text to the right of fixation; or (5) with all words other than the fixated word presented binocularly. A robust binocular advantage occurred for average fixation duration and regressions. Also, while there was a limited cost associated with monocular foveal processing, the restriction of parafoveal processing to monocular information was particularly disruptive. The findings demonstrate the critical importance of a unified binocular input for the efficient pre-processing text to the right of fixation.

1           Reading is a sophisticated uniquely human skill that requires the simultaneous  
2 operation and coordination of visual, oculomotor, attentional and linguistic processing  
3 systems. Recently, it has also been shown that binocular vision provides clear  
4 advantages for reading (Heller & Radach, 1998; Jainta, Blythe, & Liversedge, 2014;  
5 Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986). What is less clear,  
6 however, is how binocular vision and binocular coordination might influence foveal  
7 and parafoveal processing in reading, and, consequentially, what part they might play  
8 in the decision of where and when to move the eyes. In the present study, we  
9 address this issue by exploring how binocular advantages unfold throughout  
10 sentence reading, in relation to both parafoveal pre-processing as well as foveal  
11 processing of words. In the following sections, we describe the theoretical relevance  
12 of this work in relation to the influences of foveal and parafoveal information on  
13 oculomotor control decisions, the allocation of attention during reading, and the  
14 contribution of binocular coordination and binocular advantages to text processing  
15 prior to and during direct fixation. We then outline the design of a novel binocular  
16 dichoptic gaze-contingent eye tracking experiment, and explain how it allows the  
17 selective study of the influence of binocular vision processes during different stages  
18 of text comprehension.

### 19           **Oculomotor control and the allocation of attention during reading**

20           During reading, the eyes typically perform a sequence of fast ballistic  
21 movements known as saccades, which serve to direct the gaze from one word to  
22 another (i.e. version eye movements). Saccades are followed by brief periods of  
23 relative stillness known as fixations (200-300ms on average in reading), during which  
24 visual information is encoded (Raney, Campbell, & Bovee, 2014; Rayner, 1998).  
25 These eye movements are a reflection of the ongoing cognitive processes underlying

26 reading (Liversedge & Findlay, 2000). To a very significant degree, the psychological  
27 processes related to visual and linguistic processing of text determine the two most  
28 important aspects of eye movement control in reading: when and where to move the  
29 eyes. A number of research findings have demonstrated that the availability of both  
30 foveal (directly fixated) and parafoveal (upcoming in the direction of reading)  
31 information is crucial for fluent reading, and that each type of information plays a  
32 distinct role in eye movement control (Rayner & Pollatsek, 1987, 1989; Rayner,  
33 Pollatsek, Ashby & Clifton, 2012). Characteristics of the foveal word such as its  
34 length, its lexical frequency, predictability from context and semantic compatibility  
35 with the preceding text influence the speed with which it is processed (i.e. fixation  
36 duration), and therefore the decision of when to move the eyes away from it and onto  
37 another word in the sentence (Ehrlich & Rayner, 1986; Hyönä and Olson, 1995;  
38 Inhoff & Rayner, 1986; Liversedge, Rayner, White, Vergilino-Perez, Findlay, &  
39 Kentridge, 2004; Rayner & Duffy, 1986; Rayner, Liversedge, & White, 2006; Rayner,  
40 Liversedge, White, & Vergilino-Perez, 2003; Rayner, Yang, Schuett, Slattery, 2014;  
41 White, 2008; see Hyönä, 2011 & Rayner, 1998, for reviews). Interrupting foveal  
42 processing by visually degrading fixated words or masking them at fixation onset  
43 results in severe disruptions to reading, indicating the critical importance of a high-  
44 quality visual input in the fovea for text comprehension (Fine & Rubin, 1999; Legge,  
45 Ahn, Klitz, Luebker, 1997; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

46         When exploring the decision of where to move the eyes, it is important to first  
47 consider the allocation of attention during reading. Early research by McConkie and  
48 Rayner (1975, 1976) and Rayner (1975) examined the size of the perceptual span in  
49 reading, or the region from which readers obtain useful information during a fixation.  
50 This was done using the moving window paradigm, a gaze-contingent display  
51 change technique where a “window” of text with varying size is presented around the

52 point of fixation and information beyond it is masked or visually degraded. The  
53 window moves on a fixation-by-fixation basis, so that equivalent amounts of  
54 unmasked text are available on each fixation. Many studies have found that, for  
55 readers of English and other alphabetic languages that are read from left to right, the  
56 effective visual field extends asymmetrically from 3-4 characters to the left of fixation  
57 (approximately the beginning of the fixated word) to 14-15 characters (approximately  
58 three words) to the right of fixation (Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner,  
59 1986; Rayner, Castelhana, & Yang, 2009; Schotter, Angele, & Rayner, 2012). The  
60 notable asymmetry of the perceptual span indicates that for reading in English, as  
61 well as other languages with similar orthography, the critical parafoveal region from  
62 which most information is obtained is to the right of the fixated word (i.e.  
63 corresponding to the direction of reading). Experimental manipulations interfering  
64 with the availability of information in that region, such as reducing the number of  
65 visible characters or making the parafoveal word disappear after fixation onset on the  
66 preceding word, have been shown to cause considerable disruptions to fluent  
67 reading (Liversedge, et al., 2004; Rayner et al., 2006; Rayner, Liversedge et al.,  
68 2003; Rayner et al., 2014). This disruption is likely the result of the visual  
69 manipulation interfering with a reader's ability to pre-process parafoveal information  
70 to the right of fixation. Indeed, a number of studies have demonstrated that prior to  
71 directly fixating a word, readers are able to extract information about its length,  
72 orthographic and phonological features and use that information in order to direct  
73 their saccades (Juhasz, White, Liversedge, & Rayner, 2008; McConkie & Rayner,  
74 1975; Pollatsek & Rayner, 1982; Rayner & Bertera, 1979). Furthermore, there is a  
75 robust preview benefit associated with uninterrupted parafoveal pre-processing. For  
76 example, when a word is masked or presented incorrectly in the parafovea,  
77 processing times for that word increase once it is directly fixated relative to when the

78 correct version is available for pre-processing (Blanchard et al., 1989; Hyönä et al.;  
79 2004; Rayner et al., 1982). Therefore, uninterrupted pre-processing of information to  
80 the right of fixation is a core characteristic of fluent reading, as it both guides the  
81 decision of where to move the eyes and aids word identification during direct fixation.  
82 In summary, both foveal and parafoveal information appear to play a key part in the  
83 decisions of when and where to move the eyes during reading, and these findings  
84 have been incorporated into the most influential models of oculomotor control during  
85 text processing (e.g., SWIFT, Engbert, Longtin, & Kliegl, 2002; E-Z Reader, Reichle,  
86 2011; Reichle, Rayner, & Pollatsek, 2003).

### 87 **The role of binocular vision in reading**

88 Humans typically make use of both of their eyes when they read, and  
89 processes related to binocular coordination play a key role in providing a single,  
90 unified perceptual representation of written text. For most tasks at close viewing  
91 distances - including reading – high-precision binocular vision and a stable, single  
92 percept are attained via the process of fusion, which incorporates two integral  
93 components: motor and sensory fusion (Pratt-Johnson & Tillson, 2001; Schor &  
94 Tyler, 1981). Motor fusion comprises of the physiological mechanisms of vergence. A  
95 number of studies have revealed that during text processing, the two visual axes are  
96 often slightly misaligned by more than one character space (Blythe et al., 2006;  
97 Blythe et al., 2010; Jainta, Hoormann, Kloke, & Jaschinski, 2012; Liversedge et al.,  
98 2006a, Liversedge et al., 2006b, Nuthmann and Kliegl, 2009; Nuthmann, Beveridge,  
99 & Shillcock, 2014; Vernet & Kapoula, 2009). This is mainly due to transient  
100 divergence that occurs during saccades: the abducting eye typically makes a larger,  
101 faster movement than the adducting eye (Collewijn et al., 1988, Hendriks, 1996,  
102 Yang & Kapoula, 2009; Zee et al., 1992). This divergence results in fixation disparity

103 at fixation onset. Vergence eye movements (i.e. fine-grained oculomotor  
104 adjustments) are then made during fixations to counteract these disparities and to  
105 maximise the degree of correspondence between the two retinal inputs, even in  
106 reading (Jainta & Jaschinski, 2012, Jainta et al., 2010; Leigh & Zee, 2006). Sensory  
107 fusion – a neurophysiological and psychological process – serves to combine the two  
108 independent retinal representations into a single unified percept in the visual cortex  
109 as a basic step for further processing (Howard & Rogers, 1995; Worth, 1921).  
110 Sensory fusion is only possible within a limited range of fixation disparities known as  
111 Panum’s fusional area (Blythe et al., 2010; Schor et al., 1989; Steinman et al., 2000).  
112 Thus, for a large range of tasks including reading, motor fusion usually serves to  
113 reduce disparities and sensory fusion occurs when disparity falls within the functional  
114 fusional range (Jainta, Blythe, Nikolova, Jones, & Liversedge, 2014).

115         The degree to which fixation disparity and processes underlying binocular  
116 fusion play a part in oculomotor control and the pre-processing of parafoveal text  
117 during reading has been investigated in a number of recent studies. For example,  
118 Nuthmann et al. (2014) used a binocular moving window technique to explore  
119 binocular coordination when only a limited amount of text was visible to the right of  
120 fixation (i.e. reading with a binocular moving window extending from 14 characters to  
121 the left of fixation to 2 characters to the right of fixation). They postulated that under  
122 this asymmetric window condition readers might be able to unconsciously increase  
123 the magnitude of their fixation disparity in order to make more parafoveal information  
124 available for processing. While Nuthmann and colleagues demonstrated that reading  
125 was considerably impaired when only two characters were available to the right of  
126 fixation, they found only limited support for their hypothesis with respect to binocular  
127 coordination. These findings suggest that binocular fusion processes during a fixation  
128 are not immediately affected by visual manipulations of parafoveal information. Note



129 also that a further constraint with their methodological approach was that despite the  
130 use of a binocular moving window, the visual content that was available to both eyes  
131 during reading was very comparable. The lack of a dichoptic presentation method  
132 prevented the possibility of directly controlling the information that was exclusively  
133 available to one eye but not the other.

134         With respect to the limits of Panum's fusional area in reading, Blythe et al.  
135 (2010) conducted an experiment where participants were presented with  
136 stereoscopic linguistic stimuli (words or non-words) with varying degrees of horizontal  
137 disparity in a lexical decision task. The authors postulated that lexical identification –  
138 and therefore accurate lexical decision – would only be possible if participants  
139 successfully fused the disparate stimuli (otherwise it would be impossible to  
140 distinguish between a word and a pronounceable non-word). The findings revealed  
141 that participants were able to make highly accurate lexical decisions when horizontal  
142 disparity was 0.37 deg of visual angle (approximately one character space), but when  
143 disparity increased to 0.74 deg (two character spaces) performance was at chance.  
144 Furthermore, while appropriate vergence movements were made during the initial  
145 fixation on the stimulus in order to reduce the imposed stereoscopic disparity, no  
146 vergence adjustments were made during the initial saccade onto the stimulus. Thus,  
147 the authors concluded that the effective fusional range for linguistic stimuli  
148 corresponds to approximately one character space, and that participants did not use  
149 parafoveal binocular image disparity cues in order to coordinate binocular targeting of  
150 their saccades.

151         Another detailed exploration of binocular saccadic targeting was conducted by  
152 Liversedge et al. (2006). In their experiment participants read sentences with  
153 compound target words presented dichoptically, such that each eye received a

154 separate independent input (e.g. if the target word was “*cowboy*”, one eye only  
155 received the first half of the word “*cowb*” and the other eye only received the second  
156 half “*wboy*”; the remainder of the sentence was presented in full to both eyes). There  
157 were several possible ways in which saccadic targeting could operate under the  
158 experimental conditions: 1) each eye could target its own separate input, thereby  
159 suggesting independent, monocular control of saccades; 2) both eyes could target  
160 one of the word parts, thereby signifying suppression of one monocular input; 3)  
161 saccades could be targeted on the basis of the whole word, indicating that a unified  
162 percept was obtained prior to direct fixation. Indeed, the authors found that despite  
163 the dichoptic manipulation, saccadic targeting was identical to what is typically  
164 observed in normal reading: the eyes landed on the preferred viewing location (i.e.  
165 just left of the word center, Rayner, 1979; McConkie, Kerr, Reddix & Zola, 1988) of  
166 the whole word. The results demonstrated that saccades in reading are targeted  
167 towards a unified percept of the parafoveal word that is derived at an early stage of  
168 processing, prior to direct fixation.

169 In summary, the above studies demonstrate the important role of binocular  
170 coordination and binocular fusion in parafoveal pre-processing prior to direct fixation.  
171 Interestingly, with respect to processing of the fixated word, Juhasz, Liversedge,  
172 White and Rayner (2006) found a degree of dissociation between binocular  
173 coordination processes during a fixation and the lexical characteristics of the fixated  
174 word. They found that during normal sentence reading, while fixation times on high-  
175 frequency (HF) words were shorter than fixation times on low-frequency (LF) words,  
176 fixation disparity did not differ systematically between the two conditions. Therefore,  
177 in normal reading conditions where binocular fusion is achieved without difficulty,  
178 foveal processing of a fixated word appears to be primarily influenced by the  
179 cognitive demands associated with that word. This is also the key assumption of

180 influential computational models of oculomotor control in reading (e.g. E-Z Reader,  
181 Pollatsek, Reichle, & Rayner, 2006; Reichle, 2010; Reichle, 1998; Reichle, Rayner, &  
182 Pollatsek, 2003), which postulates that lexical processing is of primary importance in  
183 driving the forward movement of the eyes.

184         It is not clear, however, whether this is also the case when fusion is prevented,  
185 or when binocular information is not available. Binocular fusion is an important  
186 prerequisite for observing the advantages of binocular over monocular vision. For  
187 example, when visual input is binocular, luminance thresholds are lower and contrast  
188 sensitivities are higher (Blake & Levinson, 1977; Campbell & Green, 1965; Legge,  
189 1984). Additionally, performance at orientation discrimination (Bears & Freeman,  
190 1994) and letter recognition tasks is superior relative to when input is monocular  
191 (Eriksen et al., 1966). A number of studies have also provided evidence of global  
192 binocular advantages in a more complex task such as reading (Heller & Radach,  
193 1998; Jainta et al., 2014; Jainta & Jaschinski, 2012; Sheedy et al., 1986). Binocular  
194 visual presentation results in faster reading speed as well as fewer fixations and  
195 regressions compared to monocular presentation. More importantly, a recent study  
196 by Jainta, Blythe and Liversedge (2014) demonstrated that binocular advantages are  
197 also present in lexical processing. The authors implemented an adaptation of the  
198 boundary paradigm (Rayner, 1975) in order to study the binocular advantages in  
199 reading. They placed an invisible boundary before a target word within a sentence  
200 and altered visual presentation from binocular to monocular or vice versa once a  
201 reader's eyes crossed the boundary. The target word was either a commonly  
202 occurring, easy to process, high-frequency (HF) word or a less common, more  
203 difficult, low-frequency (LF) word. The boundary manipulation created four visual  
204 presentation conditions for the target word: it could either be 1) previewed and fixated  
205 binocularly, 2) previewed and fixated monocularly, 3) previewed binocularly but

206 fixated monocularly or 4) previewed monocularly but fixated binocularly. The authors  
207 found that the frequency effect on fixation times, which was present in binocular  
208 reading, was modulated in monocular reading, such that no significant differences  
209 were observed in processing times for high-frequency (HF) and low-frequency (LF)  
210 words. In addition, Jainta et al. (2014) observed a benefit of binocular relative to  
211 monocular text presentation in both parafoveal and foveal processing. That is, when  
212 a HF target word was monocularly presented in the parafovea but was fixated  
213 binocularly, or when direct fixation was monocular instead of binocular, processing of  
214 that word was slower relative to when binocular information was available either  
215 during preview or direct fixation. These findings provided a striking demonstration of  
216 the central role of binocular vision for efficient reading and word identification. What  
217 is less clear, however, is the extent to which binocular advantages for reading  
218 performance and word identification can be attributed entirely to the differences in  
219 binocular coordination (i.e. fixation disparity) when text is read with both eyes,  
220 relative to one eye.

## 221 **The present experiment**

222 In this context, the aim in the present study was to understand further the  
223 precise aspects of text processing that benefit from binocular vision, and to quantify  
224 the cost associated with monocular visual processing during encoding of both foveal  
225 and parafoveal words throughout sentence reading. We implemented a novel,  
226 dichoptic, gaze-contingent, moving window technique (McConkie & Rayner, 1975),  
227 which allowed us to directly control the visual presentation of foveal and parafoveal  
228 text to each eye separately, on a fixation-by-fixation basis. We programmed a  
229 window of monocular text to either (1) move with the eye across the sentence or (2)  
230 dynamically increase or decrease in the parafovea to the left or to the right of fixation

231 contingent on gaze position. Instead of using a window sized based on a fixed  
232 number of character spaces, we used word boundaries to define the margins of the  
233 moving windows. For instance, in order to pinpoint the cost of monocular foveal  
234 processing, we programmed the window such that when the eyes moved from one  
235 word in the sentence to the next, each fixated word was presented monocularly, and  
236 all the other words in the sentence were presented binocularly. In contrast, to  
237 quantify the cost of monocular parafoveal processing (either to the right or to the left),  
238 we presented each fixated word binocularly and all words either to the right or to the  
239 left of the fixated word, respectively, were presented monocularly. Thus, the number  
240 of words presented monocularly (i.e. the size of the monocular moving window)  
241 changed dynamically on a fixation-by-fixation basis, contingent on the position of the  
242 eyes within the sentence. These dichoptic moving window conditions were  
243 compared with pure binocular and pure monocular reading in order to exclusively  
244 investigate the binocular advantage associated with foveal and parafoveal  
245 processing. We analysed measures of global sentence processing and binocular  
246 coordination in order to explore the selective influence of our manipulation on reading  
247 performance and visual processing. We also embedded a target word manipulated  
248 for frequency in our sentences and investigated any potential modulations of the  
249 frequency effect that might occur in the different presentation conditions.

250         Based on previous research, we predicted that monocular text presentation  
251 would cause considerable disruption to reading, which would be observed in  
252 sentence-level measures of eye movement behaviour, in binocular coordination  
253 measures (i.e. fixation disparity and vergence) and in target word processing  
254 measures (i.e. the frequency effect would be reduced if the target word was either  
255 previewed or fixated monocularly). Furthermore, we were interested in quantifying

256 the cost of monocular foveal processing during reading relative to binocular foveal  
257 processing. Jainta et al. (2014) found that there was a substantial cost to the  
258 efficiency of lexical processing associated with monocular visual presentation when a  
259 word was directly fixated, even if that word had been previewed binocularly. We  
260 expected, therefore, a considerable level of processing difficulty to be associated with  
261 our gaze-contingent monocular presentation of the fixated word (relative to normal  
262 binocular viewing), with respect to global sentence processing, binocular coordination  
263 and target word identification. Finally, we investigated the cost associated with  
264 monocular input from the parafovea during sentence reading. Given previous findings  
265 that parafoveal monocular text causes impairment to reading, we predicted that a  
266 moving window in which words to the right of fixation were presented monocularly  
267 would affect global reading performance, even when, upon direct fixation, the word  
268 would be presented binocularly. Importantly, with relation to abovementioned findings  
269 regarding the asymmetry of the perceptual span, we predicted that the cost to  
270 processing at the sentence level would only be apparent, or at least would be far  
271 greater, when information to the right but not to the left of fixation was monocular.

272

## Method

### 273 *Participants*

274 Participants were 20 native English speakers from the University of  
275 Southampton (6 males, 14 females, average age = 21.2 years, range = 18-25 years).  
276 Participants took part in the experiment in exchange for Psychology course credits or  
277 payment at the rate of £6 per hour. All participants had normal or corrected to normal  
278 vision (with soft contact lenses) and no diagnosed reading difficulties. There were no  
279 substantial differences in acuity between the two eyes (best-corrected acuity in each

280 eye was 20/20 or better at 4m). Additionally, all participants had functional stereopsis  
281 (minimal stereoacuity of 40 seconds of arc). Participants were naïve to the purpose  
282 of the experiment.

### 283 ***Apparatus***

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

294 Prior to the experiment, participants' visual acuity was tested both binocularly  
295 and separately for each eye using a Landolt-C acuity chart and stereoacuity was  
296 tested using a Titmus Stereotest.

### 297 ***Materials and design***

298 Forty sentences with neutral content were presented, as well as YES/NO  
299 comprehension questions after 25% of trials. Sentences were presented in 14 pt red  
300 uppercase/lowercase Courier New font on black background in order to minimise  
301 dichoptic cross-talk (i.e. the "bleed-through" of visual input to the occluded eye, see  
302 also Jaschinski, Jainta, & Schurer, 2006). At the specified viewing distance, each  
303 letter subtended 0.25 deg of visual angle. On average, each sentence contained

304 76.63 (range = 72-86) characters. There were 12 words in each sentence, including  
305 a target word that was manipulated for lexical frequency. Target words were taken  
306 from the SUBTLEX-UK database (van Heuven, Mandera, Keuleers, & Brysbaert,  
307 2014) and mean frequency was calculated using Zipf values: 5.01 Zipf on average for  
308 HF words ( $SD = 0.48$ ) and 2.05 Zipf on average for LF words ( $SD = 0.58$ ). HF and LF  
309 target word pairs were matched on word length (mean target word length = 5.75  
310 characters). The words in each sentence were between four and eight characters  
311 long (mean word length = 6.38 characters). The full list of stimuli is presented in  
312 Appendix 1. We divided the sentences into five blocks and presented each block of  
313 eight sentences in one of five dichoptic gaze-contingent presentation conditions: (1)  
314 All words in the sentence were binocular. (2) Each fixated word was monocular, but  
315 all other words were monocular. (3) Each fixated word was binocular but all words to  
316 the right of fixation were monocular. (4) Each fixated word was binocular but all  
317 words to the left of fixation were monocular. (5) All words in the sentence were  
318 monocular. The sentences were presented in 5 blocks of 8 sentences (each block in  
319 a different presentation condition). A Latin Square design was used and the  
320 presentation order of blocks in different conditions was counterbalanced, such that  
321 across all participants, each sentence appeared in each condition with each version  
322 of the target word, but no sentence was repeated for any individual participant, and  
323 each participant saw the blocks in a different order. Monocular presentations were  
324 counterbalanced across the left and right eye.

### 325 ***Procedure***

326 The experimental procedure was approved by the University of Southampton  
327 Ethics and Research Governance Office and followed the conventions of the



328 Declaration of Helsinki. Informed written consent was obtained from each participant  
329 prior to the start of the experiment.

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

343         Each trial consisted of the following sequence of events. A fixation circle  
344 appeared on the centre of the screen for 1500 ms. Afterwards, another circle  
345 appeared on the left-hand side of the screen, marking the beginning of each  
346 sentence. Participants were required to fixate this circle. After 1000 ms, the fixation  
347 circle disappeared and a sentence was presented. Once the participant had finished  
348 reading the sentence, they pressed a button on a button box to indicate that they had  
349 finished reading the sentence. Comprehension questions were presented after 25%  
350 of the sentences and participants used the button box to make a YES/NO response.  
351 The next trial was initiated by the button press at the end of the sentence, or the  
352 YES/NO response. Calibration was checked for accuracy after every 4 trials and the

353 eye trackers were recalibrated if necessary. A full calibration/validation run was  
354 performed before each new block of 8 sentences was presented. Participants were  
355 given a break halfway through the experiment, as well as additional breaks whenever  
356 required. The entire procedure lasted for approximately 45-60 minutes.

### 357 ***Data Analyses***

358 Custom-designed software was used for the data analyses. Fixations and  
359 saccades were manually identified in order to avoid contamination by dynamic  
360 overshoots (Deubel & Bridgeman, 1995) or artefacts due to blinks. We excluded trials  
361 with track loss, fixations longer than 1200 ms or shorter than 80 ms, as well as the  
362 first and the last fixation on each trial. The following analyses were conducted on the  
363 remaining 86% of data (8891 fixations).

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

375 We constructed Linear Mixed-effect Models (LMMs) using the lmer program  
376 from package lme4 (version 1.1-11, Bates, Maechler, Bolker, & Walker, 2014) in R,

377 an open-source programming language and environment for statistical computation  
378 (R Development Core Team, 2012). Participants and items were included as random  
379 effects. We used the lmerTest package to compute  $p$ -values (Kuznetsova,  
380 Brockhoff, & Christensen, 2016). Values for mean fixation duration, first fixation  
381 duration (FFD) and gaze duration (GD) were log-transformed prior to running the  
382 models due to the skewed right tails of their distributions. We report regression  
383 coefficients ( $bs$ ), which estimate the effect size relative to the intercept, as well as  
384 standard errors ( $SEs$ ) and  $t$ -values. Given the number of participants and  
385 observations per participant, the  $t$ -distribution will approximate the  $z$ -distribution;  
386 therefore we consider as statistically significant those cases where  $|t| > 1.96$   
387 (Baayen, Davidson & Bates, 2008). For binary dependent variables such as  
388 regression probability we used generalised linear mixed models (glmer function from  
389 package lme4) and report the Wald  $z$  and its associated  $p$ -value. All reported models  
390 were computed in the way that was most appropriate for our research questions. In  
391 each subsection, we first estimate binocular advantages in reading by comparing  
392 binocular and monocular presentation conditions. Because binocular reading  
393 represents the optimal condition for word processing and binocular coordination, we  
394 used it as baseline for all the models with a single predictor variable (i.e. presentation  
395 condition). We then estimated the specific cost of presenting foveal and parafoveal  
396 input monocularly relative to that baseline in order to establish whether binocular  
397 advantages are present during processing of text prior to or during direct fixation (or  
398 both). For models with interaction terms we computed successive difference  
399 contrasts using the `contr.sdif` function from the MASS package (Venables & Ripley,  
400 2002).

401

## Results

402 Comprehension rate was at ceiling in all presentation conditions (mean  
403 accuracy = 98%). At the end of the experiment, we obtained subjective reports from  
404 each participant, asking about their visual experience. None of the participants were  
405 aware of the experimental manipulations. In fact, often participants did not believe  
406 that they had been reading monocular text at all, and asked us to repeat the viewing  
407 conditions after the experiment was completed to demonstrate that visual input to  
408 one of their eyes had been partially or entirely blocked during 80% of the trials. They  
409 were very surprised when we did this. This is a strong demonstration that in our  
410 sample of participants with normal vision, there was no immediate difference in  
411 perceptual experience between a binocular and a monocular visual presentation.

412 Below we report measures of global sentence processing, binocular coordination,  
413 and target word processing. All reported models were computed in the most  
414 appropriate way for our research questions. In each subsection, we first estimated  
415 binocular advantages in reading by comparing binocular and monocular presentation  
416 conditions. Because binocular reading represents the optimal reference level for  
417 word processing and binocular coordination, we used it as baseline for all the models  
418 with a single predictor variable (i.e. presentation condition). We then estimated the  
419 specific cost of presenting foveal and parafoveal input monocularly relative to that  
420 baseline, rather than the grand mean, in order to establish whether the availability of  
421 binocular input is more critical for the processing of text prior to or during direct  
422 fixation (or both).

## 423 **Global sentence processing measures**

424 **1.1. Comparison between binocular and monocular presentation.** When  
425 comparing binocular and monocular reading, we successfully replicated previous  
426 findings of binocular advantages for language processing in global measures of eye

427 movement behaviour (see Table 1). Total sentence reading times were considerably  
428 shorter in binocular reading compared to monocular reading. Furthermore,  
429 monocular reading resulted in a significant increase in mean fixation duration, more  
430 fixations and more regressive saccades than in the binocular presentation condition.  
431 These results indicate that monocular text presentation substantially impaired  
432 reading.

433 **1.2. Monocular foveal processing.** For this portion of the analyses we  
434 compared the monocular foveal viewing condition with binocular and monocular  
435 reading. The results for global sentence processing revealed no difference in  
436 sentence reading times between binocular monocular foveal presentations. However,  
437 average fixation durations were longer in the monocular foveal condition compared to  
438 binocular reading ( $b = 0.02$ ,  $SE = 0.02$ ,  $t = 1.35$ ,  $p = .08$ ) and were in fact not  
439 significantly different from monocular reading ( $t < 1$ ). As for the remaining measures  
440 (total sentence reading time, number of fixations and regression probability), we  
441 found no difference between binocular reading and the monocular foveal condition. It  
442 appears that whilst there was clearly a cost associated with restricting foveal  
443 processing to monocular input on a fixation-by-fixation basis, this level of disruption  
444 was not as great as was the case when the entire sentence was presented  
445 monocularly.

446 **1.3. Monocular rightward parafoveal processing.** When comparing the  
447 monocular parafoveal presentation to the right of the fixated word with binocular  
448 reading, we found no differences in mean fixation duration or regression probability  
449 (Table 1). We did, however, find a significant increase in total sentence reading times  
450 when text to the right of fixation was monocular, relative to binocular reading ( $b =$   
451  $304.60$ ,  $SE = 129.30$ ,  $t = 2.34$ ,  $p < .001$ ). This increase in sentence reading time

452 when text to the right of fixation was monocular was not significantly different from  
453 that observed when the entire sentence was presented monocularly ( $t < 1$ ).  
454 Participants also made more fixations when parafoveal information to the right of  
455 fixation was monocular, compared to binocular reading ( $b = 1.01$ ,  $SE = 0.41$ ,  $t = 2.49$ ,  
456  $p = 0.04$ ). This increase was again not significantly different from the increase  
457 observed in monocular reading ( $t < 1$ ). These data clearly suggest that monocular  
458 presentation of parafoveal words to the right of fixation caused a similar degree of  
459 disruption to reading as when the entire sentence was presented monocularly.

460 **1.4. Monocular leftward parafoveal processing.** As a final step in the analysis,  
461 we investigated whether the cost associated with restricting parafoveal processing to  
462 monocular visual input was present exclusively when the direction of the gaze-  
463 contingent manipulation matched the direction of reading. We therefore compared  
464 reading with monocular parafoveal text to the left of the fixated word against  
465 binocular and monocular reading. We found that measures of global sentence  
466 processing did not differ significantly between this condition and binocular reading  
467 (Table 1).<sup>1</sup>

468 - INSERT TABLE 1 ABOUT HERE -

## 469 2. Binocular coordination measures

---

<sup>1</sup> In order to rule out any potential practice effects, we also included trial order as a fixed effect in the LMEs. We found no effect of trial order for any of the reported measures (all  $t$ s  $< 1$ ), showing that the blocked design (compared to a random, trial-by-trial design) did not induce additional effects across the sentence presentations within each block or interactions with reading conditions.

470 Below we report findings regarding fixation disparity at the beginning and at the end  
471 of fixations, as well as proportion of aligned, crossed and uncrossed fixations. In  
472 accordance with previous research, aligned fixations were defined as those where  
473 both fixation points were within one character of each other within a word; crossed  
474 fixations were those where fixation disparity exceeded one character space and the  
475 left eye fixated further to the right than the right eye (eso); and uncrossed were those  
476 fixations where disparity exceeded one character space and the left eye was fixating  
477 further to the left than the right eye (exo). Fixation disparity measures and model  
478 parameters are reported in Table 2.

479 - INSERT TABLE 2 ABOUT HERE -

480 **2.1. Comparison between binocular and monocular presentation.** We  
481 replicated previous results relating to vergence behaviour during binocular reading  
482 (see Table 2). The average magnitude of fixation disparity in the binocular condition  
483 was 0.23 deg at the start of fixations, which is less than a character space. By the  
484 end of fixations, that disparity was significantly reduced to 0.16 deg ( $t = -29.92$ ,  $p <$   
485  $.001$ ). Critically, the magnitude of fixation disparity was significantly larger in  
486 monocular relative to binocular reading both at the start and at the end of fixation,  
487 although we did observe a significant reduction in disparity from start to end of  
488 fixation in the monocular condition ( $t = -13.41$ ,  $p < .001$ ). We also replicated  
489 previously reported patterns of fixation disparity during binocular reading at the  
490 beginning and at the end of fixations (Blythe et al., 2010, Blythe et al., 2006,  
491 Liversedge et al., 2006a, Liversedge et al., 2006b). Disparities in the majority of  
492 fixations were aligned. Out of the remaining fixations, the majority of fixation  
493 disparities were uncrossed, and a small proportion were crossed. During monocular  
494 reading a smaller proportion of fixations were aligned at the beginning of the fixation

495 period than in binocular reading, with uncrossed disparities accounting for the  
496 majority of misaligned fixations (see *Figure 1*). Those differences in proportion of  
497 misaligned fixations between the binocular and monocular presentation condition  
498 were significant for the start ( $b = .50$ ,  $z = 5.75$ ,  $p < .001$ ) but not for the end of the  
499 fixation period ( $b = -0.06$ ,  $z = -0.69$ ,  $p = 0.50$ ), suggesting that readers were able to  
500 compensate for the substantial initial misalignment that occurred for monocular  
501 fixations.

502 Next, we were interested in how binocular coordination changed throughout each  
503 trial, both in the binocular and monocular control conditions and in the gaze-  
504 contingent conditions. We therefore examined how the absolute magnitude of  
505 fixation disparity at the beginning of fixations changed as a function of fixation  
506 position within the sentence from left to right and whether this varied between  
507 experimental conditions. In our comparison between binocular and monocular  
508 reading (i.e. our baseline conditions), we found a significant main effect of position  
509 within the sentence ( $b = 0.01$ ,  $SE = 0.01$ ,  $t = 10.43$ ,  $p < .001$ ) and a significant  
510 interaction between position and viewing condition ( $b = -0.01$ ,  $SE = 0.01$ ,  $t = -5.751$ ,  $p$   
511  $< .001$ ). As is evident from *Figure 2*, while fixation disparity magnitude in the  
512 binocular presentation condition tended to increase as the eyes moved from left to  
513 right along the sentence, it did so to a considerably lesser extent when reading was  
514 monocular. Similar findings were reported by Heller and Radach (1999) and Jainta et  
515 al. (2010). These results suggest that binocular coordination processes differ  
516 considerably between monocular reading both during a single fixation period and  
517 throughout an entire sentence reading trial.

518 **2.2. Monocular foveal processing.** With regard to fixation disparity, the  
519 magnitude of fixation disparity did not differ between binocular and monocular foveal



520 presentation (see Table 2). There were no differences in the overall pattern of fixation  
521 disparities between binocular reading and the monocular foveal condition at the start  
522 of the fixation period (see *Figure 1*); there was, however, a significantly larger  
523 proportion of aligned fixations ( $b = 0.76$ ,  $z = 2.09$ ,  $p = .021$ ) at the end of the fixation  
524 period in the monocular foveal condition. Further, there was a significant interaction  
525 between position within the sentence and visual presentation ( $b = -0.01$ ,  $SE = 0.00$ ,  $t$   
526  $= -5.51$ ,  $p < .001$ ). We found that an accumulation of fixation disparity occurred as  
527 readers moved from left to right, but the initial magnitude of disparity and the extent  
528 to which disparity increased was smaller than in binocular reading. This pattern  
529 differed considerably from monocular reading, indicating that although in the  
530 monocular foveal condition each fixated word was only presented to one of the eyes,  
531 binocular coordination processes remained efficient.

532 **2.3. Monocular rightward parafoveal processing.** The findings regarding  
533 fixation disparity were somewhat surprising. Firstly, when text to the right of fixation  
534 was monocular, the magnitude of fixation disparity was considerably reduced in  
535 comparison to binocular reading both at the start and at the end of the fixation period.  
536 Furthermore, when parafoveal information to the right was monocular, 72% of  
537 fixations were aligned at the start of the fixation period, which was a significantly  
538 larger proportion than fixations in binocular reading ( $b = 0.94$ ,  $z = 2.53$ ,  $p = .002$ ). By  
539 the end of the fixation period the proportion of aligned fixations increased to 82%,  
540 which again was significantly different from binocular reading ( $b = 1.22$ ,  $z = 2.19$ ,  $p =$   
541  $.012$ ). Furthermore, there was a significant interaction between viewing condition and  
542 position within the sentence ( $b = -0.01$ ,  $SE = 0.00$ ,  $t = -3.724$ ,  $p < .001$ ), such that  
543 when text to the right of fixation was monocular, initial fixation disparity magnitude  
544 was smaller than in binocular reading, and an accumulation of disparity occurred to a  
545 lesser extent (see *Figure 2*). Note that in this condition, participants started reading

546 the sentence while only the first word that itself was under direct fixation, was  
547 presented binocularly, while all the other words in the sentence were presented  
548 monocularly. As the participants moved their eyes through the text, each newly  
549 fixated word was presented binocularly, until the final word of the sentence was  
550 fixated, at which point, all the words in the sentence appeared binocularly. Thus,  
551 despite the fact that different proportions of the sentence were available to both eyes  
552 on each fixation, binocular coordination processes were not impaired.

553 **2.4. Monocular leftward parafoveal processing.** Binocular fixation disparity at  
554 the start and at the end of fixations when text to the left of fixation was presented to  
555 only one of the eyes did not differ significantly from binocular reading (see Table 3) .  
556 The proportion of aligned and misaligned fixations also did not differ significantly  
557 between the two conditions (*Figure 1*). Interestingly, we found a significant effect of  
558 fixation position within the sentence on absolute disparity magnitude ( $b = 0.01$ ,  $SE =$   
559  $0.00$ ,  $t = 8.11$ ,  $p < .001$ ) and a significant interaction between fixation position and  
560 viewing condition ( $b = -0.01$ ,  $SE = 0.00$ ,  $t = -5.71$ ,  $p = .005$ ): it is evident from *Figure 2*  
561 that the increase in disparity magnitude as the eyes moved from left to right along the  
562 sentence was smaller when text to the left of fixation was monocular than in binocular  
563 reading. Note that in this dichoptic moving-window condition, when participants  
564 started reading a sentence all words aside from the fixated word were binocular. As  
565 participants moved their eyes through the text, words to the left of fixation were  
566 presented monocularly until only the final word in the sentence was binocular and all  
567 other words were monocular. This dynamic viewing situation, however, did not seem  
568 to interfere with efficient binocular coordination.

569 - INSERT FIGURE 1 AND FIGURE 2 ABOUT HERE -

570 **3. Target word analysis: the effect of lexical frequency**

571 Recall that each sentence contained a target word manipulated for lexical  
572 frequency. Below we report first fixation durations (FFD) and gaze durations (GD) on  
573 the target word, as well as the number of first-pass fixations and number of  
574 regressions into the target region. Observed means and standard deviations are  
575 presented in Table 3. To estimate the differences between our different presentation  
576 conditions for the target word, we fit separate LMMs which estimated the effect of  
577 lexical frequency (HF vs LF target word), viewing condition and the interaction  
578 between the two for the 4 dependent variables: FFD, GD, number of first-pass  
579 fixations and number of regressions into the target region (see Table 4).

580 - INSERT TABLE 3 AND TABLE 4 ABOUT HERE -

581 **3.1. Comparison between binocular and monocular presentation.** We found a  
582 significant main effect of lexical frequency in FFD and GD, though neither the effect  
583 of condition, nor the interaction between frequency and condition were significant.  
584 Similarly, we found that participants made more first-pass fixations on, and more  
585 regressions into LF than HF target words, but neither of those effects was modulated  
586 by presentation condition or the interaction between the two factors. These findings  
587 suggest that participants processed HF words faster than LF words in both binocular  
588 and the monocular presentation conditions. Nevertheless, Table 3 clearly shows a  
589 numerical reduction in the frequency effect in monocular relative to binocular reading:  
590 we observed a 20 ms reduction in the frequency effect in FFD and a 98 ms reduction  
591 in GD. These reductions in the frequency effect were not significant in FFD ( $b = 1.04$ ,  
592  $t = 0.03$ ,  $p = .98$ ), but were significant in GD ( $b = -112.89$ ,  $t = -2.44$ ,  $p = 0.03$ ). In other  
593 words, under monocular compared to binocular viewing conditions GD was increased  
594 for HF words relative to LF words. This pattern of effects is similar to that reported by  
595 Jainta et al. (2014).

596       **3.2. Monocular foveal processing.** We found a significant effect of lexical  
597 frequency when foveal input was monocular in FFD and GD. Those effects did not  
598 differ from binocular reading ( $t_s < 1$ ). We did not find a significant effect of  
599 presentation condition or of the interaction between the two fixed factors. Similar to  
600 binocular reading, participants made more first-pass fixations and more regressions  
601 into the target region if the target was LF relative to HF, but neither effect was  
602 modulated by presentation condition or the interaction between the fixed effects  
603 (Table 4). In other words, when a target word was previewed binocularly but fixated  
604 monocularly, participants were able to process it as efficiently as they did in binocular  
605 reading.

606       **3.3. Monocular rightward parafoveal processing.** Similarly to the other  
607 conditions, we found a significant effect of lexical frequency in FFD and GD when  
608 text to the right of fixation was monocular. We also found an increase in the number  
609 of first-pass fixations and regressions into the target region for LF relative to HF  
610 target words. Neither of those effects was modulated by visual presentation, nor did  
611 we find an interaction between them. Finally, we explored whether participants were  
612 able to obtain a larger preview benefit if the target word was previewed binocularly  
613 rather than monocularly. We found no effect of preview condition in either FFD ( $b =$   
614  $0.03$ ,  $SE = 0.05$ ,  $t = 0.53$ ) or GD ( $b = 0.06$ ,  $SE = 0.06$ ,  $t = 0.94$ ), suggesting that  
615 previewing the word monocularly did not affect fixation times when the word was  
616 directly fixated binocularly.

617       **3.4. Monocular leftward parafoveal processing.** We found that the significant  
618 effect of lexical frequency in FFD, GD, number of first-pass fixations and regressions  
619 into the target region did not vary as a function of condition or of the interaction

620 between the fixed effects (see Table 4). Thus, lexical processing when text to the left  
621 of fixation was monocular was not impaired by the visual presentation.

## 622 **Discussion**

623 The present research replicated previous findings of global binocular  
624 advantages in reading. Our results clearly demonstrate that when visual input is  
625 binocular, sentence processing is faster and readers make fewer, shorter fixations  
626 than when it is monocular. These findings are in accord with previous research  
627 (Heller & Radach, 1999; Jainta et al., 2014; Jainta & Jaschinski, 2012; Sheedy,  
628 Bailey, Buri, & Bass, 1986) and provide a further demonstration of the importance of  
629 binocular vision for the delivery of high-quality visual information necessary for fluent  
630 and efficient reading.

631 We then explored whether the binocular advantages observed in reading  
632 could be attributed to more efficient encoding of foveal information for binocular  
633 viewing, or more effective pre-processing of parafoveal information in binocular  
634 relative to monocular presentation conditions. Previous findings by Jainta et al.  
635 (2014) suggested that while binocular visual input both prior to, and during direct  
636 fixation on a word facilitates lexical processing, this facilitation is less pronounced  
637 when the word is monocularly fixated. We hypothesized, therefore, that restricting  
638 visual input to monocular information on a fixation-by-fixation basis would also result  
639 in considerable disruption to reading. Our findings were partially, but not entirely,  
640 consistent. We only observed a limited cost to processing in the monocular foveal  
641 condition, expressed in slightly longer mean fixation durations compared to binocular  
642 reading. That decrease in processing speed for the fixated words did not result in  
643 robust effects for total sentence reading time, nor did it result in a significantly  
644 increased rate of fixations and regressions. Our findings suggest, therefore, that

645 when each word in a sentence is previewed binocularly but fixated monocularly,  
646 reading can proceed comparatively efficiently, relative to when larger portions of the  
647 sentence are presented monocularly. Critically, our results indicate that the  
648 considerable disruption to reading observed in the majority of eye movement  
649 measures in the monocular presentation condition cannot be attributed solely to  
650 disruption associated with encoding of foveal information. Instead, our data  
651 demonstrate that binocular input plays a key part in the efficient pre-processing of  
652 information to the right of fixation. As reported above, reading time increases and  
653 readers make more fixations when only monocular information is available in the  
654 parafovea to the right. In other words, binocular vision was associated with marked  
655 advantages in parafoveal pre-processing of upcoming text. Note also that we  
656 observed no differences between binocular reading and reading when text to the left  
657 of fixation is monocular, indicating that reading performance only suffered when  
658 binocular visual input was denied in the direction of reading. This finding is in line  
659 with previous studies (Liversedge et al., 2004; Rayner et al., 2003, 2006; Rayner et  
660 al., 2013), which have demonstrated that the critical region from which readers obtain  
661 information during reading of English and other languages read from left to right is to  
662 the right of fixation. Importantly, our results do not imply that there is a functional  
663 difference between the binocular fusion processes in the right and left visual field.  
664 They suggest, instead, that because in English more attention is allocated to text to  
665 the right of fixation than to the left, and because processing demands associated with  
666 that text guide eye movements, the need for a high-quality unified binocular input is  
667 more pronounced in the pre-processing of that text prior to direct fixation.

668           It is possible that the qualitative difference between a binocular and a  
669 monocular parafoveal presentation is such that when parafoveal input is monocular,  
670 the perceptual span is reduced. That is, the amount of useful information that readers

671 extract during a single fixation may be influenced by the quality of the visual input.  
672 Although our experiment provides no direct evidence for this hypothesis, previous  
673 research by Legge, Ahn, Klitz, and Luebker (1997) and Legge, Cheung, Yu, Cheung,  
674 Lee and Owens (2007) has found that the visual span – the number of letters that  
675 can be reliably identified during a single fixation – to the left and to the right of the  
676 fixation point – varies as a function of certain stimulus characteristics, such as  
677 contrast. Alternative explanations, for example, that binocular visibility could yield  
678 higher visual acuity or facilitate inter-hemispheric transfer, are also plausible (though  
679 see Dehaene, Cohen, Sigman, & Vinckier, 2005 for further discussion). Further work  
680 is needed to test these different alternatives and to explore any potential differences  
681 in the size of the perceptual span – or indeed the degree to which readers can obtain  
682 useful information from text to the right of fixation – during binocular and monocular  
683 reading. To summarise, the present experiment replicated previous findings of  
684 binocular advantages in reading and demonstrated that, while binocular vision is  
685 important for the encoding of foveal information during reading, it plays a critical part  
686 in the efficient pre-processing of information to the right of fixation.

687         Aside from global reading behaviour, we also investigated the effect of our  
688 dynamic, gaze-contingent manipulations on binocular coordination. First, we  
689 replicated previous findings of binocular coordination in normal reading. When visual  
690 input was binocular, participants made predominantly convergent vergence  
691 movements in order to reduce fixation disparity throughout the fixation period.  
692 Fixation disparities that exceeded one character space were predominantly  
693 uncrossed (*exo*) and a small proportion were crossed (*eso*). This pattern of results is  
694 compatible with existing research (Blythe et al., 2010; Blythe et al., 2006; Jainta &  
695 Jaschinski, 2012; Jainta et al., 2009; Liversedge et al., 2006a, Liversedge et al.,  
696 2006b, though see Nuthmann & Kliegl, 2009 and Nuthmann et al., 2014 for a

697 different pattern of results). It is important to note, though, that during monocular  
698 reading, the magnitude of fixation disparity at the beginning of fixation was larger  
699 than during binocular reading. Although we did observe some reduction throughout  
700 the fixation period, likely reflecting the adaptability of tonic vergence (Schor & Horner,  
701 1989), monocular fixations remained significantly more disparate than binocular  
702 fixations (see also Jainta & Jaschinski, 2012). These findings are not surprising:  
703 under monocular viewing conditions, where a fusion stimulus is not present and there  
704 is no disparity feedback (open-loop), the occluded eye tends to diverge to a fusion-  
705 free vergence position termed the phoria (Howard & Rogers, 1995; Steinman et al.,  
706 2000). As a result, the observed disparity between the eyes is larger than in the  
707 binocular condition, where a fusion stimulus is present on each fixation. Our data  
708 demonstrate, furthermore, that during binocular reading there is an accumulation of  
709 fixation disparity as the eyes move from left to right throughout a sentence but that  
710 accumulation is not sufficient to disrupt fusional processes and cause diplopia (see  
711 also Heller & Radach, 1998; Nuthmann & Kliegl, 2009). Jainta et al. (2010) explained  
712 that this disparity accumulation throughout sentence reading is affected by each  
713 individual's ability to compensate for saccadic disconjugacy. This was not the case in  
714 monocular reading, where the magnitude of fixation disparity was increased from the  
715 first fixation in the sentence and remained relatively unchanged as readers moved  
716 their eyes from left to right.

717         Out of all comparisons between the five viewing conditions, the most striking  
718 results with respect to binocular coordination emerged when text to the right of  
719 fixation was monocular. For this condition, there was a larger overall reduction in  
720 fixation disparity at the beginning and at the end of fixations than in binocular  
721 reading. In addition, a significantly smaller proportion of fixations in this condition had  
722 a disparity magnitude that exceeded one character space. Furthermore, the



723 accumulation of disparity throughout the sentence, which was present in binocular  
724 reading, was significantly reduced when text to the right of fixation was monocular.  
725 Importantly, these effects were maintained even when we controlled for factors such  
726 as saccade amplitude, fixation duration and recalibration rate, all of which could  
727 potentially influence the magnitude of fixation disparity. These results do not lend  
728 support to theories suggesting that readers may be able to adaptively increase their  
729 fixation disparity in order to make more information available parafoveally (Nuthmann  
730 et al., 2014). It is possible that the dynamic characteristics of the visual presentation  
731 in our experiment affected binocular coordination. Recall that when text to the right of  
732 fixation was monocular, an increasing proportion of the sentence was presented  
733 binocularly during each forward fixation (i.e. while initially only the first word was  
734 binocular, more words to the left of fixation became binocular as the eyes moved  
735 from left to right). This continuous increase in the amount of binocular information  
736 available during each fixation may have resulted in a reduction in fixation disparity  
737 and an overall tighter coupling of the eyes. Another potential explanation for our  
738 findings may be related to binocular saccadic targeting. Recall that Liversedge et al.  
739 (2006a) established that saccades in reading are targeted towards a unified  
740 parafoveal percept achieved at an early stage of processing. Furthermore, Blythe et  
741 al. (2010) found that when a lexical stimulus was presented dichoptically with  
742 imposed horizontal binocular image disparity, participants targeted their saccades  
743 towards it on the basis of a unified – but not fused – percept (i.e. if a 6-letter word  
744 was presented in the parafovea with 2 characters of horizontal disparity, saccades  
745 towards it were programmed on the basis of an 8-letter stimulus). In other words,  
746 binocular image disparity in the parafovea did not trigger vergence movements or  
747 affect the coupling of the eyes during saccades, but only upon direct fixation. A  
748 monocular parafoveal preview, on the other hand, may provide a less ambiguous

749 saccadic target than a binocular one, because it will not be affected by binocular  
750 image disparity by definition, since only one visual input will be available for  
751 parafoveal processing. It might have been the case, therefore, that in the present  
752 experiment a monocular preview to the right of fixation affected saccadic coupling,  
753 and this in turn caused the reduced transient divergence and a smaller magnitude of  
754 fixation disparity at fixation onset.

755         Critically, however, the present results allow for an important distinction to be  
756 made between reading performance and the efficiency of binocular coordination  
757 processes. Although presenting text to the right of fixation monocularly was as  
758 disruptive to reading as an entirely monocular visual presentation, there was no cost  
759 to binocular coordination. That is, in contrast to monocular reading, the vergence  
760 system operated with a high degree of efficiency when text to the right of fixation was  
761 monocular (but the fixated word was binocular). These results indicate that there is  
762 dissociation between binocular coordination processes and reading performance  
763 when text to the right of fixation is monocular.

764         It is worth noting that current implementations of computational models of eye  
765 movements during reading do not specify a role for binocular fusion processes, either  
766 during direction fixation or in parafoveal pre-processing (Engbert, et al., 2002;  
767 Reichle, 2011; Reichle et al., 2003). The present data set clearly demonstrates,  
768 however, that binocular coordination impacts upon fixation times in reading; for  
769 example, word reading times were inflated following a monocular preview of that  
770 word. In the context of models of eye movement control, information from both the  
771 fixated word and the next word in the sentence is processed during fixations on the  
772 current word. Parafoveal pre-processing of the next word in the sentence, prior to its  
773 direct fixation, is known to be a key component of skilled sentence reading, and is

774 integrated in all major theoretical/ computational models of eye movements during  
775 reading (Engbert, et al., 2002; Reichle, 2011; Reichle et al., 2003). If such pre-  
776 processing is either eliminated or reduced, then reading suffers – the reader takes  
777 longer to identify the word once it is directly fixated. One potential explanation for the  
778 observed pattern of results is that the monocular input to the right of fixation makes it  
779 difficult to extract useful features such as, for example, orthographic information. In  
780 this way, the efficiency of parafoveal pre-processing may have been reduced for  
781 monocular viewing conditions, thus reducing preview benefit on direct fixation times  
782 for each word. This may be somewhat mitigated by the fact that the subsequent,  
783 direct fixation on each word is binocular and word identification can operate in its  
784 optimal capacity at that point. These examples (1) demonstrate that binocular  
785 coordination impacts upon fixation times and (2) offer a possible explanation, within  
786 the framework of current models of eye movement control in reading, for why such  
787 effects occur. Adaptation of these models to accommodate the growing body of  
788 research that demonstrates such effects would be useful.

789         As a final point of interest, we included a lexical frequency manipulation in our  
790 experiment in order to explore the effect of the different visual presentation conditions  
791 on word identification. Recall that Jainta et al. (2014) found that the robust frequency  
792 effect present in binocular reading was modulated when sentence presentation was  
793 monocular. Further, they observed an increase in the processing time for HF words  
794 when they appeared monocularly during either parafoveal preview or direct fixation.  
795 In contrast, the present study found a significant frequency effect across all  
796 presentation conditions. Nevertheless, when focusing only on purely binocular and  
797 purely monocular reading – the two conditions where visual presentation was  
798 identical across the two experiments – the pattern of our results is compatible with  
799 that reported by Jainta and colleagues. They found 44 ms frequency effect in FFD

800 and a 45 ms effect in GD during binocular presentation. These effects were  
801 drastically reduced to 1ms in FFD and 8 ms in GD during monocular reading. In the  
802 present experiment, we found a 48 ms frequency effect in FFD and a 174 ms effect  
803 in GD during binocular reading, which were reduced considerably in monocular  
804 reading (28 ms in FFD and 76 ms in GD). This reduction in the frequency effect from  
805 binocular to monocular viewing conditions was statistically significant in GD in the  
806 present study, implying that the efficiency of processing for HF words suffered when  
807 reading was monocular. Thus, our findings map onto the pattern reported in previous  
808 research and suggest that an uninterrupted binocular input is an important  
809 prerequisite for efficient lexical identification. The differences in findings between the  
810 two experiments could potentially be due to the fact that Jainta and colleagues used  
811 a modification of the boundary paradigm (Rayner, 1975) whereby crossing an  
812 invisible boundary around the centre of each sentence switched visual presentation  
813 from binocular to monocular or vice versa. In contrast, the present experiment  
814 employed a gaze-contingent technique whereby visual presentation changed  
815 continuously, on a fixation-by-fixation basis and varying proportions of the text were  
816 binocular/monocular on each fixation. Secondly, while Jainta et al. (2014) presented  
817 their stimuli in randomised order, the present study used a blocked design. Taken  
818 together, these factors may have allowed for some degree of adaptation to occur  
819 across trials, thus contributing to a significant frequency effect in all presentation  
820 conditions. Future experimental work is necessary to test this possibility.

821 In conclusion, the present research explores the role of binocular vision for  
822 uninterrupted sentence reading. We used a novel, dichoptic, moving window,  
823 binocular, gaze-contingent change presentation technique and found that restricting  
824 foveal word processing during direct fixation to a monocular visual input did not  
825 cause a considerable disruption to reading. Instead, reading performance suffered

826 when parafoveal information to the right of fixation was presented monocularly.  
827 These results indicate that binocular vision provides clear advantages for the pre-  
828 processing of upcoming, parafoveal text. Our findings speak to the complex interplay  
829 between the human visual system and the language comprehension system, which is  
830 fundamental for efficient reading performance.

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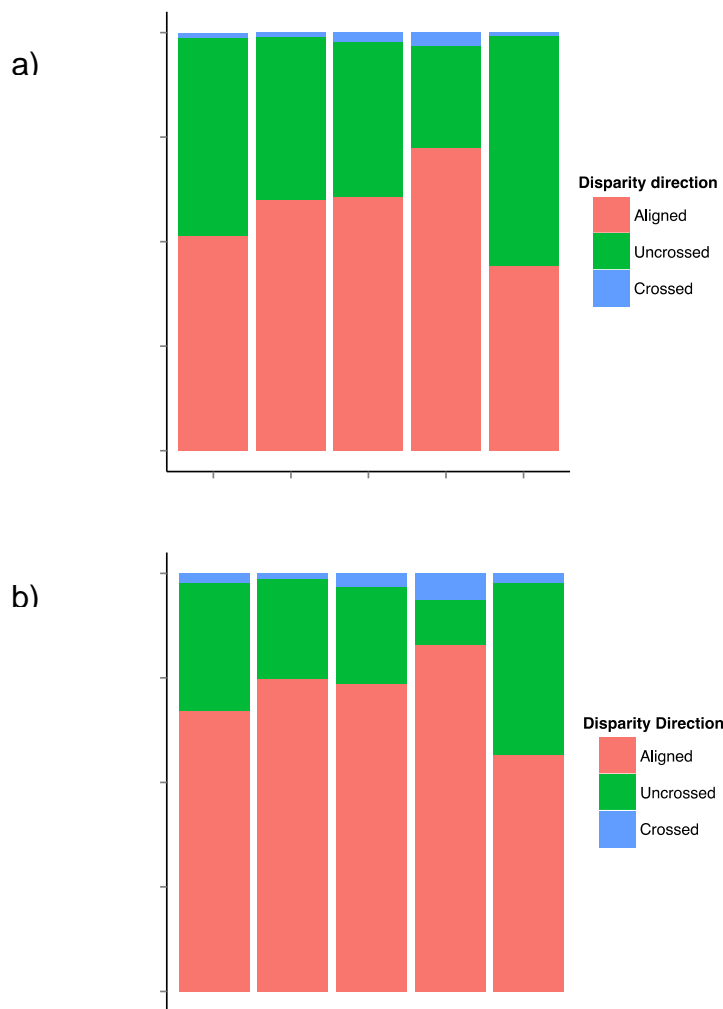
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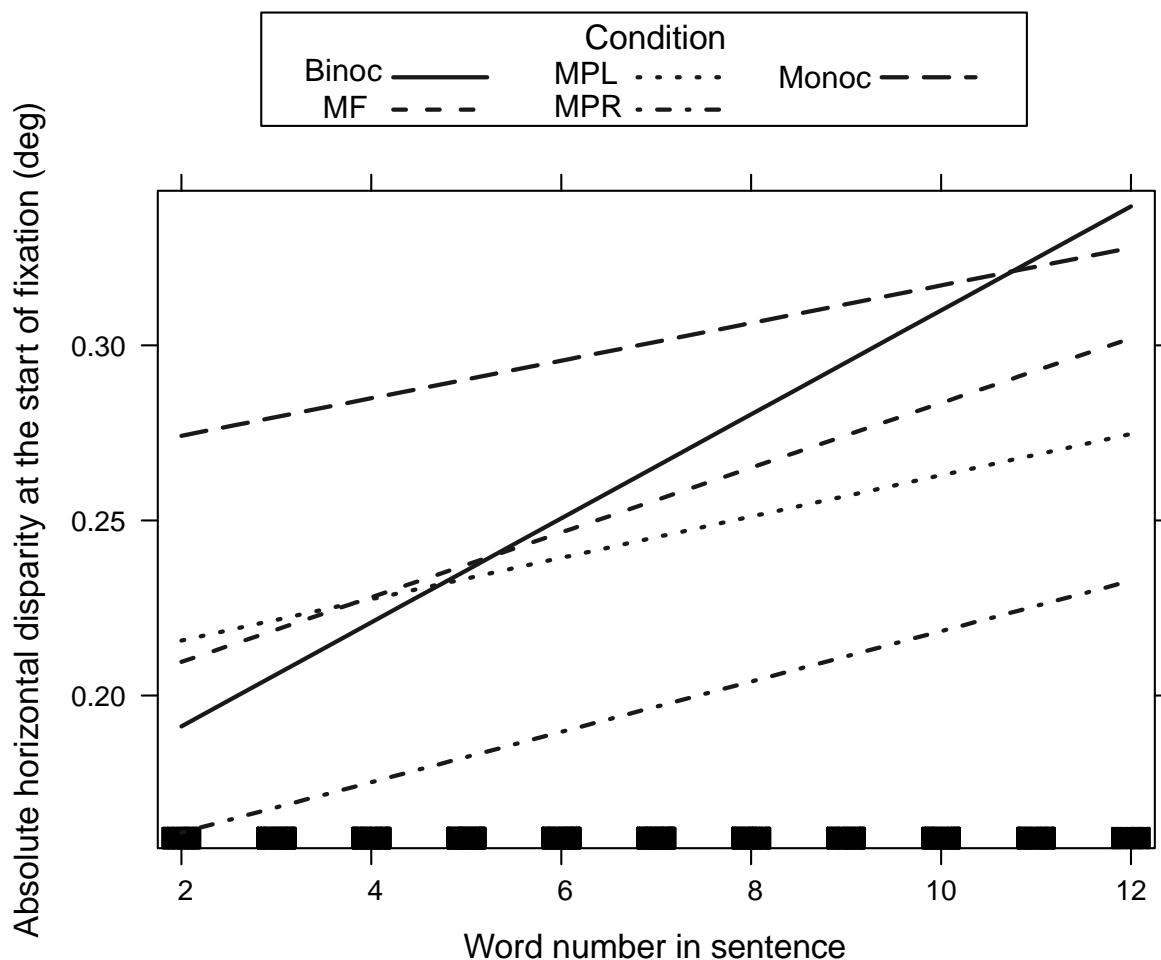
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## Figures and Tables



*Figure 1.* Proportion of aligned, uncrossed and crossed fixations across the different presentation conditions at the start (a) and at the end (b) of fixations. (1 – Binocular; 2 – MF, 3 – MPL, 4 – MPR, 5 – Monocular).

Figure 2. Interaction between fixation disparity at the beginning of fixations and the position of the eyes from left to right within the sentence.



\*Legend:

“Binoc” = binocular presentation of the entire sentence; “MF” = monocular presentation of the fixated word; “MPL” = monocular presentation of parafoveal text to the left of fixation; “MPR” = monocular presentation of parafoveal text to the right of fixation; “Monoc” = monocular presentation of the entire sentence

The figure was plotted using the Effects library in R, based on a model with the following structure:



*ModelName = lmer(DV ~ Condition\*Position\_In\_Sentence +  
(Condition\*Position\_In\_Sentence|Participant) + (1|Item), data = DataFile)*

Table 1. Global measures of text processing.

<u>Variable name</u>	<u>Model estimates</u>				<u>Observed descriptive values</u>	
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	Mean (ms)	<i>SD</i> (ms)
Mean fixation duration						
Binocular (intercept)	5.59	0.03	177.64	<.001	289	118
Monocular Foveal	0.04	0.02	2.34	.03	298	115
Monocular Parafoveal Right	0.02	0.02	1.20	.97	287	115
Monocular Parafoveal Left	0.00	0.02	-0.26	.15	291	109
Monocular	0.06	0.01	3.29	.001	306	117
Total Sentence Reading Time						
Binocular (intercept)	3284.50	231.30	14.20	<.001	3299	1249
Monocular Foveal	195.50	153.21	1.28	.12	3486	1310
Monocular Parafoveal Right	304.60	129.30	2.34	.002	3641	1329
Monocular Parafoveal Left	207.90	152.90	1.36	.16	3492	1434
Monocular	443.30	171.10	6.73	<.001	3813	1640
Total Number of Fixations						
Binocular (intercept)	11.42	0.69	16.65	<.001	11.4	4
Monocular Foveal	0.33	0.48	0.70	.44	11.71	4.07
Monocular Parafoveal Right	1.01	0.41	2.49	.04	12.53	5.03
Monocular Parafoveal Left	0.78	0.54	1.49	.15	12.33	4.54
Monocular	0.98	0.43	2.27	.004	12.46	4.79
Regression probability						
Binocular (intercept)	-1.13	0.37	-3.07	<.001	-	-
Monocular Foveal	0.05	0.09	0.40	.68	-	-
Monocular Parafoveal Right	0.14	0.09	1.54	.12	-	-
Monocular Parafoveal Left	0.11	0.10	0.83	.41	-	-
Monocular	0.20	0.10	2.11	.03	-	-

\* Each of the reported measures was entered as a dependent variable in a separate LME, with the following structure: *Model.Name = lmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile)*. The model for regression probability was computed as follows: *Model.Name = glmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile, family = binomial)*

Table 2

Model estimates and descriptive values for fixation disparity at the beginning and at the end of each fixation, reported in degrees of visual angle.

<u>Variable</u>	<u>Model Estimates</u>				<u>Observed descriptive values</u>	
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	Mean  (deg)	SD  (deg)
Disparity (start of fixation)						
Binocular (intercept)	-0.23	0.04	233.11	<.001	0.25	0.16
MF	0.01	0.01	1.00	.86	0.25	0.22
MPR	0.09	0.03	2.80	.002	0.17	0.13
MPL	-0.04	0.04	-1.10	.42	0.23	0.17
Monocular	-0.09	0.05	-2.00	.001	0.31	0.20
Disparity (end of fixation)						
Binocular (intercept)	-0.16	0.06	146.19	<.001	0.18	0.15
MF	0.01	0.01	0.86	.82	0.19	0.20
MPR	0.09	0.03	2.71	.002	0.14	0.11
MPL	-0.02	0.08	-0.26	.41	0.18	0.15
Monocular	-0.11	0.05	-2.02	.004	0.24	0.18

\* “Binoc” = binocular presentation of the entire sentence; “MF” = monocular presentation of the fixated word; “MPL” = monocular presentation of parafoveal text to the left of fixation; “MPR” = monocular presentation of parafoveal text to the right of fixation; “Monoc” = monocular presentation of the entire sentence

\*\* Each of the reported measures was entered as a dependent variable in a separate LME, with the following structure: *Model.Name = lmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile)*

Table 3.

Observed means (*SD*) for measures of target word processing for high-frequency (HF) and low-frequency (LF) words.

\* “Binoc” = binocular presentation of the entire sentence; “MF” = monocular presentation of the fixated word; “MPL” = monocular presentation of parafoveal text to the left of fixation; “MPR” = monocular presentation of parafoveal text to the right of fixation; “Monoc” = monocular presentation of the entire sentence

Variable	Frequency	<u>Condition</u>				
		<u>Binocular</u>	<u>MF</u>	<u>MPR</u>	<u>MPL</u>	<u>Monocular</u>
Regressions into region	HF	0.13 (0.47)	0.19 (0.40)	0.32 (0.68)	0.30 (0.66)	0.24 (0.56)
	LF	0.69 (0.90)	0.48 (0.68)	0.45 (1.08)	0.76 (0.71)	0.94 (1.60)
Number of first pass fixations	HF	1.25 (0.48)	1.2 (0.45)	1.21 (0.41)	1.18 (0.43)	1.27 (0.45)
	LF	1.62 (0.90)	1.47 (0.89)	1.46 (0.76)	1.47 (0.78)	1.40 (0.63)
First fixation duration (ms)	HF	289 (121)	284 (85)	284 (91)	275 (136)	301 (105)
	LF	337 (120)	342 (138)	320 (128)	333 (138)	329 (159)
Gaze duration (ms)	HF	352 (155)	355 (230)	344 (146)	331 (197)	385 (197)
	LF	526 (276)	509 (322)	459 (242)	483 (310)	461 (271)

Table 4. Model estimates for measures of target word processing.

	<u>First fixation duration</u>				<u>Gaze Duration</u>				<u>Number of first-pass fixations</u>				<u>Regressions into target region</u>			
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Binocular (intercept)	5.67	0.05	104.01	<.001	5.76	0.08	75.57	<.001	1.38	0.06	23.89	<.001	0.55	0.12	4.50	<.001
Frequency (LF)	0.14	0.05	2.90	<.001	0.38	0.11	3.45	<.001	0.25	0.09	2.80	<.001	0.74	0.19	3.88	<.001
Presentation (monoc)	0.02	0.05	0.44	.45	0.07	0.11	0.68	.48	0.13	0.09	-1.53	.23	0.29	0.18	1.68	.13
Frequency x Presentation	0.04	0.11	-1.75	.11	0.23	0.16	-1.74	.12	0.27	0.17	-1.59	.16	0.36	0.33	1.11	.28
Frequency (MF)	0.14	0.04	3.49	<.001	0.39	0.11	3.49	<.001	0.25	0.09	2.82	<.001	0.60	0.14	4.40	<.001
Presentation (MF)	0.01	0.05	0.28	0.60	0.00	0.10	0.00	.63	0.11	0.09	-1.24	0.23	0.07	0.12	0.56	.64
Frequency x Presentation	0.02	0.09	0.17	.41	0.05	0.15	-0.32	.75	0.12	0.18	-0.71	0.55	0.25	0.19	1.30	.16
Frequency (MPR)	0.12	0.04	2.95	<.001	0.39	0.11	3.49	<.001	0.25	0.08	2.96	<.001	0.54	0.14	3.83	<.001
Presentation (MPR)	0.01	0.05	-0.23	0.45	0.00	0.10	0.00	.82	0.11	0.08	-1.31	.23	0.03	0.12	0.26	0.89
Frequency x Presentation	0.07	0.09	-0.72	0.35	0.05	0.15	-0.32	.19	0.15	0.16	-0.90	.49	0.21	0.20	1.54	.14
Frequency (MPL)	0.17	0.04	4.20	<.001	0.30	0.06	5.05	<.001	0.27	0.08	3.17	<.001	0.64	0.16	4.06	<.001
Presentation (MPL)	0.02	0.05	-0.48	.47	0.10	0.06	-1.61	.54	0.13	0.08	-1.61	.19	0.12	0.13	0.96	.38
Frequency x Presentation	0.09	0.09	0.91	.31	0.01	0.13	-0.09	.39	0.10	0.16	-0.62	.43	0.09	0.24	0.37	.88

\* Each of the reported measures was entered as a dependent variable in a separate LME, with the following structure: *Model.Name = lmer(DV ~ Condition\*Frequency + (Condition + Frequency|Participant) + (1|Item), data = DataFile)*

## Appendix 1.

## Experimental stimuli

1. Alice waters those exotic white *flowers/orchids* every five days during warmer months.
2. George always makes lovely fresh *coffee/crepes* when Jenny comes back from running.
3. Lizzie bought that purple silky *dress/cloak* while shopping with Laura last Friday.
4. When police officers went inside that large *house/crypt*, they found more clues.
5. Julie often drank tasty fresh *orange/lychee* juice during that long summer trip.
6. During cold months, Katie wears that *yellow/pastel* woollen scarf when walking outside.
7. During rugby games, fans always *cheer/ovate* when their team scores more points.
8. Those shallow lakes turned into thick *nasty/fetid* swamps after another long drought.
9. Roses were planted around father's *garden/vinery* years before those houses were built.
10. Those clever young thieves *quickly/niftily* covered their tracks before they were seen.
11. Anne never liked John's cousin, whose *stupid/oafish* remarks upset everyone last night.
12. Kings always fought with their loyal *friends/vassals* beside them, thus gaining power.
13. Some older liberal party members *think/opine* that civil laws need more changes.
14. Mary worried that extreme heat could *damage/deform* those rare delicate black pearls.
15. They feared their aunt's stern *voice/glare*, which always made them very nervous.
16. This business plan could *bring/incur* large costs unless someone offers expert advice.
17. After last night's party, Harry managed some *broken/fitful* sleep until sunrise came.
18. Jack could hardly hear Lilly's *quiet/reedy* voice after closing that heavy door.
19. Bold young cowboys often chase wild *horses/dingos* across those vast desert lands.
20. That small ship cruised along another *river/fjord* while tourists took more photos.
21. Their mother seemed very *happy/jolly* after finding those lost letters last night.
22. That greedy mayor made plans without *thought/scruple* about people from remote areas.
23. Alex would need better trading *profit/acumen* before opening another large bike shop.
24. Many people face this common *problem/pitfall* when changing their mobile phone number.
25. After that debate, Jake could never *accept/recant* other people's views about religion.
26. Their maths teacher would always *explain/iterate* complex rules until they were clear.
27. They never learned that critical *story/axiom* which affected their exam results poorly.
28. Locals often drink from those *little/turbid* streams, but tourists should avoid that.



29. Anne's twin girls both have long *black/mousy* hair framing their round faces.
30. Track runners usually have *strong/sinewy* lean muscles after training for many years.
31. That famous French chef *cooked/glazed* fresh carrots, then served them with sauce.
32. They were driving through that lovely *town/glen* when their engine suddenly seized.
33. Linda knew that famous young *doctor/sleuth* because they studied together years ago.
34. While Alex finds those books very *scary/vapid*, John really loves reading them.
35. With that smile Kelly easily *tricks/coaxes* others into doing very boring work.
36. After coming home, they noticed some *sweet/acrid* smell coming from their kitchen.
37. Bill looked across that narrow *field/chasm* where several small houses once stood.
38. The young couple felt that their *lunch/tryst* could have been planned better.
39. Many ideas vary between different pagan *groups/covens*, often even among single members.
40. Many staff members will *bother/accost* John with questions after that budget meeting.