

# Lexical parafoveal previewing predicts reading speed

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## Article

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# 1 Lexical parafoveal previewing predicts reading speed

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6

## 7 **Abstract**

8 **While reading is an essential human skill, the neuronal mechanisms supporting**  
9 **proficient reading are not well understood. In spite of the reduced visual acuity,**  
10 **parafoveal information plays a critical role in natural reading. However, it is debated**  
11 **whether words are previewed parafoveally at the lexical level. This is a key dispute for**  
12 **competing models on reading. We found neural evidence for lexical parafoveal**  
13 **previewing by combining a novel rapid invisible frequency tagging (RIFT) approach**  
14 **with magnetoencephalography (MEG) and eye-tracking. In a silent reading task, target**  
15 **words were tagged (flickered) subliminally at 60 Hz. The tagging responses measured**  
16 **when fixating on the pre-target word reflected parafoveal previewing of the target**  
17 **word. We observed stronger tagging responses during pre-target fixations when**  
18 **followed by low compared to high lexical frequency targets. Moreover, this lexical**  
19 **previewing predicted individual reading speed. Our findings demonstrate that reading**  
20 **unfolds in the fovea and parafovea simultaneously to support fluent reading.**

21

22

## 23 **Introduction**

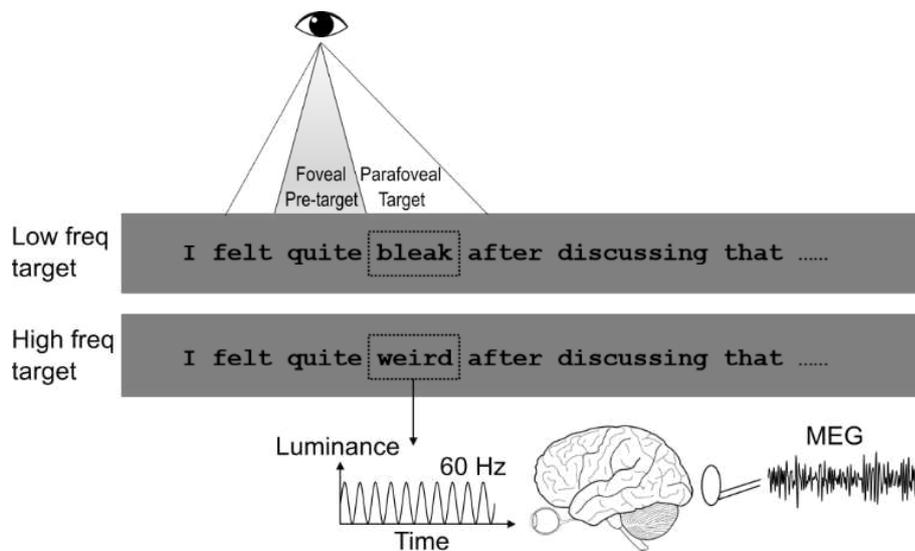
24 Humans have developed the remarkable skill of reading, allowing for efficient acquisition of  
25 information from busy pages or screens of text. Given the importance of written text for  
26 communication, individuals with reading disabilities are highly disadvantaged in modern  
27 society. Yet, we know little about the neuronal mechanism underlying natural reading.

28 It is well known that reading is severely impaired when masking out the parafoveal area (i.e.,  
29 2 to 5 visual degrees to the current fixation)<sup>1-5</sup>. This finding shows that parafoveal  
30 information plays a critical role in fluent reading regardless of its relatively low visual acuity.  
31 How much and what type of information is previewed from the parafoveal area is highly  
32 controversial<sup>6</sup>. Lexical information denotes word recognition and impacts when to move our  
33 eyes (for a review see<sup>7</sup>), which is predicted by word frequency (i.e., how often a given word  
34 occurs in the language). Serial attention shift models for reading argue that lexical  
35 information is not generally extracted from the parafovea<sup>8-13</sup>. Accordingly, the ‘attentional  
36 spotlight’ is allocated to one word at a time during each fixation, making it impossible to  
37 simultaneously extract lexical information from the foveal and parafoveal words. In contrast,  
38 parallel graded processing models assume that attention is allocated to several words within  
39 reader’s perceptual span in a graded way<sup>14,15</sup>. The lexical information of both foveal and  
40 parafoveal words can be extracted in parallel.

41 Most studies based on eye-tracking have produced data in support of serial attention shift  
42 models. This is based on the finding that fixation durations on a given foveated word is not  
43 impacted by the lexical frequency of the upcoming parafoveal word<sup>16-20</sup>. However, while  
44 eye-tracker studies have been hugely informative, the technique only indirectly allows for  
45 measuring the allocation of parafoveal attention. Here, we applied a novel technique, *rapid*  
46 *invisible frequency tagging* (RIFT)<sup>21</sup> in combination with magnetoencephalography (MEG)

47 to measure previewing, i.e. attention allocated to upcoming words in the parafovea. RIFT  
48 measures the neuronal excitability associated with attention by flickering stimuli at high  
49 frequencies that are invisible to participants. In previous MEG studies, we have demonstrated  
50 that RIFT captures covert attention, reflected by stronger tagging responses for attended  
51 compared with unattended stimuli<sup>21–24</sup>.

52 In this study we aimed at answering if lexical information is retrieved for upcoming words in  
53 the parafovea during natural reading. We flickered the parafoveal (target) words at 60Hz and  
54 measured the tagging responses during the current (pre-target) fixation. If the tagging  
55 responses during pre-target fixations are modulated by the lexical information of the target  
56 words, then it would indicate that lexical information can be extracted from the parafovea and  
57 provide neural evidence for parallel models.



58  
59 **Fig. 1 The reading task.** Participants (n = 39) read sentences silently, while eye-movements  
60 and brain activity were recorded. Each sentence contained either a low or high lexical  
61 frequency target word (see dashed rectangle; not shown in the experiment). A Gaussian  
62 smoothed patch beneath the target word was flickered at 60 Hz continuously when the  
63 sentence was on the screen. This allowed us to measure neural responses associated with  
64 lexical previewing using rapid invisible frequency tagging (RIFT). One-quarter of the  
65 sentences were followed by a simple yes-or-no comprehension question to ensure that  
66 participants read the sentences carefully.

67  
68 **Results**

69

## 70 **No lexical parafoveal previewing effect on eye movement data**

71

72 In the present study, 39 participants read 228 sentences in total (composed of two sets of  
 73 sentences). All sentences were plausible and contained unpredictable target words of either  
 74 low or high lexical frequency (see Supplementary information for plausibility and  
 75 predictability pre-tests details). Word length for both pre-target and target words were  
 76 matched with respect to low and high lexical frequency of the target words (Table 1). Target  
 77 words were flickering at 60 Hz throughout the reading of each sentence while the neuronal  
 78 activity was measuring by MEG (Fig. 1). When participants fixated on the pre-target word,  
 79 the flickering target induced reliable tagging responses at 60 Hz, reflecting the neural  
 80 resources for parafoveal previewing. Thus, this experimental design allowed us to investigate  
 81 neural activity associated with lexical parafoveal previewing without interfering with natural  
 82 reading.

Table 1 | Characteristics of words in the experimental materials

Measure	Pre-target	Target			Post-target	
	Length	Low frequency	High frequency	Length	Position	Length
Mean	6.1	5.3	95.3	5.8	6.7	6.7
SD	1.5	4.5	135.5	0.8	2.3	1.7

83

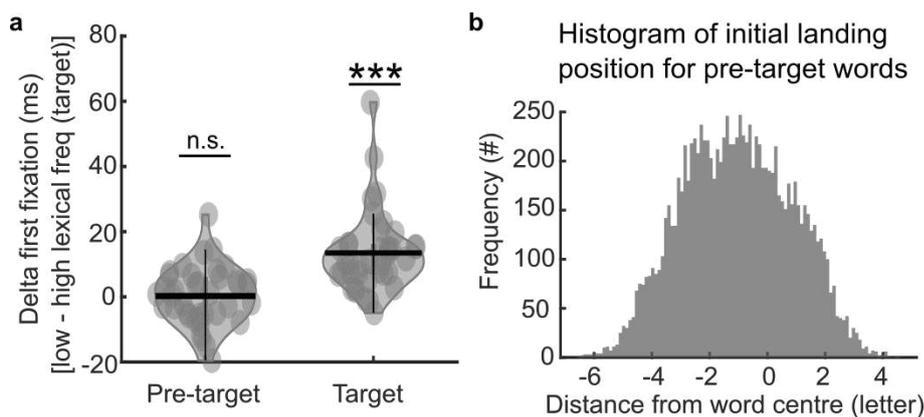
84 **Table 1. Characteristics of words used in the current study.** Low (<10) and high lexical  
 85 frequency (>30) target words are reported in terms of the total CELEX frequency per  
 86 million<sup>25</sup>. Length is the number of letters in a word. Position refers to the location in a  
 87 sentence where the target word is presented and is measured in the number of words. These  
 88 sentences contain  $11.2 \pm 2.1$  words.

89

90 In line with previous studies<sup>16-20</sup>, we did not find an effect of target word lexical frequency  
 91 on pre-target first fixation durations (i.e. the duration of the *first* fixation on a word) ( $t_{(38)} =$   
 92  $0.17, p = 0.86, d = 0.03$ , two-tailed pairwise t-test, Fig. 2a). This finding demonstrates that  
 93 eye movement data provides no evidence for parafoveal lexical previewing. However, the

94 target fixation durations were longer for low compared with high lexical frequency targets  
95 ( $t_{(38)} = 6.94, p = 3 \times 10^{-8}, d = 1.11$ , two-tailed pairwise t-test). The classic word frequency  
96 effect indicates a successful manipulation of target lexical frequency. We observed the same  
97 pattern using gaze durations (i.e. the sum of all fixations on a word when it is first  
98 encountered during reading; Supplementary Fig. 1).

99 Some researchers argue that mislocated fixations and/or oculomotor errors explain the  
100 existence of lexical parafoveal previewing<sup>26,27</sup>. In such cases, fixations intended for the target  
101 word are undershoot and landed on the pre-target word. Thus, the information extracted from  
102 the target word during the pre-target fixation was wrongly associated with ‘foveal’ processing  
103 since the fixation was originally intended for the target word. We performed a *landing*  
104 *position analysis* to examine the accuracy of landing positions. The first fixations landed on  
105 pre-target words with a high accuracy (Fig. 2b,  $-1.1 \pm 1.9$  letters to the word centre, mean  $\pm$   
106 SD) and slightly left-shifted. The landing position accuracy together with the absence of a  
107 lexical frequency effect on the pre-target word (Fig. 2a), indicating that the source of our  
108 neural parafoveal effect (see below) was not linked to mislocated fixations.



109

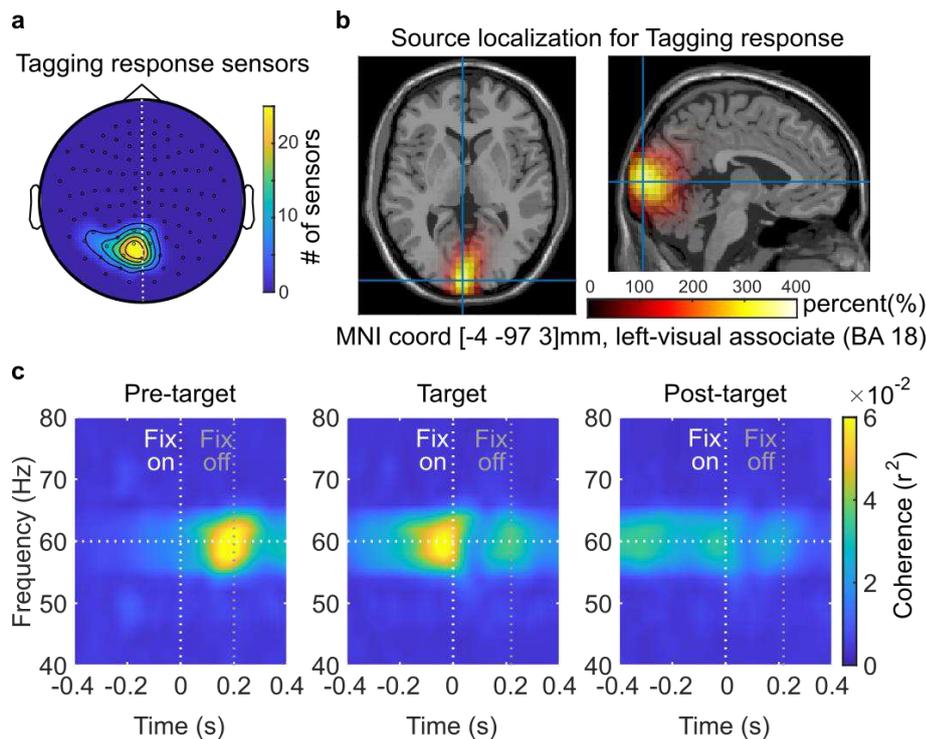
110 **Fig. 2. Eye movement metrics.** (a) The first fixation duration difference for pre-target and  
111 target words when comparing low versus high lexical frequency target words. (\*\*\*)  $p < 0.001$ ,  
112  $n = 39$ ). The horizontal bar in the violin plots indicates the mean value; each dot represents  
113 one participant. (b) Landing positions for the first fixation on pre-target words were estimated  
114 in the unit of letter, aligning according to the word centre ( $-1.1 \pm 1.9$ , mean  $\pm$  SD).

115

## 116 **Rapid invisible frequency tagging captures lexical parafoveal previewing**

117 We analyzed the MEG data to uncover the brain activity associated with lexical processing  
118 before saccading to the target word. A measure of time-resolved coherence ( $r^2$ ) between the  
119 60 Hz visual flicker and the brain activity was used to quantify the tagging responses (see  
120 Methods for details).

121 We found strong taggings response over the left visual cortex sensors (Fig. 3a), reflecting the  
122 neural resources associated with parafoveal previewing. This was observed as a robust 60 Hz  
123 visual flicker-to-MEG coherence during pre-target fixations (caused by the target flickering  
124 in the parafovea) as compared with a baseline period (the cross-fixation presented before  
125 sentence onset). This analysis was conducted by pooling data over the target lexical  
126 frequency conditions. In 26 out of the 39 participants, one or more sensors showed significant  
127 tagging responses ( $5.4 \pm 4.0$  sensors per participant, mean  $\pm$  SD). The subsequent analyses  
128 were based on these participants and sensors. A source modelling approach revealed that the  
129 generators of this 60 Hz coherence were localized in the early visual cortex (Brodmann area  
130 17, 18; Fig 3b). The time course of the 60 Hz coherence is shown in Fig. 3c. Note the robust  
131 60 Hz coherence from the target word when fixating on the pre-target word. These results  
132 demonstrate that RIFT is a sensitive tool for measuring brain activity associated with  
133 parafoveal previewing during natural reading.



134

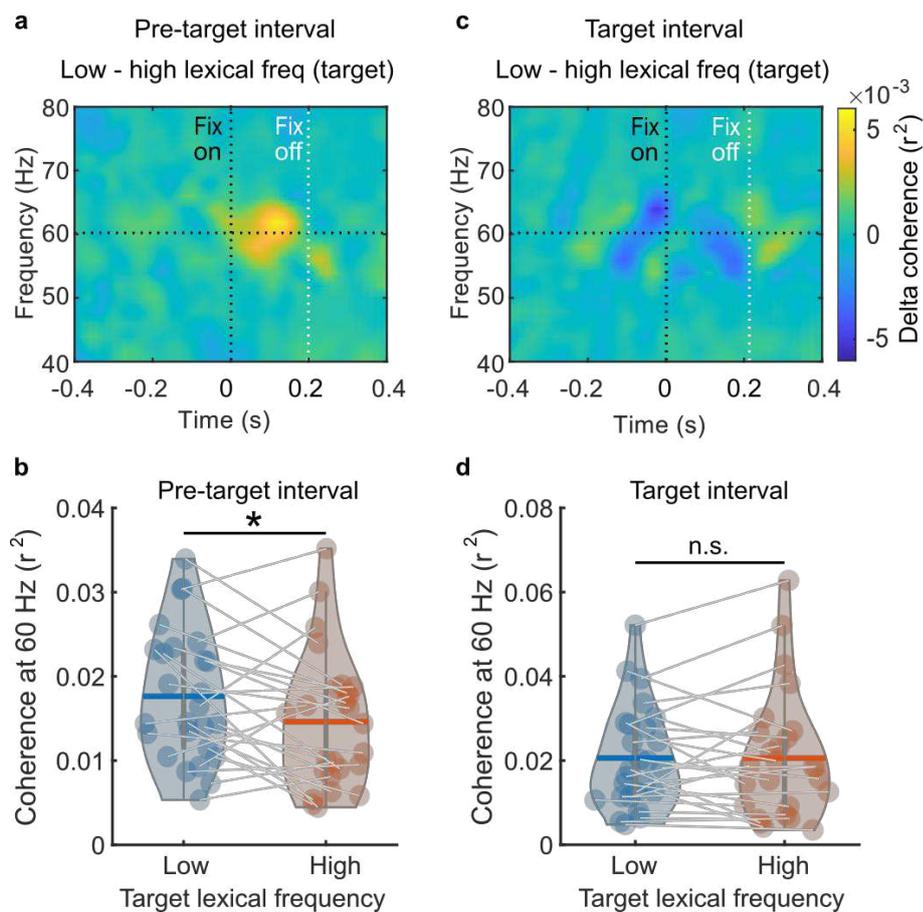
135 **Fig. 3. Neural responses of the rapid invisible frequency tagging.** (a) Topography for  
 136 sensors from all participants that showed stronger tagging responses during the pre-target  
 137 period (flicker) compared with the baseline period (no-flicker, n=26). (b) These tagging  
 138 responses were localized in the left visual cortex. (c) The time-course of neural tagging  
 139 responses during the pre-target (left panel), target (middle panel), and post-target  
 140 fixation periods (right panel). Vertical white and gray lines indicate fixations onsets and average  
 141 offsets.

142

### 143 Neural evidence for lexical parafoveal previewing

144 Next, we addressed if the RIFT responses were modulated by the lexical frequency of target  
 145 words. Our key finding was that the coherence at 60 Hz during the pre-target fixation was  
 146 significantly stronger when followed by a low compared with a high lexical frequency target  
 147 word (Fig. 4a; Fig. 4b,  $t_{(25)} = 2.20$ ,  $p = 0.037$ ,  $d = 0.43$ , two-tailed pairwise t-test). To ensure  
 148 that the coherence in pre-target fixation was not contaminated by temporal smoothing from  
 149 the target fixation, the time window for averaging coherence was adjusted individually  
 150 according to the shortest pre-target fixation duration ( $88.3 \pm 8.9$  ms across participants, mean  
 151  $\pm$  SD). Because the number of trials biases coherence magnitude, we subsampled the same  
 152 number of trials for both conditions in each participant (by randomly selecting trials from the

153 condition with more trials). In sum, we found neural evidence that lexical information was  
 154 extracted from the parafovea. Furthermore, we also assessed the timing for lexical parafoveal  
 155 previewing. Onset latency for the pre-target 60 Hz coherence was measured for different  
 156 target conditions using the Jackknife-based method<sup>28</sup>. An earlier onset latency was observed  
 157 for pre-target words that followed by low compared with high lexical frequency target words  
 158 (see Supplementary Figure 2). However, we only observed this effect to be robust in the  
 159 sentence set with short words, which indicates the importance of word length in parafoveal  
 160 previewing<sup>29-31</sup> (see Supplementary note for details). Importantly, this effect was already  
 161 visible around the first 100ms of the pre-target fixation (72ms for low lexical frequency  
 162 target; 116ms for high lexical frequency target).



163  
 164 **Fig. 4. Neuronal evidence for lexical parafoveal previewing.** (a) Time-resolved coherence  
 165 differences during pre-target word fixations (low minus high lexical frequency target words;  
 166  $n = 26$ ) revealing a lexical previewing effect around 100 ms after fixation onset. (b) The  
 167 averaged pre-target coherence at 60 Hz during pre-target fixations for low (blue) and high

168 (orange) lexical frequency target words (\*  $p = 0.037$ ). (c, d) During target word fixations we  
169 did not observe a coherence difference with respect to lexical frequency. Horizontal bars in  
170 the violin plots indicate mean value. Each dot presents one participant.

171

## 172 **No frequency tagging contamination of lexical effect from foveal processing**

173 Next we tested whether the lexical frequency effect could also be observed during target  
174 fixations (Fig. 4c). As in the pre-target analysis, the averaging time window for the coherence  
175 was the minimum target fixation duration for each participant ( $87.1 \pm 9.4$  ms, mean  $\pm$  SD).

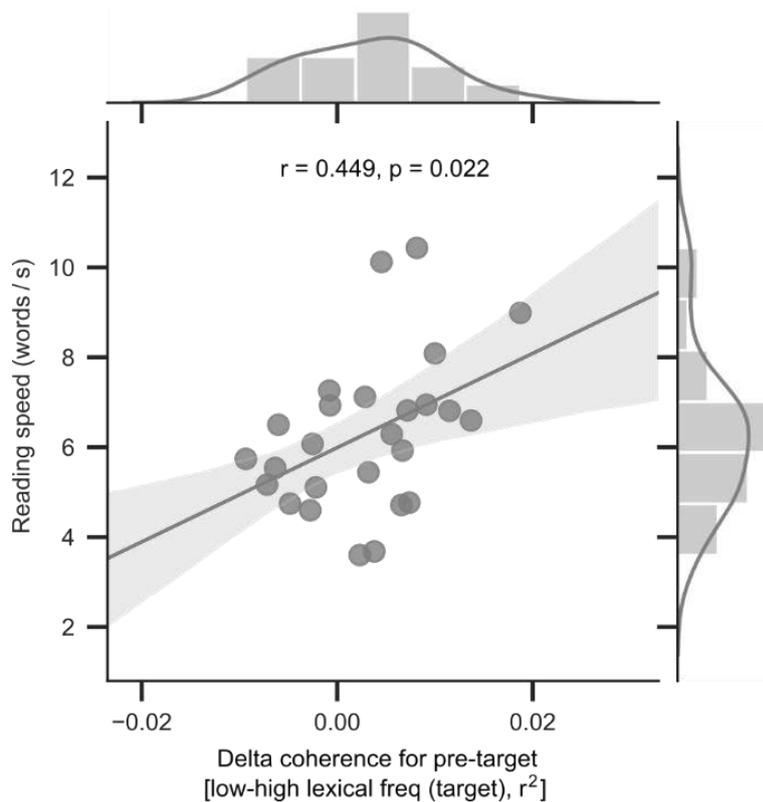
176 We observed no significant coherence difference when fixating on low versus high lexical  
177 frequency target words (Fig. 4d;  $t_{(25)} = 0.01$ ,  $p = 0.992$ ,  $d = 0.002$ , two-tailed pairwise t-test).

178 Presumably, the finding that the flickering did not affect target word viewing might be related  
179 to the fact that flicker sensitive photoreceptors (rod cells) mainly exist in the parafovea of the  
180 retina<sup>32</sup>. As a consequence, there would be reduced sensitivity to flickering when the target  
181 word is in foveal vision. We conclude that the lexical effect that we observed during pre-  
182 target fixations was not due to a contamination from target fixations.

183

## 184 **Lexical parafoveal previewing facilitates reading**

185 We correlated the coherence difference with respect to lexical frequency of the target word  
186 when fixating the pre-target word with individual reading speed. Reading speed was  
187 quantified as the number of words read per second (calculated as the total number of words in  
188 a sentence divided by the respective sentence reading time). We found a positive correlation  
189 (Fig. 5;  $r_{(25)} = 0.45$ ,  $p = 0.022$ , Spearman correlation), indicating that participants who  
190 captured more lexical information in the parafovea were also faster readers.



191

192 **Fig. 5. Relation between lexical parafoveal processing difference and individual reading**  
 193 **speed.** The coherence-difference with respect to target lexical frequency during fixations on  
 194 pre-target words were derived per participant (see **Fig. 4b**). The reading speed was quantified  
 195 as the number of words read per second. Each dot represents a participant. A Spearman  
 196 correlation demonstrated a significant relation ( $n = 26$ ). The shaded area indicates a 95%  
 197 confidence interval. Histograms of individual reading speed and pre-target coherence  
 198 differences are shown on the top and to the right.

199

## 200 Discussion

201 Our findings shed new light on the long-standing debate between models arguing for either  
 202 serial attention shift<sup>8,9</sup> or parallel graded processing<sup>14,15</sup>. Both models regard spatial attention  
 203 as important for reading but they differ on whether more than one word can be accessed  
 204 simultaneously at the lexical level. Parallel graded models predict that the lexical frequency  
 205 of both foveal and parafoveal words can be processed simultaneously. This idea is challenged  
 206 by the fact that only a few correlation-based corpus studies found lexical parafoveal effects in  
 207 eye movement data<sup>33,34</sup>, while more well-controlled experimental studies did not<sup>16-18</sup> (for a  
 208 meta-analysis study see<sup>27</sup>), and neither did our eye movement results (Fig. 2a). But these

209 conclusions are based on eye movement studies, we found neural support for parallel graded  
210 models: lexical parafoveal effects were observed within 100ms from pre-target onset (Fig.  
211 4b). This finding does not seem to be compatible even with the most temporally compressed  
212 version of a serial model, in which the attentional shift and a significant amount of lexical  
213 parafoveal previewing occur during saccadic programming<sup>35-37</sup>. Moreover, evoked response  
214 studies based on EEG<sup>38,39</sup> and MEG<sup>40</sup> provide evidence for lexical frequency effects for  
215 foveally fixated words no earlier than 100 ms. Our results showed a lexical frequency effect  
216 for the parafoveal word at around 100 ms, which supports the idea of parallel processing of  
217 foveal and parafoveal information. In particular, we provide evidence that parafoveal lexical  
218 frequency modulates neural excitability, in support of a parallel model of reading.

219 One might ask why lexical parafoveal previewing is reflected in the neuronal responses (Fig.  
220 4b) but not in fixation durations (Fig. 2a)? This discrepancy indicates that two systems are at  
221 play simultaneously: covert and overt attention. The fixation duration on a foveal word (pre-  
222 target) captures overt attention, while the RIFT, which reflects the steady-state response to  
223 the parafoveal word (target), captures covert attention. However, these two parallel processes  
224 might not get equal attentional resources. Because the parafoveal word attracts less attention  
225 than the foveal word, its activation level might be insufficient to affect the current foveal  
226 saccade planning and fixation duration. Other studies using a rapid simultaneous visual  
227 presentation paradigm also show that words can be identified in parallel without rising to a  
228 high level of awareness<sup>41</sup>. Nevertheless, even though readers might not be consciously aware  
229 of their parafoveal previewing, it does accelerate individual reading as shown in our  
230 correlation analysis (Fig. 5). Taken together, our study shows that natural reading involves  
231 the simultaneous processing of several words, providing novel neural evidence for the idea  
232 that “readers are parallel processors”<sup>42</sup>.

233 The neuronal response reflecting previewing was observed in the early visual cortex. This  
234 might be a surprise, as functional Magnetic Resonance Imaging studies have localized lexical  
235 frequency to e.g. the visual word form area<sup>43</sup>. According to interactive processing theories,  
236 higher-level lexical information interacts with lower-level visual information during word  
237 recognition<sup>38,44</sup> and the top-down modulation can be measured by MEG over sensory  
238 cortices<sup>45</sup>. Thus, lexical frequency information extracted in the parafovea could direct visual  
239 attention covertly. Increased spatial attention will boost tagging responses<sup>21,22</sup>, resulting in  
240 stronger coherence for the pre-target word followed by a low compared with a high lexical  
241 frequency target word.

242 Our results show that RIFT is a new powerful technique to investigate parafoveal reading. A  
243 classic paradigm in this field is the gaze-contingent boundary task developed by Keith  
244 Rayner in 1975<sup>46</sup>. In this task, parafoveal information is manipulated by changing the target  
245 word while saccading to it<sup>17,47</sup>. This approach allows for manipulating parafoveal previewing  
246 and has made great contributions to studies on parafoveal previewing (for reviews see<sup>7,48</sup>).  
247 However, the approach is limited, as changing the target word inevitably disrupts the  
248 integration of information across fixations and interferes with natural reading. This  
249 interference has been shown in many gaze-contingent studies in which reading performance  
250 is reduced when words are manipulated in the parafovea<sup>17,49-51</sup>. Fixation or event-related  
251 potentials based on EEG is another method used in reading studies<sup>52-55</sup>, and have shown  
252 different brain activity patterns for different word presentation rates, addressing the  
253 importance of using natural reading paradigms<sup>56</sup>. While fixation-related potentials method  
254 has provided important insights by demonstrating a lexical frequency effect for foveal word  
255 recognition on the N1 component<sup>38,39</sup>, it has failed to provide conclusive results with regard  
256 to parafoveal lexical processing<sup>17,18</sup>. The novel approach we present in this study based on

257 subliminal frequency tagging allows for capturing brain activity associated with parafoveal  
258 previewing during natural reading.

259 It will be important for future studies to use the RIFT to investigate other factors of parallel  
260 information capture during reading, such as whether parafoveal information can be extracted  
261 at the semantic level. Another direction is investigating the primary determinants of reading  
262 proficiency in relation to parafoveal previewing. For instance, previewing at the phonological  
263 and orthographic level<sup>57</sup> has been found to reflect reading proficiency. We found that the  
264 neuronal signature of lexical previewing predicted reading speed, which could be used as a  
265 potential indicator to diagnose reading disorders such as dyslexia. Besides, some researchers  
266 argue that dyslexia is due to spatial processing problems in the magnocellular visual  
267 pathway<sup>58</sup>, as shown in an MEG study<sup>59</sup>. Our frequency tagging approach could be helpful to  
268 understand the underlying neural mechanism of dyslexia in relation to the allocation of  
269 spatial attention.

270 In sum, the present study demonstrates that RIFT is a powerful tool for investigating natural  
271 reading, and provides novel neural evidence for lexical parafoveal previewing in support of  
272 parallel graded models of reading.

273

## 274 **Methods**

### 275 **Participants**

276 Our study recruited forty-three participants (28 females), aged  $22 \pm 2.6$  (mean  $\pm$  SD), right-  
277 handed, with normal or corrected-to-normal vision, and without a neurological history or  
278 language disorder diagnosis. Four of them were excluded from analysis due to poor eye  
279 tracking or falling asleep during the recordings, which left thirty-nine participants (25

280 females). The University of Birmingham Ethics Committee approved the study. The  
281 participants provided written informed consent and received £15 per hour or course credits as  
282 compensation for their participation.

## 283 **Stimuli**

### 284 *1<sup>st</sup> sentence set*

285 We constructed 142 sentences embedded with 71 target word pairs (low/high lexical  
286 frequency). For each sentence, the pre-target, target, and post-target words were in the same  
287 structure as adjective + noun + verb. For each target pair, two different sentence frames were  
288 made, and each participant read both target words embedded in these two different frames.  
289 For example, for the target pair **waltz/music** (low/high lexical frequency), one participant  
290 read version A, another one read version B (see below, targets are in bold for illustration, but  
291 not in the real experiment).

292 A. Mike thought this difficult **waltz** received lots of criticism.

293 It was obvious that the beautiful **music** captured her attention.

294 B. Mike thought this difficult **music** received lots of criticism.

295 It was obvious that the beautiful **waltz** captured her attention.

296 The sentences in version B were made from version A by circular shifting the first and  
297 second half of the sentences. For both versions, no more than 3 successive sentences were  
298 from the same target lexical frequency condition.

### 299 *2<sup>nd</sup> sentence set*

300 This sentence set was adapted from Degno et al., 2019<sup>17</sup>. We removed sentences that  
301 contained the same pre-target or target words as in the 1<sup>st</sup> sentence set, which left 86  
302 sentences. Each sentence was embedded with two target words from the same lexical

303 frequency condition (see below, version A contained two low lexical frequency targets, while  
304 version B contained two high lexical frequency targets).

305 A. I felt quite **bleak** after discussing that really **risky** subject with Paul.

306 B. I felt quite **weird** after discussing that really **nasty** subject with Paul.

307 Each participant read either version A or B. The same control for sentence presentation was  
308 counterbalanced as in the 1<sup>st</sup> set.

309 We conducted pre-tests with another group of participants to make sure all sentences were  
310 plausible with either low- or high-lexical frequency target word, and that the target words  
311 were not predictable (see Supplementary information).

## 312 **Procedure**

313 Participants were seated comfortably in the MEG gantry, 145 cm away from the projection  
314 screen in a dimly-lit magnetically shielded room. One-line sentences were presented on a  
315 middle-grey screen using Psychophysics Toolbox -3<sup>60</sup>. Every sentence started at the same  
316 position: two degrees to the right of the middle of the screen left edge and was presented on  
317 the vertical centre. Words were displayed in black font colour with an equal-spaced Courier  
318 New font (size 22). Each letter and space between two words occupied 0.35 visual degrees. In  
319 total, no sentence was longer than 27 visual degrees horizontally. Two sets of sentences,  
320 consisting of respectively 142 and 86 sentences, were divided into 7 blocks. Each block took  
321 approximately 7 minutes to read and was followed by a rest for at least 1 minute. Participants  
322 were instructed to read each sentence silently at their own pace and to keep their head and  
323 body as stable as possible during the MEG session. Eye movements were acquired during the  
324 whole session.

325 Each trial started with a central fixation cross on a grey screen centre presented for 1.2 – 1.6  
326 s. Then followed by a square (1 degree wide) presented 2 degrees to the right of the middle of

327 the screen left edge. A gaze of at least 0.2 s on this square triggered sentence onset. The  
328 square was replaced by the first word of the sentence. The text was presented in the equal  
329 spaced Courier New font, and each letter occupied 0.35 visual degrees (Fig. 1). After reading  
330 the sentence, participants were instructed to fixate on a square below the screen centre for 0.1  
331 s to trigger the sentence offset. One-quarter of the trials were followed by a simple yes-or-no  
332 comprehension question to ensure careful reading. All participants answered the questions  
333 with high accuracy ( $95.4\% \pm 4.7\%$ , mean  $\pm$  SD).

### 334 **Rapid invisible frequency tagging**

#### 335 *Projector*

336 To generate the rapid invisible frequency tagging, sentence stimuli were presented with a  
337 refresh rate up to 1440 Hz using a PROPiXX DLP LED projector (VPiXX Technologies Inc.,  
338 Canada). This was done by presenting the sentence stimuli repeatedly in four quadrants on  
339 the stimulus computer screen ( $1920 \times 1200$  pixels resolution) with a refresh rate of 120 Hz.  
340 For each quadrant, the stimuli were coded in RGB three colour channels. The projector  
341 interpreted these 12 colour channels (3 channels  $\times$  4 quadrants) as 12 individual grayscale  
342 frames and projected them onto the projector screen separately in rapid succession. Hence,  
343 the refresh rate for stimuli presentation was 1440 Hz (120 Hz  $\times$  12).

#### 344 *Flickering of the target word*

345 To flicker the target word, we added a rectangular patch underneath the target. The width of  
346 the patch was the width of the target word plus the spaces on both sides. The height of the  
347 patch was 1.5 times the word height. The target word was placed in the centre of this  
348 rectangular patch. All pixels within the patch were flickered at 60 Hz by multiplying the  
349 luminance of the pixels with a 60 Hz sinusoid (the modulation depth was 100%). Typically,  
350 the patch was perceived as indistinguishable from the middle-grey screen background, which

351 made it invisible to participants. To reduce the visibility of the patch edges during saccades, a  
352 Gaussian smoothed transparent mask was applied on top of the flickering patch. The mask  
353 was created by a two-dimensional Gaussian function:

$$354 \text{ mask} = \exp\left(-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}\right)$$

355 where,  $x$  and  $y$  are the mesh grid coordinates for the flickering patch, and  $\sigma$  is the x and y  
356 spread of the blob with  $\sigma = 0.02$  degrees. By applying a Gaussian smoothed mask, the  
357 flickering patch was hardly perceived. Only three out of all the thirty-nine participants  
358 noticed the flickering patch according to a questionnaire after the MEG session.

359 A custom made photodiode (Aalto NeuroImaging Centre, Finland) was attached to the right-  
360 below corner of the screen to record tagging signal from a square whose luminance was kept  
361 the same as the flickering patch.

## 362 **Data acquisition**

### 363 *MEG*

364 MEG data were acquired using a 306-sensor TRIUX Elekta Neuromag system with 204  
365 orthogonal planar gradiometers and 102 magnetometers (Elekta, Finland). The data were  
366 band-pass filtered online using anti-aliasing filters from 0.1 to 330 Hz and then sampled at  
367 1,000 Hz. We used a Polhemus Fastrack electromagnetic digitizer system (Polhemus Inc,  
368 USA) to digitize the locations for three bony fiducial points: the nasion, left and right  
369 preauricular points. Then, four head-position indicator coils (HPI coils) were digitized: two  
370 coils were attached on the left and right mastoid bone and another two were on the forehead  
371 with at least 3 cm distance in between. Furthermore, at least 200 extra points on the scalp  
372 were acquired for each participant in order to spatially co-register the MEG source analysis

373 with individual structural MRI image. After preparations, participants were seated upright  
374 under the MEG gantry with the back rest at a 60° angle.

### 375 *Eye movements*

376 The eye-tracker (EyeLink 1000 Plus, SR Research Ltd, Canada) was placed on a wooden  
377 table in front of the bottom edge of the projector screen. The distance between the eye-tracker  
378 camera and the centre of the participant's eyes was 90 cm. It was used throughout the whole  
379 experiment to acquire horizontal and vertical positions of the left eye as well as the pupil size.  
380 Eye movements were sampled at 1,000 Hz. We also placed one pair of electrodes above and  
381 below the right eye (vertical electrooculogram, EOG) and another pair to the left and right of  
382 the eyes (horizontal EOG) to provide additional measures for ocular and eye-blink artefacts.

383 Each session began with a nine-point calibration and validation test. After every three trials,  
384 we performed a one-point drift checking test. If a participant failed to pass drift checking or  
385 was unable to trigger sentence onset through gazing, the nine-point calibration and validation  
386 test was conducted again. The eye-tracking error was limited to below 1 visual degree both  
387 horizontally and vertically.

### 388 *MRI*

389 After MEG data acquisition, we acquired the T1-weighted structural MRI image using a 3-  
390 Tesla Siemens PRISMA scanner (TR = 2000 ms, TE = 2.01 ms, TI = 880 ms, flip angle = 8  
391 degrees, FOV = 256×256×208 mm, 1 mm isotropic voxel). Out of all the thirty-nine  
392 participants, three dropped out of the MRI acquisition, one of them showed robust tagging  
393 responses at the sensor level. For this participant, the MNI template brain (Montreal, Quebec,  
394 Canada) was used instead in later source analysis.

### 395 **MEG data analyses**

396 The data analyses were performed in MATLAB R2019b (Mathworks Inc, USA) by using the  
397 FieldTrip<sup>61</sup> toolbox (version 20200220) and custom-made scripts.

### 398 *Pre-processing*

399 The MEG data were band-pass filtered from 0.5 to 100 Hz using phase preserving two-pass  
400 Butterworth filters. First, the MEG segments were extracted from -0.5 to 0.5 s intervals  
401 aligned with the first fixation onset for pre-target, target, and post-target words, respectively.  
402 Only segments with fixation durations ranging from 0.08 to 1 s entered further analyses.  
403 Segments with too short or too long fixations were discarded. We also extracted 1 s long  
404 baseline segments aligned with the presentation onset for the cross-fixation, which was the  
405 period before sentence onset. Next, the MEG data were demeaned by removing the linear  
406 trend and the mean value. After removing malfunctioning sensors (0 to 2 sensors per  
407 participant), these segments entered an independent component analysis (ICA)<sup>62</sup>. Before the  
408 ICA, a PCA approach was applied to reduce the rank of the data to 30 components. Next, the  
409 components related to eye blinks, eye movements, and heartbeat were rejected. Finally, we  
410 manually inspected all these segments to further identify and remove any segments that were  
411 contaminated by excessive noise like ocular, muscle, or movement artefacts.

### 412 *Coherence calculation*

413 To measure the tagging response associated with target word processing, coherence was  
414 estimated between the MEG sensors and the tagging response of the photodiode (for MEG  
415 sensor selection see below). First, 1s segments were filtered using a phase preserving, two-  
416 pass, Butterworth bandpass filters (4<sup>th</sup> order) with a hamming taper. The centre filter  
417 frequencies were from 40 to 80 Hz in steps of 2 Hz with a 10 Hz frequency smoothing. For  
418 each frequency step, the analytic signals were determined by the Hilbert transform which  
419 then was used as the input for coherence at time point  $t$ :

$$coh(t) = \frac{\left| n^{-1} \sum_{j=1}^n m_{x_j}(t) m_{y_j}(t) e^{i\phi_{xy_j}(t)} \right|^2}{n^{-1} \sum_{j=1}^n m_{x_j}(t)^2 m_{y_j}(t)^2}$$

420 where  $j$  is the trial,  $n$  is the number of trials,  $m_x(t)$  and  $m_y(t)$  are the time-varying  
 421 magnitude of the analytic signals from respectively a MEG sensor and a photodiode,  $\phi_{xy}(t)$   
 422 is the phase difference as a function of time between them. A time-frequency coherence  
 423 representation was obtained as applied in Fig. 3c and Fig. 4a and Fig. 4c.  
 424

#### 425 *RIFT response sensor selection*

426 To identify the MEG sensors that showed reliable tagging responses, we compared the 60 Hz  
 427 coherence during pre-target segments with the coherence during baseline segments. We used  
 428 a non-parametric statistics method named Monte-Carlo to estimate the significance for the  
 429 coherence difference. This method was developed by Maris et al., 2007<sup>63</sup>, and implemented  
 430 in the Fieldtrip<sup>61</sup> toolbox. Both pre-target and baseline segments were 1 s long and were  
 431 aligned with the first fixation onset for pre-target words and the onset for baseline cross-  
 432 fixation separately. The pre-target segments were constructed by pooling the target lexical  
 433 frequency conditions together. Several previous RIFT studies from our lab observed robust  
 434 tagging responses from the visual cortex for visual flickering stimuli<sup>21-24</sup>. Therefore, only  
 435 MEG sensors in the visual cortex (52 planar sensors) entered this sensor selection procedure.  
 436 Here, we regarded pre-target and baseline segments as two conditions in the coherence  
 437 calculation. For a given MEG sensor and photodiode combination, coherence at 60 Hz was  
 438 estimated over trials for each condition. Therefore, one coherence value was obtained for  
 439 each condition. Then, we calculated the z-statistic value for this coherence difference  
 440 between pre-target and baseline using the following equation (for details please see Maris et  
 441 al., 2007<sup>63</sup>) :

$$Z = \frac{(\tanh^{-1}(|coh_1|) - bias_1) - (\tanh^{-1}(|coh_2|) - bias_2)}{\sqrt{bias_1 + bias_2}},$$

$$bias_1 = \frac{1}{2n_1 - 2}, \quad bias_2 = \frac{1}{2n_2 - 2}$$

where  $coh_1$  and  $coh_2$  denote the coherence value for pre-target and baseline condition,  $bias_1$  and  $bias_2$  is the term used to correct for the bias from trial numbers of pre-target ( $n_1$ ) and baseline condition ( $n_2$ ). So, all trials from the pre-target and baseline conditions were used. After obtaining the z statistic value for the empirical coherence difference, a permutation procedure was conducted to estimate the significance probability.

We randomly shuffled the trial labels between pre-target and baseline conditions for 10,000 times. During each permutation, coherence values for both conditions were re-computed so that a z statistic value was estimated for the coherence difference. After all the shuffles, a null distribution for z-values was established. If the empirical z-value was larger than 99% of the null distribution, which meant that the coherence difference between pre-target and baseline was larger than zero at the 0.01 significance level, this sensor was considered to have robust tagging responses. This sensor selection procedure was performed for every sensor in the visual cortex (52 planar sensors in total). Twenty-six out of all the thirty-nine participants showed robust tagging responses at one or more sensors ( $5.4 \pm 4.0$  sensors per participant, mean  $\pm$  SD; Fig. 3a). For each participant, the coherence values were averaged over all tagging response sensors to obtain an averaged coherence.

#### 460 *Source analysis for RIFT*

In order to localize the neural sources that were coherent with the photodiode signals during RIFT, a beamforming approach was performed using Dynamic Imaging Coherent Sources (DICS)<sup>64</sup> implemented in the FieldTrip<sup>61</sup> toolbox. The DICS technique enabled us to calculate the source estimates in the frequency domain with a focus on 60 Hz, which was the

465 RIFT frequency. The beamformer was based on adaptive spatial filters derived for each grid  
466 in the discretized brain volume. In this source analysis, only participants with robust tagging  
467 responses were included ( $n = 26$ ; see Fig. 3a).

468 A semi-realistic head models was constructed using a procedure developed by Nolte in  
469 2003<sup>65</sup>, which uses spherical harmonic functions to fit the brain surface. We first aligned the  
470 individual structural MRI image with the MEG data. This was done by spatially co-  
471 registering the three fiducial anatomical markers from the head shape digitization during the  
472 MEG session (nasion, left and right ear canal). For one participant whose MRI image was  
473 unavailable, the MNI template brain was used instead. Next, this aligned MRI image was  
474 segmented into a grid. Then, we prepared the single-shell head model based on the segmented  
475 MRI image

476 The individual source model was constructed by inverse-warping a 5 mm spaced regular grid  
477 in the MNI template space to each participant's segmented MRI image in the native space.  
478 This regular grid was from the Fieldtrip template folder and was constructed before doing the  
479 source analysis. In this way, the beamformer spatial filter was constructed on the direct grid  
480 that mapped to the MNI template space.

481 The Cross-Spectral Density (CSD) matrix was calculated between all the MEG sensor  
482 combinations and between the MEG sensor and the photodiode combination at 60 Hz in the  
483 whole 1 s time window, with a smoothing of 4 Hz using the hanning taper. For each  
484 participant, we estimated CSD matrices for both the pre-target and baseline segments.

485 Next, a common spatial filter was computed based on the individual single-shell head model,  
486 source model, and CSD matrices using DICS. This spatial filter was applied to both the pre-  
487 target and baseline CSD matrices for coherence computation. This was done by normalizing  
488 the magnitude of the summed CSD between the MEG sensor and the photodiode by their

489 respective power. After the grand average over participants, the relative change for pre-target  
490 coherence was estimated as the ratio between coherence difference and baseline coherence  
491 ( $(coh_{pretarget} - coh_{baseline})/coh_{baseline}$ ). Finally, this source analysis localized the RIFT  
492 neural sources to the left-visual associate, Brodmann area 18, MNI coordinates [-4 -97 3] (see  
493 Fig. 3b, n = 26).

#### 494 **Statistical information**

495 All the t-tests in this study were two-sided pairwise student's t-tests and were conducted in  
496 R<sup>66</sup>.

#### 497 **Data and code availability**

498 The data in this study, as well as the codes to generate the associated figures, will be  
499 available upon request from the corresponding author.

500

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663

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671

## 672 **Author Contributions**

673 Y.P. , S. F., and O.J. devised and designed the experiments, Y.P. made the sentences with  
674 assistance from S.F, Y.P. programmed and conducted the experiments, Y.P. carried out the  
675 analyses with assistance from O.J. and S.F., Y.P., O.J. and S.F. wrote the paper together.

676

## 677 **Competing interests**

678 The authors declare no competing interests.

# Figures

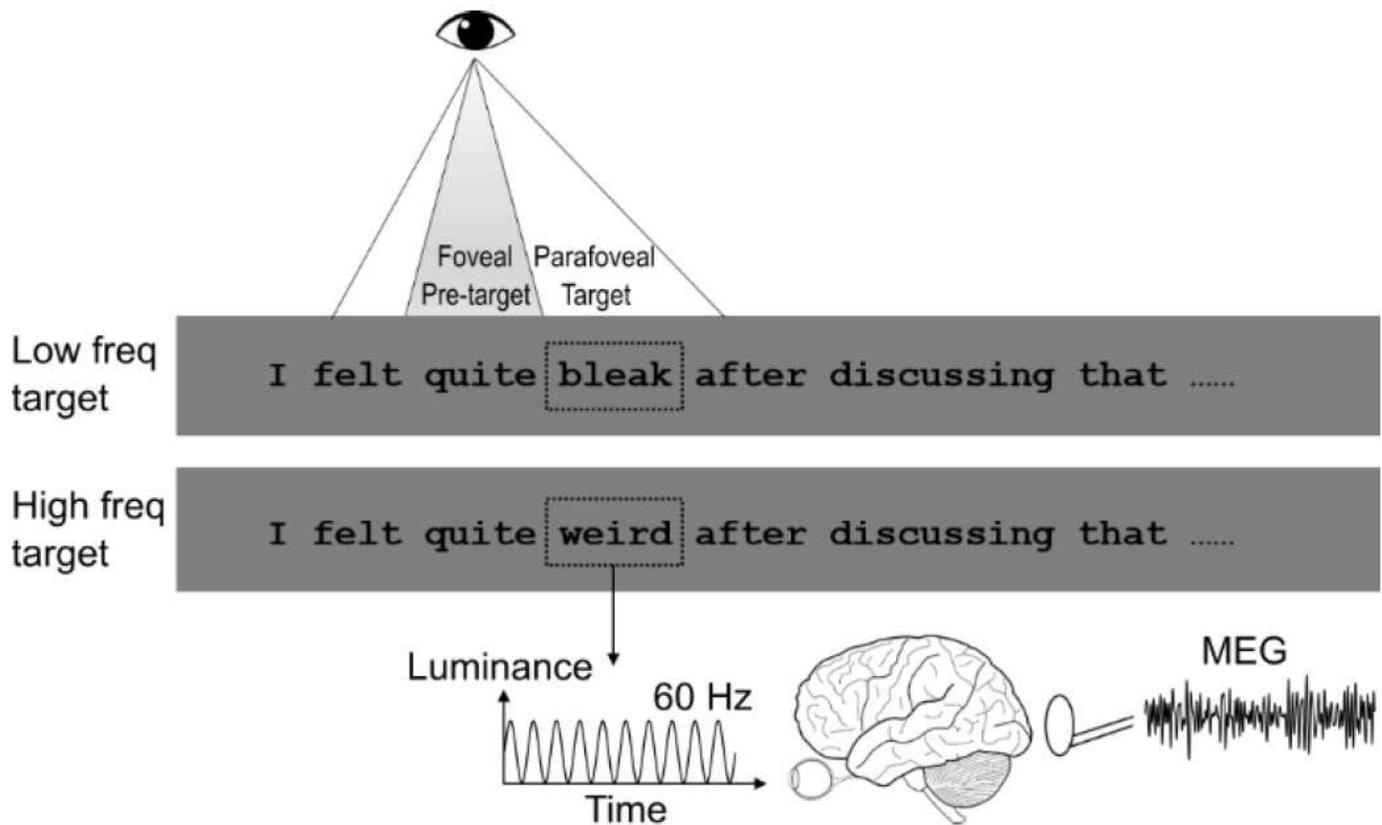
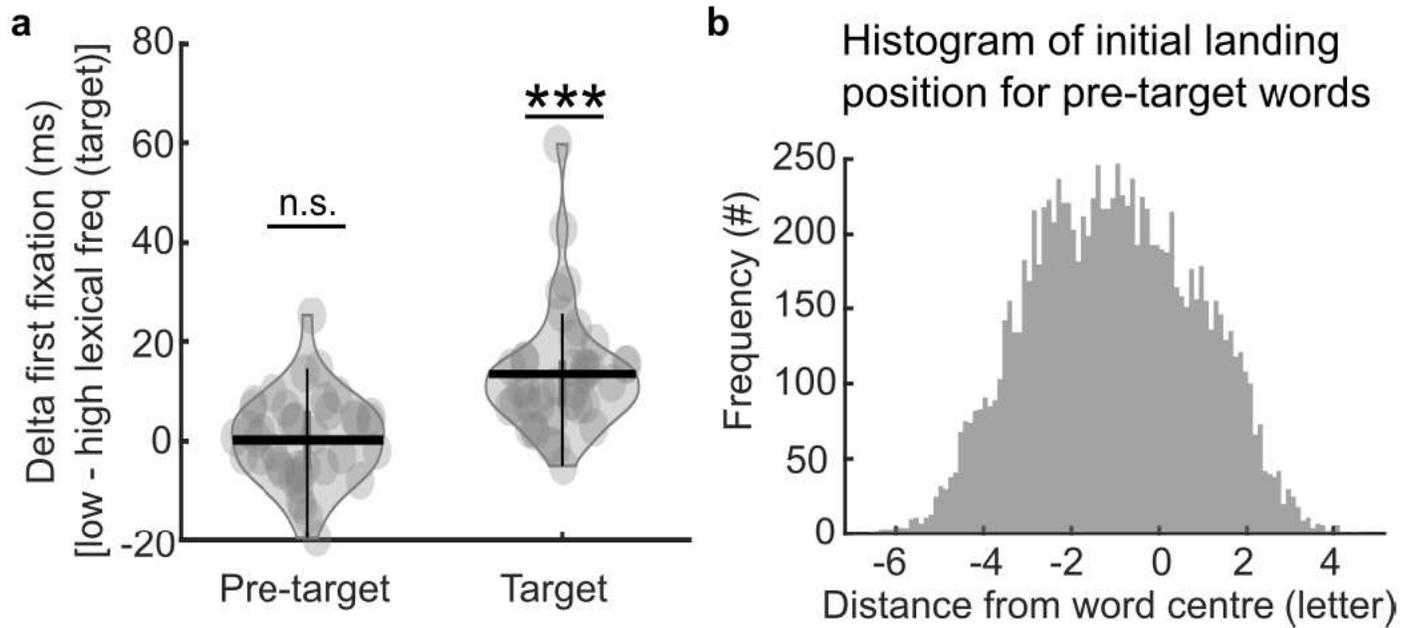


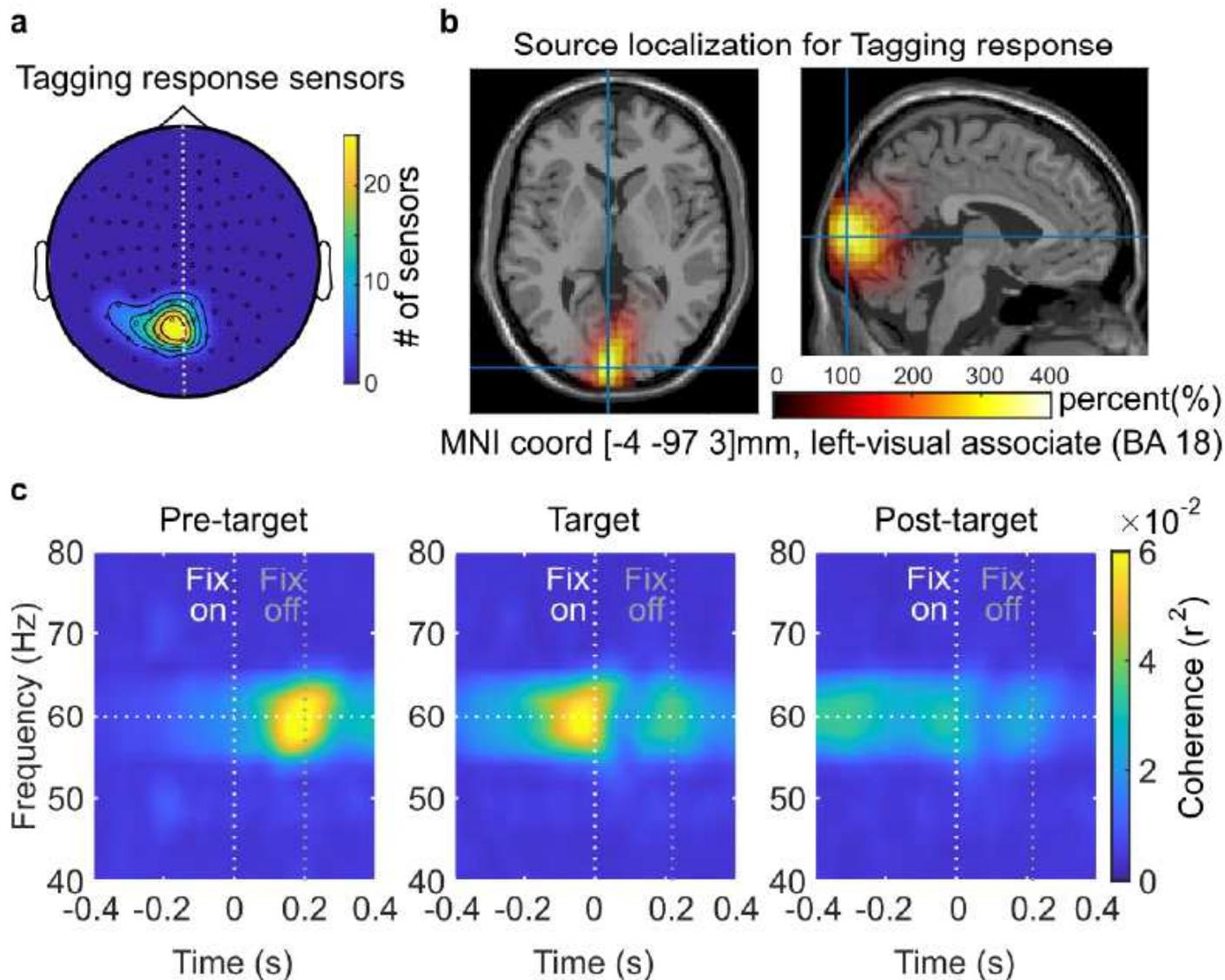
Figure 1

The reading task. Participants ( $n = 39$ ) read sentences silently, while eye-movements and brain activity were recorded. Each sentence contained either a low or high lexical frequency target word (see dashed rectangle; not shown in the experiment). A Gaussian smoothed patch beneath the target word was flickered at 60 Hz continuously when the sentence was on the screen. This allowed us to measure neural responses associated with lexical previewing using rapid invisible frequency tagging (RIFT). One-quarter of the sentences were followed by a simple yes-or-no comprehension question to ensure that participants read the sentences carefully.



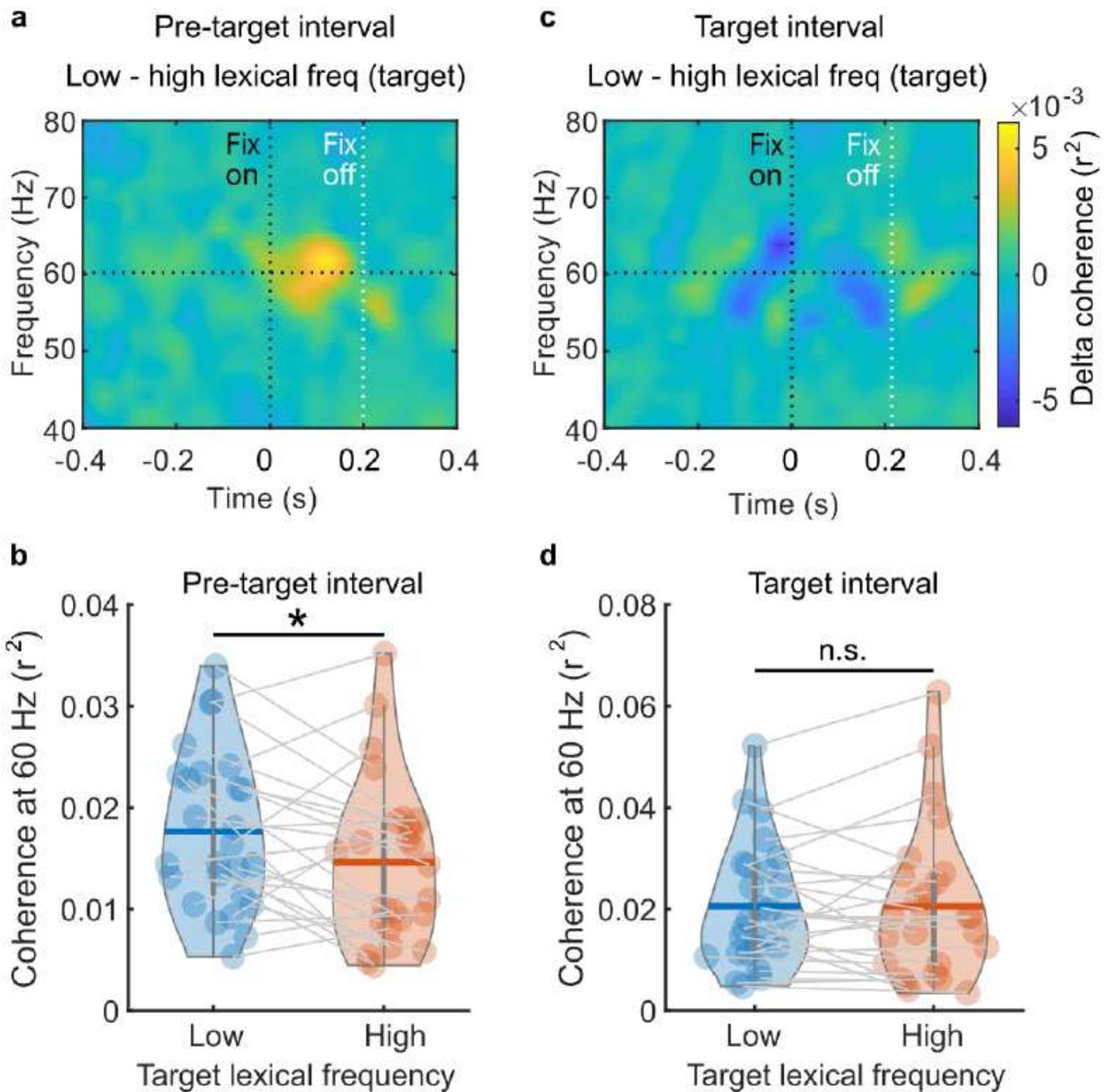
**Figure 2**

Eye movement metrics. (a) The first fixation duration difference for pre-target and target words when comparing low versus high lexical frequency target words. (\*\*\*)  $p < 0.001$ ,  $n = 39$ ). The horizontal bar in the violin plots indicates the mean value; each dot represents one participant. (b) Landing positions for the first fixation on pre-target words were estimated in the unit of letter, aligning according to the word centre ( $-1.1 \pm 1.9$ , mean  $\pm$  SD).



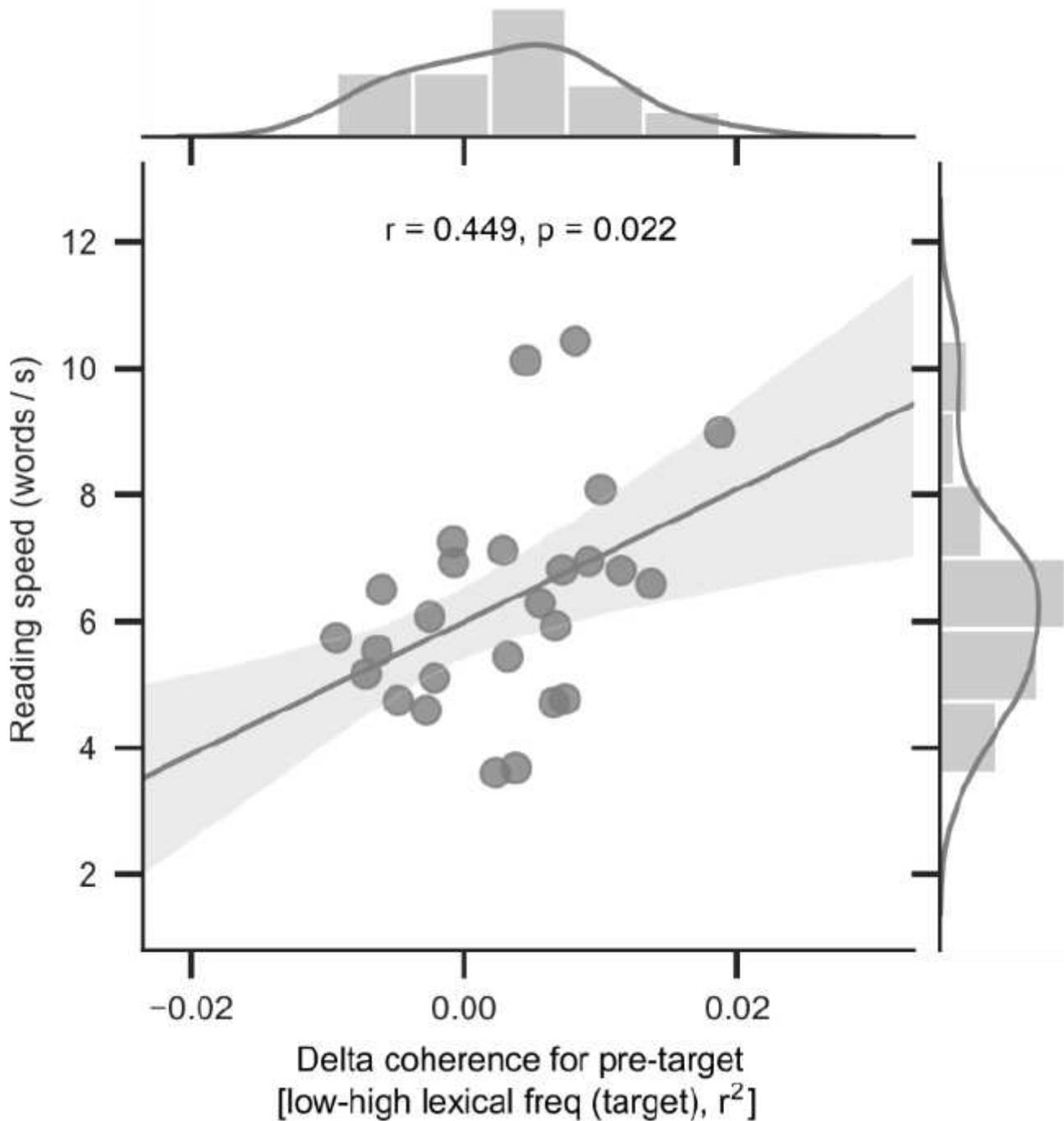
**Figure 3**

Neural responses of the rapid invisible frequency tagging. (a) Topography for sensors from all participants that showed stronger tagging responses during the pre-target period (flicker) compared with the baseline period (no-flicker,  $n=26$ ). (b) These tagging responses were localized in the left visual cortex. (c) The time-course of neural tagging responses during the pre-target (left panel), target (middle panel), and post-target fixation periods (right panel). Vertical white and gray lines indicate fixations onsets and average offsets.



**Figure 4**

Neuronal evidence for lexical parafoveal previewing. (a) Time-resolved coherence differences during pre-target word fixations (low minus high lexical frequency target words;  $n = 26$ ) revealing a lexical previewing effect around 100 ms after fixation onset. (b) The averaged pre-target coherence at 60 Hz during pre-target fixations for low (blue) and high (orange) lexical frequency target words ( $* p = 0.037$ ). (c, d) During target word fixations we did not observe a coherence difference with respect to lexical frequency. Horizontal bars in the violin plots indicate mean value. Each dot presents one participant.



**Figure 5**

Relation between lexical parafoveal processing difference and individual reading speed. The coherence-difference with respect to target lexical frequency during fixations on pre-target words were derived per participant (see Fig. 4b). The reading speed was quantified as the number of words read per second. Each dot represents a participant. A Spearman correlation demonstrated a significant relation ( $n = 26$ ). The shaded area indicates a 95% confidence interval. Histograms of individual reading speed and pre-target coherence differences are shown on the top and to the right.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [NCsupplementary.pdf](#)