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Processing of parafoveally presented words. An fMRI study

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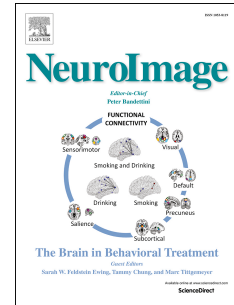
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51 **Abstract**

52

53 The present fMRI study investigated neural correlates of parafoveal preprocessing
54 during reading and the type of information that is accessible from the upcoming - not
55 yet fixated - word. Participants performed a lexical decision flanker task while the
56 constraints imposed by the first three letters (the initial trigram) of parafoveally
57 presented words were controlled. Behavioral results evidenced that the amount of
58 information extracted from parafoveal stimuli, was affected by the difficulty of the
59 foveal stimulus. Easy to process foveal stimuli (i.e., high frequency nouns) allowed
60 parafoveal information to be extracted up to the lexical level. Conversely, when
61 foveal stimuli were difficult to process (orthographically legal nonwords) only
62 constraining trigrams modulated the task performance. Neuroimaging findings
63 showed no effects of lexicality (i.e., difference between words and pseudowords) in
64 the parafovea independently from the difficulty of the foveal stimulus. The constraints
65 imposed by the initial trigrams, however, modulated the hemodynamic response in the
66 left supramarginal gyrus. We interpreted the supramarginal activation as reflecting
67 sublexical (phonological) processes. The missing parafoveal lexicality effect was
68 discussed in relation to findings of experiments which observed effects of parafoveal
69 semantic congruency on electrophysiological correlates.

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74 **Keywords:** parafoveal preprocessing, fMRI, constraining trigrams,
75 supramarginal, sublexical, lexical.

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103 1. Introduction

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105 While we read we do not only process the currently fixated word, but information is
106 also extracted from upcoming – not yet fixated – words. This process is known as
107 parafoveal preprocessing. To date, a large amount of research has focused on
108 investigating the timeline ('when') and type ('what') of parafoveally accessed
109 information (see Schotter, Angele and Rayner, 2012 for a review). Concurrently,
110 cognitive models of visual word recognition used this (mostly behavioral) data in the
111 attempt to explain 'how' parafoveal word recognition is carried out in terms of
112 cognitive operations. Importantly, however, studies focusing on internal mechanisms
113 ('where') of parafoveal preprocessing are scarce. The study of 'where' could prove
114 relevant in order to gain a deeper understanding of the 'what' and 'how' of parafoveal
115 preprocessing (Carreiras, Armstrong, Perea and Frost, 2013). Furthermore, detailed
116 anatomical information offers an opportunity for unique advance in developing more
117 biologically plausible models of natural reading (Carreiras et al., 2013). The aim of
118 the present study was to use functional magnetic resonance imaging (fMRI) to
119 investigate neural correlates ('where') of parafoveal preprocessing during reading and
120 the type of information that can be extracted from a parafoveal word ('what' and
121 'how').

122 Beyond a general interest in the understanding of the functional neuroanatomy
123 of the reading system, the present study is motivated by a controversy that emerged
124 from previous studies investigating the extent of parafoveal preprocessing. We will
125 now briefly describe the nature of this controversy in respect to the two most widely
126 adopted techniques in this field of research: eye tracking (ET) and
127 electroencephalography (EEG).

128 Typically, ET studies recorded the eye movements of participants while they
129 read sentences that had various linguistic or non-linguistic features manipulated
130 (Schotter et al., 2012). Eye movement behavior can then be analyzed in relation to
131 stimulus properties and used to infer cognitive processes underlying parafoveal
132 preprocessing (Rayner, 1998). Although there is little doubt that proficient readers are
133 able to extract and process information from upcoming words (McConkie and
134 Rayner, 1975; Rayner, 1975), the type of such information (e.g., sublexical, lexico-
135 semantic) is still a controversial topic. To illustrate, whereas it is widely accepted that
136 sublexical (i.e., orthographic or phonological) information can be extracted from the
137 parafoveal word (Balota and Rayner, 1983; Chanceaux and Grainger, 2012;
138 Chanceaux, Vitu, Bendahman, Thorpe and Grainger, 2012; Dare and Shillock, 2013;
139 Grainger, Mathôt and Vitu, 2014; Henderson, Dixon, Petersen, Twilley and Ferreira,
140 1995; Rayner, McConkie, and Ehrlich, 1978; Rayner, McConkie, and Zola, 1980;
141 Tiffin-Richards and Schroeder, 2015, for reviews see Brothers, Hoversten and
142 Traxler, 2017; Schotter et al., 2012), evidence for parafoveal lexical processing is
143 sparse (Hohenstein, Laubrock and Kliegl, 2010; Tsai, Kliegl and Yan, 2012; White,
144 Bertram and Hyönä, 2008; Yan, Richter, Shu and Kliegl, 2009).

145 On a similar line of research, several studies attempted to investigate which
146 type of information can be extracted from parafoveally presented words by means of
147 electroencephalography (EEG). These studies focus on parafoveal-on-foveal effects
148 (POF, Kennedy, Pynte and Ducort, 2002). In brief, POF effects occur when properties
149 of the - not yet fixated - word $n+1$ affect the processing of the currently fixated word
150 (word n). Accordingly, EEG experiments would time-lock the analysis of event-
151 related potentials (ERPs) to the point in time when processing of word n begins (e.g.,
152 stimulus onset of or fixation onset on word n). The time course and morphology of

153 the ERPs could then be analyzed in relation to the psycholinguistic properties of word
154 $n+1$. Thanks to the millisecond resolution of the EEG signal, these studies contributed
155 to our understanding of ‘when’ parafoveal information becomes accessible (see
156 Kliegl, Dambacher, Dimigen, Jacobs and Sommer, 2012). However, as far as it
157 concerns the specific issue of the type of information that can be extracted from the
158 parafoveal words, EEG studies do not offer clear-cut answer to the controversies that
159 emerged in the ET literature (see above). More specifically, whereas several studies
160 reported effects of parafoveal semantic congruency on ERPs (Baccino and Manunta,
161 2005; Barber, Doñamayor, Kutas and Münte, 2010; Barber, Ben-Zvi, Bentin and
162 Kutas, 2011; Barber, Van der Meij and Kutas, 2013; López-Pérez, Dampuré,
163 Hernández-Cabrera, and Barber, 2016), others could not replicate these findings
164 (Dimigen, Sommer, Hohlfield, Jacobs and Kliegl, 2011; Simola, Holmqvist and
165 Lindgren, 2009).

166 In summary, findings from a large body of ET as well as EEG studies
167 indicated that only sublexical information can be preprocessed from the parafoveal
168 stimulus. A few other studies, to the contrary, found evidence for lexico-semantic
169 parafoveal processing.

170 The aim of the present study was to further investigate the ‘what’ information
171 (i.e., sublexical, lexico-semantic) and ‘how’ is this extracted from the parafoveal
172 words by looking at ‘where’ in the brain is this information processed. We therefore
173 measured brain activity with functional magnetic resonance imaging (fMRI). With a
174 considerably higher spatial resolution than EEG, fMRI allows detailed anatomic
175 estimates of neural activity. Furthermore, we adopted a well-established paradigm
176 from the EEG literature, that is, the flanker task (Barber et al., 2010; Barber et al.,
177 2011; Barber et al., 2013; López-Pérez et al., 2016). In a flanker task the participant is
178 presented simultaneously with (minimum) two stimuli, one foveally and one
179 parafoveally. Accordingly, our stimulus material consisted of foveally and
180 parafoveally presented words (W) and pseudowords (P). Participants were instructed
181 to indicate the presence of a real word (i.e., lexical decision flanker task).

182 Considering that parafoveal lexical processing was inconsistently reported in
183 the literature (see above) our research hypothesis did not exclusively rely on the
184 participants’ ability to recognize parafoveally presented words. Instead, we enclosed
185 in our experimental paradigm an additional manipulation at the sublexical level. More
186 in detail, we manipulated the constraint imposed by the initial trigram of parafoveally
187 presented words (for a similar manipulation see Gagl et al., 2013). A constraining
188 trigram is defined as a unique three-letters-sequence at the beginning of a word.
189 Evidence stemming from previous behavioral studies suggests that constraining
190 trigrams (e.g., DWA which is only found in the word DWARF) can facilitate lexical
191 access when parafoveally preprocessed (compared to words whose trigram is less
192 constraining; Gagl, Hawelka, Richlan, Schuster and Hutzler, 2014; Hand, O’Donnel
193 and Sereno, 2012; Lima and Inhoff, 1985). In summary, we manipulated both lexical
194 and sublexical stimulus characteristics of parafoveally presented items.

195 At the behavioral level, the aim was to replicate classical lexical decision
196 findings. More specifically, one would predict a processing benefit (i.e., faster
197 reaction times, lower error rates) for foveally presented words as compared to
198 foveally presented pseudowords (Cattell, 1886; Rayner, 1998). Moreover, it will be
199 interesting to see whether lexical properties of parafoveal stimuli will affect
200 behavioral performance, which would be indicative that parafoveal stimuli are
201 processed at the lexical level. Last, in line with findings from the eye movement
202 literature (Gagl et al., 2013; Hand et al., 2012; Rayner, Well, Pollatsek and Bertera,

203 1982) we expected parafoveally presented words which contained constraining
204 trigrams to induce a higher word-likeness estimate (thus reflected in a higher number
205 of “YES” responses) as compared to those which contained unconstraining trigrams.

206 At the neural level we expected lexical properties of foveal items to induce
207 activation within brain areas evidenced by a recent meta-analysis summarizing results
208 of 36 neuroimaging studies for word and pseudoword reading (Taylor, Rastle and
209 Davis, 2013). More specifically Taylor et al., (2013) identified a mainly left-
210 lateralized network that included (among others) the occipitotemporal cortex, the
211 anterior fusiform and middle temporal gyrus, the inferior parietal cortex and the
212 inferior frontal gyrus. With regard to our sublexical manipulation, we can only
213 speculate about brain activation induced (if any) by the processing of parafoveal
214 stimuli. It is now a commonly accepted view that the reading network encompasses
215 two paths towards visual word recognition, that is a dorsal and a ventral pathway (see
216 Carreiras et al., 2013; Price, 2012 for reviews). The dorsal pathway has been
217 associated with sublexical processing (i.e., the processing of small units for visual
218 word recognition such as the process of grapheme-phoneme conversion). The ventral
219 pathway has been characterized as lexico-semantic route and is involved in whole-
220 word recognition through activation of lexical nodes in an orthographic lexicon.
221 Following this dual-route perspective, one would assume lexical access of
222 parafoveally presented words to activate areas along the ventral lexico-semantic route.
223 Conversely, one could expect the constraining trigrams manipulation to induce
224 activity within the dorsal sublexical route.

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226 **2. Materials and Methods**

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228 *2.1. Participants*

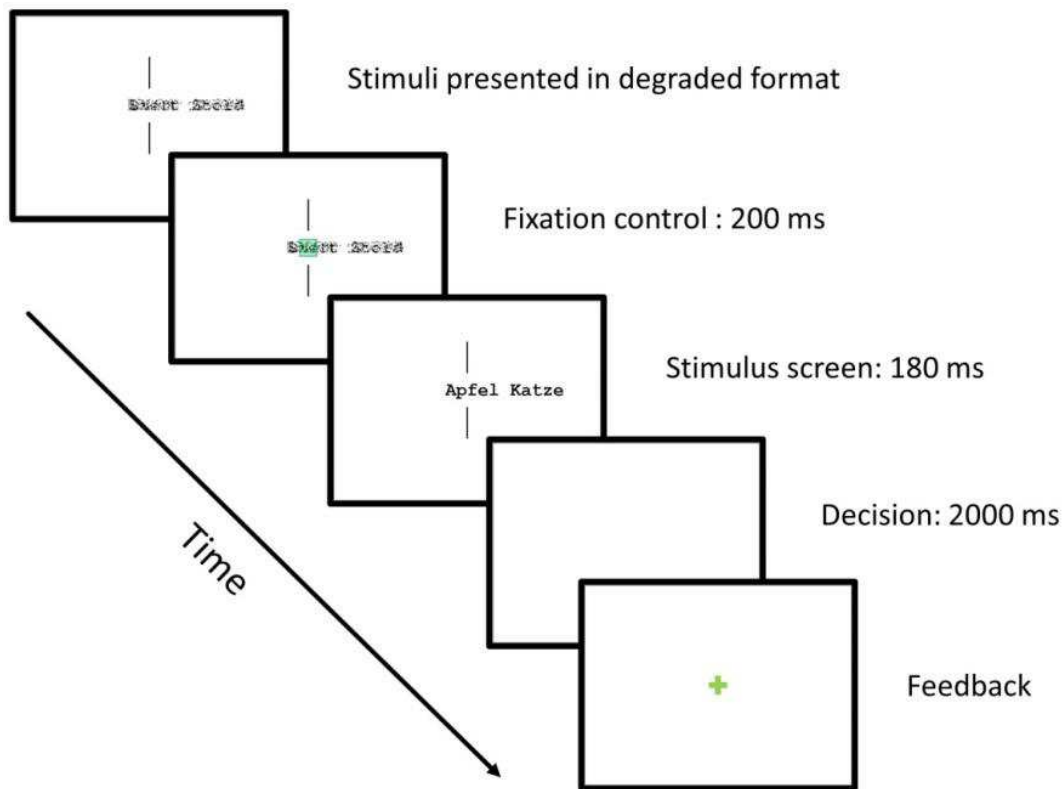
229 We tested a total of twenty one native German speaking students (10 male, $M = 25.8$
230 years, $SD = 8.2$ years). All participants had normal or corrected-to-normal vision, no
231 history of neurological or psychiatric disease and gave their written informed consent.
232 Before testing, all participants undertook a standardized reading speed test currently
233 developed in our lab (preliminary norms are based on a sample of 309 University
234 students). The test was administered to prevent the inclusion of participants with
235 reading difficulties and required to silently read sentences and mark them as correct
236 (e.g., “Mafia is a criminal organization”) or incorrect (e.g., “In the library you can
237 rent cars”). These statements were assessments of common knowledge and hence
238 judging them as true or false was easy. Thus, the number of correctly marked
239 sentences within 3 minutes is an index of reading speed. All participants exhibited a
240 reading speed greater than percentile 16 ($M =$ percentile 74). The study was
241 conducted in accordance with the Declaration of Helsinki and was approved by the
242 ethical review committee of the University of Salzburg.

243

244 *2.2. Experimental procedure*

245 At the beginning of each trial, we presented illegibly blurred versions of the
246 upcoming stimuli (see Fig. 1). In order to trigger stimulus appearance in the
247 undegraded format participants had to fixate for a minimum of 200 ms a 1° visual
248 area (green box in Fig. 1) indicated by two vertically aligned bars.

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252 **Fig. 1. Schematic representation of stimuli and task. Each trial started with stimuli being**
253 **presented in a visually degraded format. A fixation of 200 ms between two vertically aligned bars**
254 **triggered stimulus appearance. Stimuli remained on the screen for 180 ms. Followed a blank**
255 **screen of 2000 ms where button presses were recorded. Last, a feedback (red or green cross) was**
256 **displayed. (Stimuli are not drawn to scale.)**
257

258 This procedure allowed participants to correctly pre-allocate attentional resources
259 across the visual span. Eye tracking measures, allowed us to ensure central fixation at
260 the moment of stimulus appearance (between the second and the third letter of foveal
261 stimuli). The stimuli remained on the screen for 180 ms and were followed by a 2000
262 ms blank screen where the responses via button press were recorded. The short
263 presentation duration of the stimuli was an additional precaution to avoid eye
264 movements towards the parafoveal stimulus.

265 Participants were instructed to press a green button whenever they could
266 recognize a word, independently whether foveally or parafoveally presented
267 (conditions: WW, WP, PW). Only in the case of two pseudowords (condition PP)
268 they were instructed to press a red button. At the end of each trial, a visual feedback
269 in the form of a green or red cross indicated the correctness of the response. Before
270 the beginning of the experiment, the participants were familiarized with the task in a
271 short training session (40 trials) performed outside the scanner. Each experimental
272 session was divided in four runs of 125 trials each (about 9-10 min per run). The
273 overall experiment lasted about 1 hour.
274

275 2.3. Stimuli

276 Stimuli were presented in a bold, monospaced font via a mirror on an MR-compatible
277 LCD screen (NordicNeuroLab, Bergen, Norway) with a refresh rate of 60 Hz and a
278 resolution of 1024 × 768 pixels. Four experimental conditions of 100 trials each were
279 presented in a pseudorandomized order and intermixed with one hundred null-events
280 (no stimuli appeared on the screen). In each trial two stimuli simultaneously appeared

281 on the screen (see Fig. 1), one foveally and one parafoveally. The stimulus pair
 282 covered a total width of 5° of visual angle and extended from 0.9° left of the fixation
 283 control up to 4.1° to the right of the fixation control (each stimulus covered 2.3° of
 284 visual angle). The four experimental conditions were: foveal word and parafoveal
 285 word (WW), foveal word and parafoveal pseudoword (WP), foveal pseudoword and
 286 parafoveal word (PW) and foveal and parafoveal pseudoword (PP). For the sublexical
 287 manipulation we manipulated the initial trigram of parafoveally presented words
 288 (conditions WW and PW). This resulted in conditions WW and PW having half of the
 289 parafoveally presented words containing a constraining trigram, and half an
 290 unconstraining trigram (50 trials each). A constraining trigram was defined as a
 291 unique three-letters-sequence at the beginning of a word as compared to all 5-letter
 292 nouns in the CELEX database (Baayen, Piepenbrock and van Rijn, 1993). The
 293 unconstraining trigrams had a mean frequency of 3.04 (difference: $t(198) = 14.22$).

294 The pseudowords were generated using the Wuggy software (Keuleers and
 295 Brysbaert, 2010). All stimuli were 5-letters long and were matched on various lexical
 296 and sublexical characteristics between the four experimental conditions (see Table 1).
 297

Table 1. Means (and standard deviations) of the item characteristics. The column names denote the condition. The capitalized letter indicates the position (foveal or parafoveal) of the stimulus category under consideration Ww, for example, refers to the foveal words in the word-word condition and wW_C refers to the parafoveal words (in the word-word condition) containing constraining trigrams. All reported values for word and bigram frequency are *log*-transformed.

Condition	Ww	wW_C	wW_U	Wp	pW_C	pW_U	wP	Pw	Pp	pP
Frequency	1.71(.47)	1.71(.59)	1.71(.75)	1.71(.47)	1.72(.65)	1.70(.72)	-	-	-	-
First Bigr. ^a	2.50(.35)	2.51(.41)	2.54(.33)	2.50(.36)	2.50(.38)	2.53(.34)	2.50(.36)	2.50(.35)	2.50(.35)	2.50(.35)
Avg Bigr. ^b	3.97(.18)	3.97(.17)	3.97(.18)	3.97(.18)	3.97(.18)	3.97(.18)	3.98(.2)	3.97(.2)	3.97(.2)	3.97(.2)
Levenshtein Distance	1.82(.25)	1.82(.13)	1.82(.14)	1.82(.26)	1.82(.15)	1.82(.12)	1.84(.27)	1.86(.27)	1.86(.27)	1.85(.27)

Note. ^a First bigram frequency. ^b Average bigram frequency

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300 2.4. *fMRI*

301 Functional and structural neuroimaging data were collected with a Siemens
 302 Magnetom Trio 3 Tesla Scanner (Siemens AG, Erlangen, Germany) using a 12-
 303 channel head-coil. Functional images consisted of a T2*-weighted gradient echo EPI
 304 sequence (TR 2250 ms, TE 30 ms, matrix 64 x 64, FOV 192 mm, flip angle 70°).
 305 Within the TR thirty-six slices with a slice thickness of 3 mm and a slice gap of 0.3
 306 mm were acquired. In addition to the functional images, a gradient echo field map
 307 (TR 488 ms, TE 1 = 4.49 ms, TE 2 = 6.95 ms) and a high resolution (1 x 1 x 1 mm)
 308 structural scan with a T1-weighted MPRAGE sequence were acquired from each
 309 participant. Scanning proceeded in 4 runs separated by short breaks. Each run had a
 310 variable number of scans that depended on the participants' viewing behavior and the
 311 number of required calibration procedures (ranging from 204 to 563 scans, $M = 257$
 312 scans).
 313

314 2.5. *Eye tracking*

315 Eye movements were recorded monocularly from the right eye with an SR Research
 316 (Ontario, Canada) Eyelink CL system (sampling rate: 1 kHz) in the long-range setup.
 317 The camera was mounted on the head side of the scanner bore at a distance of 90 cm

318 from the participant's head and 120 cm from the LCD screen. A 3 points calibration
319 routine was administered at the beginning of each run. The average tracking error was
320 kept below 0.5° of visual angle. The calibration routine was repeated every time the
321 fixation control at the beginning of a trial (see Fig. 1) failed. Stimulus presentation
322 was controlled by the Experiment Builder software (SR Research Ltd., Canada).
323

324 2.6. Accuracy rate and reaction time analysis

325 For each participant, we excluded all trials where reaction times were shorter than 150
326 ms or three standard deviations above or below the individual mean (total data loss
327 1.3%). All reaction times were log-transformed and accuracy rates were defined as
328 mean percent of correct responses for each condition. In order to test for effects of
329 lexicality in the fovea and in the parafovea we used a 2x2 repeated measures ANOVA
330 entering as within-subject factors Lexicality (words vs. pseudowords) and Position
331 (foveal vs. parafoveal). Post-hoc contrasts followed significant Lexicality*Position
332 interactions. Accordingly, analysis of constraining (abbreviated as wW_C and pW_C)
333 and unconstraining trigrams (abbreviated as wW_U and pW_U) was performed using
334 a repeated measure ANOVA having as factors Condition (WW vs. PW) and Trigram
335 (constraining trigrams vs. unconstraining trigrams). Post-hoc contrasts followed
336 significant interactions Condition*Trigram. Data were analyzed with the package ez
337 (Lawrance, 2011) in R (R Core Team, 2013).
338

339 2.7. fMRI data preprocessing and analysis

340 For preprocessing and statistical analysis of fMRI data, SPM8 and SPM12 software
341 were used (<http://www.fil.ion.ucl.ac.uk/spm/>) running in a MATLAB 8.1
342 environment (Mathworks, Inc., Natick, MA, USA). Functional images were corrected
343 for geometric distortions by use of the FieldMap toolbox, realigned and unwrapped,
344 slice time corrected, and then coregistered to the high-resolution structural image. The
345 structural image was normalized to the MNI T1 template image, and the resulting
346 parameters were used for normalization of the functional images, which were
347 resampled to isotropic 3 x 3 x 3 mm voxels and smoothed with a 8 mm FWHM
348 Gaussian kernel.

349 Statistical analysis was performed in a two-stage mixed effects model. In a
350 participant-specific first level model, the onsets of the stimuli were modeled by a
351 canonical hemodynamic response function with no time and dispersion derivatives.
352 The movement parameters derived from the realignment step during preprocessing
353 were modeled as covariates of no interest. The functional data in these first level
354 models were highpass filtered with a cut-off of 128 s and corrected for autocorrelation
355 by an AR(1) model (Friston et al., 2002). In order to investigate effects of lexicality
356 on brain activation patterns, the parameter estimates reflecting signal change for each
357 individual condition (WW, WP, PW, PP) versus baseline (which consisted of the
358 inter-stimulus intervals, the null-events, and the eye tracker recalibration procedures)
359 were calculated in the context of a GLM (Henson, 2004). These participant-specific
360 contrast images were used for the second-level random effect analysis. Differences
361 between conditions were examined by *t*-tests thresholded at a voxel-level (height) of p
362 < 0.001 (uncorrected) and a cluster-level (extent) of $p < 0.05$ (corrected for multiple
363 comparisons using the false discovery rate).

364 A similar procedure was adopted to calculate effects of the constraining
365 trigrams manipulation on brain activation patterns. First-level contrast images were
366 estimated for those condition where we manipulated the constraint imposed by the
367 trigrams (wW_C, wW_U, pW_C, pW_U). These participant-specific contrast images

368 were used for the second-level random effect analysis. Differences between
369 conditions were examined by t -tests thresholded at a voxel-level (height) of $p < 0.001$
370 (uncorrected) and a cluster-level (extent) of $p < 0.05$ (corrected for multiple
371 comparisons using the false discovery rate).

372

373 **3. Results**

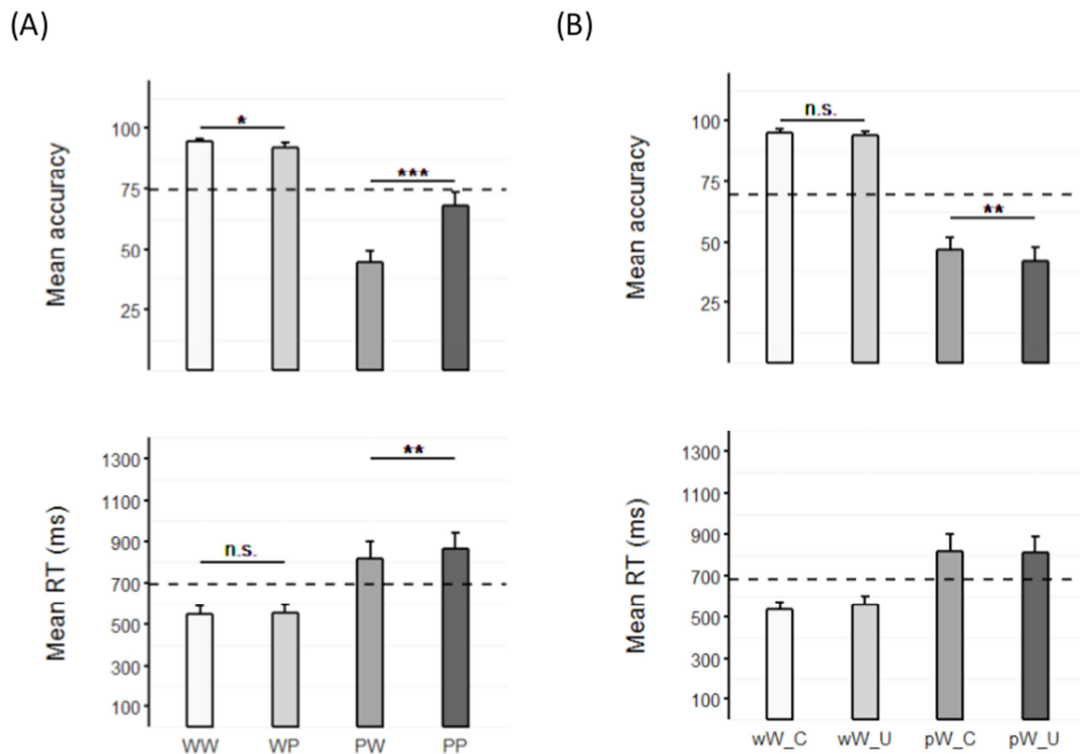
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375 *3.1. Behavioral results*

376 Figure 2 displays the behavioral results. As evident from panel (A), conditions with
377 foveally presented words showed higher accuracy rates and shorter reaction times
378 than conditions with foveally presented pseudowords. ANOVA results showed a
379 significant interaction Lexicality*Position in both accuracy rates ($F(1,20) = 21.38, p <$
380 $.001$) and reaction times ($F(1,20) = 9.63, p = .006$). Post-hoc contrast showed a
381 significant difference in accuracy rates between WW and WP conditions (WW: $M =$
382 95% , $SD = 2.5$; WP: $M = 92.2\%$, $SD = 4.8$; $t(20) = 2.7, p = .014$). This result was not
383 supported by reaction time measures (WW: $M = 542$ ms, $SD = 86$; WP: $M = 548$ ms,
384 $SD = 91$; $t < 1$). Differently, post-hoc t -tests showed significant differences between
385 the PW and PP conditions in both accuracy rates (PW: $M = 45.9\%$, $SD = 14.4$; PP: M
386 $= 67.5\%$, $SD = 13.9$; $t(20) = 4.18, p < .001$) and reaction time measures (PW: $M = 807$
387 ms, $SD = 201$; PP: $M = 963$ ms, $SD = 178$; $t(20) = 3.33, p = .003$). It is important to
388 note that performance in the PW condition did not significantly differ from chance
389 performance (i.e., 50% accuracy rate; $t(20) = 1.3, p = .208$).

390

391 For the constraining trigram manipulation results are illustrated in Figure 2B.
392 ANOVAs results revealed a significant Condition*Trigram interaction in ACC
393 ($F(1,20) = 5.15, p = .034$) but not in reaction time measure ($F(1,20) = 3.61, p = .072$).
394 Post-hoc contrast on accuracy rates revealed that in the PW condition constraining
395 trigrams significantly increased word-likeness judgments of parafoveally presented
396 words (as compared to unconstraining trigrams, $t(20) = 2.89, p = .009$). This result
397 was not replicated in the WW condition, $t(20) = 1.01, p = .323$.



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Fig. 2. Behavioral results. (A) Mean accuracy rates (percent correct) and reaction times (RTs) in the four experimental conditions. (B) Mean accuracy and reaction times (RTs) for constraining and unconstraining trigrams conditions. Error bars represent 95% confidence intervals. Dashed lines represent mean accuracy rates and mean reaction times across conditions. Significant differences between conditions are marked with asterisks: * $p < 0.5$, ** $p < 0.01$, * $p < 0.001$. WW, word word; WP, word pseudoword; PW, pseudoword word; PP, pseudoword pseudoword; wW_C, constraining trigrams condition WW; wW_U, unconstraining trigrams condition WW; pW_C, constraining trigrams condition PW; pW_U, constraining trigrams condition PW.**

409 3.2. Neural correlates of the lexicality effect

410 For the analysis of the neuroimaging data we initially focused on neural correlates of
411 the effect of lexicality. To this end, we contrasted those conditions where both foveal
412 and parafoveal stimuli differed in their lexical properties (WW vs. PP).

413 The results from the contrast WW > PP are shown in Figure 3 (blue tones) and details
414 of all clusters of activation are given in Table 3A. The largest cluster was observed in
415 the left middle occipital cortex encompassing left angular gyrus and precuneus. Other
416 large clusters were observed in the bilateral occipito-temporal cortex and in the
417 middle frontal gyrus. Additionally we observed smaller clusters of activation in the
418 left putamen, right caudate and in the right somatosensory cortex.

419 Results from the reversed contrast (i.e., PP > WW) are shown in Figure 3 (red
420 tones) and details of all clusters are given in Table 3B. This contrast evidenced a main
421 cluster of activation in the left supramarginal gyrus extending horizontally over the
422 intraparietal sulcus and postcentral gyrus. In the right hemisphere we observed a
423 similar (but less extensive) cluster. Furthermore, we observed bilateral activation of
424 the insular regions as well as activation in the paracingulate cortex. Minor clusters of
425 activation for this contrast were in the left and right thalamus.

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(A) WW > PP

Cluster	Label	Number of Voxels	Z	MNI coordinates		
				x	y	z
1	Left middle occipital cortex	2624	Inf	-45	-73	25
	Left Precuneus		7.4	-6	-52	10
	Right Precuneus		5.94	9	-55	10
2	Left middle frontal gyrus	1431	7.2	-24	23	49
	Left medial prefrontal cortex		6.31	-9	53	-11
	Left medial superior frontal gyrus		5.93	-9	62	22
3	Left occipito-temporal cortex	742	6.58	-30	-37	-20
	Left middle temporal gyrus		5.61	-57	-10	-20
	Left Hippocampus		5.61	-24	-19	-23
4	Left frontal orbital cortex	96	5.95	-33	32	-17
5	Right occipito-temporal cortex	1121	5.75	30	-31	-20
	Right fusiform gyrus		5.64	24	-37	-20
	Right Hippocampus		5.51	27	-19	-23
6	Right middle frontal gyrus	159	5.26	27	32	40
7	Left Putamen	85	4.88	-27	-10	7
	Left Caudate		3.22	-15	-1	19
8	Right Caudate	91	4.55	18	5	19
	Right Caudate		4.46	18	14	13
	Right Caudate		3.38	21	-10	19
9	Right somatosensory cortex	133	4.55	42	-28	58
	Right somatosensory cortex		4.42	48	-13	52
	Right primary motor cortex		4.25	30	-25	58

(B) PP > WW

Cluster	Label	Number of Voxels	Z	MNI coordinates		
				x	y	z
1	Left supramarginal gyrus	640	7.35	-48	-34	46
	Left postcentral gyrus		5.62	-42	-25	55
	Left precentral gyrus		4.59	-24	-13	49
2	Right Anterior Insula	621	7.21	33	23	-5
	Right inferior frontal gyrus opercularis		6.28	48	17	1
	Right inferior frontal gyrus opercularis		4.82	45	8	25
3	Left Anterior Insula	281	6.89	-33	20	-5
4	Right paracingulate gyrus	432	6.27	9	17	43
	Right paracingulate gyrus		5.13	6	29	31
	Left paracingulate gyrus		4.71	-6	14	46
5	Right intraparietal sulcus	132	4.5	42	-46	43
	Right supramarginal gyrus		4.32	48	-37	46
	Right intraparietal sulcus		3.43	30	-49	40
6	Right Thalamus	84	4.22	6	-22	-2
	Right Thalamus		3.82	6	-13	-5
	Left Thalamus		3.8	-9	-13	-2

429

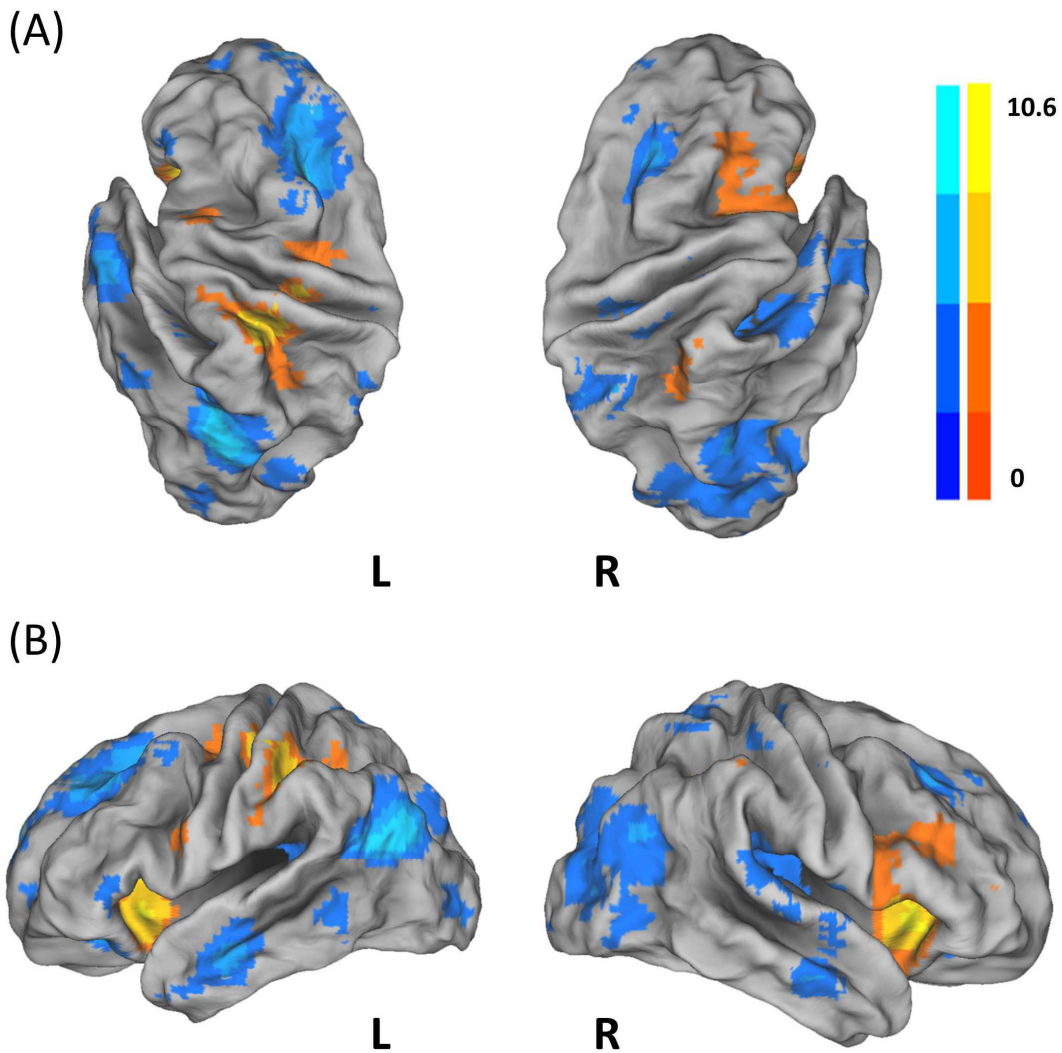
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432

Table. 3 - Clusters of activation for the foveal lexicality effect. (A) peaks of activation for the contrast WW > PP (B) peaks of activation for the contrast PP > WW. x, y and z refer to MNI coordinates of statistical centre of mass. Z refers to z-scores of statistical significance.

433



434

435 **Fig. 3 - Contrasts of interest. Surface rendering of the WW > PP (blue tones) and PP > WW (red**
 436 **tones) contrasts, (A) dorsal view rotated inwards by 45° (B) lateral view. L, left; R, right.**
 437

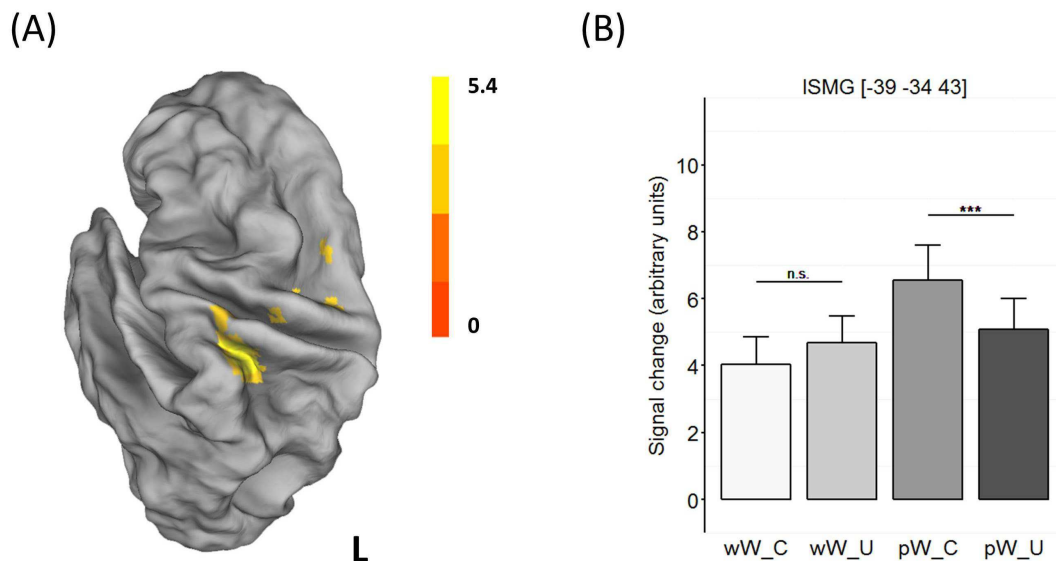
438 3.3. *Neural correlates of the parafoveal lexicality effect*

439 In order to investigate the parafoveal lexicality effect we focused on the contrast
 440 between conditions that had comparable foveal lexical information but differed in the
 441 parafoveal lexical information (i.e., WW vs. WP and PW vs. PP). Interestingly, none
 442 of the four possible combinations (i.e., WW > WP, WP > WW, PW > PP, PP > PW)
 443 evidenced significant clusters of activation. This result speaks against lexical
 444 processing of parafoveally presented words.
 445

446 3.4. *Neural correlates of the constraining trigram manipulation*

447 To investigate effects of constraining trigrams on brain activation patterns we focused
 448 on the conditions which contained parafoveally presented words (WW and PW). We
 449 compared conditions which contained constraining trigrams to those containing
 450 unconstraining trigrams (i.e., wW_C vs. wW_U and pW_C vs. pW_U). The contrasts
 451 wW_C > wW_U, wW_U > wW_C and pW_U > pW_C did not evidence significant
 452 clusters of activation. The contrast pW_C > pW_U revealed a significant cluster of
 453 activation in the left supramarginal gyrus (LSMG; -39, -34, 43; Z = 4.84; 152 voxels).

454 That is, constraining trigrams induced higher activation in the ISMG as compared to
 455 unconstraining trigrams (see Fig. 4).
 456
 457



458

459 **Fig. 4 - Neural correlates of constraining trigrams. Surface rendering of the pW_C > pW_U, (A)**
 460 **dorsal view rotated inwards by 45°. L, left (B) Bar plots represent signal change estimates (in**
 461 **arbitrary units). Error bars represent 95% confidence intervals. Significant differences between**
 462 **conditions are marked with asterisks: *** $p < 0.001$. MNI coordinates for individual ROI**
 463 **reported between []. ISMG, left supramarginal gyrus. wW_C, constraining trigrams condition**
 464 **WW; wW_U, unconstraining trigrams condition WW; pW_C, constraining trigrams condition**
 465 **PW; pW_U, unconstraining trigrams condition PW.**
 466

467

468 4. Discussion

469

470 The objective of the present study was to investigate the neural correlates of
 471 parafoveal preprocessing during reading and the type of information that becomes
 472 accessible from the parafoveal word. We asked participants to recognize words -
 473 independently whether foveally or parafoveally presented (i.e., lexical decision
 474 flanker task). Furthermore, we manipulated the constraint imposed by the initial
 475 trigram of parafoveally presented words. Whereas behavioral results provided
 476 evidence for both lexical and sublexical processing of parafoveal stimuli,
 477 neuroimaging findings were indicative of only sublexical information being processed
 478 from the parafovea.
 479

480

480 4.1. Behavioral findings

481

482 Expectedly, conditions with foveally presented words induced shorter reaction times
 483 and higher accuracy rates as compared to conditions with foveally presented
 484 pseudowords (Cattell, 1886; Rayner, 1998). Conversely, effects of lexicality in the
 485 parafovea showed a less clear pattern of results. Contrasts between word word (WW)
 486 and word pseudoword (WP) conditions evidenced a significant effect in accuracy
 487 rates, but not in reaction times. Moreover, performance in the pseudoword word (PW)
 488 condition was at chance level, indicative that, in this condition, participants were not
 able to recognize parafoveally presented words. Because performance was at chance

489 level in the PW condition we reasoned that the relatively high accuracy rate (67.5%)
490 observed in the pseudoword pseudoword (PP) condition can hardly be explained in
491 terms of parafoveal pseudowords being fully processed. Instead, a more likely
492 explanation for this finding is that participants were more inclined toward a “no”
493 response when unable to correctly identify parafoveally presented stimuli.

494 This pattern of results is not without precedent. Bendahman, Vitu, and
495 Grainger (2010) presented words and pseudowords parafoveally (i.e., left and right of
496 central fixation). The instruction of the participants was to move their eyes towards
497 the word. The findings revealed that it is very difficult to differentiate parafoveally
498 presented words from pseudowords (mean accuracy was only 58%). In a similar
499 experiment Chanceaux et al., (2012) had participants to discriminate parafoveally
500 presented words from unpronounceable consonants strings. In this experiment the
501 performance of the participants was substantially better (mean accuracy 75%). These
502 findings led Chanceaux et al., (2012) to conclude that sublexical and not lexical
503 information is the key factor determining word/nonword discrimination processes in
504 the parafovea.

505 In the present study, however, the amount of information extracted from
506 parafoveal stimuli was affected by the difficulty of the foveal stimulus. In line with
507 the foveal load hypothesis (Henderson and Ferreira, 1990; Payne, Stites &
508 Federmeier, 2016), less information was acquired parafoveally when foveal
509 processing was difficult. To illustrate, when foveal stimuli were high frequency
510 nouns, parafoveal information could be extracted up to the lexical level. Accordingly,
511 one might speculate that lower accuracy rates in the WP as compared to WW
512 condition could be explained with parafoveal difficulty modulating concurrent foveal
513 processing (i.e., parafoveal on foveal effect, POF).

514 With regard to the conditions with foveally presented pseudowords (i.e PW
515 and PP), behavioral results provided no evidence in favor of lexical processing of
516 parafoveal words, whereas the sublexical factor (i.e., the constraint imposed by the
517 initial trigram) significantly modulated behavioral performance.

518 More in detail, constraining trigrams induced a higher word-likeness
519 judgment (i.e., a higher number of “YES” responses) than unconstraining trigrams.
520 While the lack of evidence in favour of lexical processing in the parafovea hints at the
521 pre-lexical nature of this finding, it is still not clear if the trigram manipulation should
522 be located in the orthographical or phonological domain. We aim to use fMRI results
523 in the attempt to further clarify the nature of this effect (see below).

524 At this point, it is important to note, that the existence of POF effects is a
525 highly controversial topic in the eye tracking literature (Rayner, 2009). According to
526 Rayner (2009), POF effects arise due to mislocated fixations (Drieghe, Rayner &
527 Pollatsek, 2008b) and are often observed when a large corpus of data is taken into
528 account (see Kliegl, Nuthmann & Engbert, 2006; Kliegl, 2007). Conversely, with
529 more constraining paradigms, POF effects were almost exclusively observed when
530 orthographically illegal non-words were parafoveally presented (Drieghe, 2011;
531 Drieghe, Brysbaert & Desmet, 2005) or when foveal and parafoveally presented
532 words were semantically related (see Payne et al., 2016). As far as it concerns the
533 present study, all pseudowords were orthographically legal non-words and stimulus
534 pairs shared no semantic relationships. To conclude, lower accuracy rates in the WP
535 condition as compared to the WW condition indicate parafoveal lexical processing.
536 This effect, however, must be interpreted with caution given that it finds no support in
537 our neuroimaging findings (see below).

538

539 In summary, foveal load significantly contributed to the amount of
540 parafoveally extracted information (see also Payne et al., 2016). In conditions with
541 low foveal load (i.e, WW and WP) parafoveal information could be extracted up to
542 the lexical level. Conversely, in the conditions where foveal stimuli were more difficult
543 to process (i.e, PW and PP), only pre-lexical information could be extracted from the
544 parafovea. Furthermore, behavioral evidence confirmed the special role that words'
545 initial letters play during parafoveal preprocessing (Rayner et al., 1982). Former
546 studies, which also found an effect of the initial trigrams (Gagl et al., 2013; Hand et
547 al., 2012), interpreted the effect in accordance to the lexical constraint hypothesis
548 proposed by Lima and Inhoff (1985). The lexical constraint hypothesis assumes that
549 parafoveally processed word-initial letters are used in accessing the word's meaning.
550 Moreover, the advantage for constraining over unconstraining initial trigrams stems
551 out of the fact that constraining trigrams will pre-activate smaller lexical
552 neighborhoods (e.g., Hawelka, Schuster, Gagl and Hutzler, 2013). To illustrate,
553 whereas the three letters sequence "dwa" can only pre-activate the word "dwarf", the
554 sequence "ang" will pre-activate words like "angle", "anger", "angel". The
555 difference in the number of potential lexical candidates activated by the initial letters
556 of a word can result in the processing benefit observed in the present as well as other
557 studies (Gagl et al., 2013; Hand et al., 2012).

559 4.2. *Neuroimaging findings*

560 Neural underpinnings of the lexicality effects (contrast between WW and PP
561 conditions) largely overlapped with a network of brain regions evidenced by a recent
562 meta-analysis of word and pseudoword reading experiments (Taylor et al., 2013). It is
563 important to note, however, that in left ventral occipitotemporal cortex (LvOT) the
564 activation profile observed in the present study does not conform to Taylor et al.'s
565 (2013) findings. More in detail, Taylor et al., (2013) reported higher activation for
566 pseudowords than words in the LvOT whereas, for the same area, we did not find
567 differences across conditions. This result nicely fits the ongoing debate concerning
568 levels of activation within the LvOT during word and pseudoword reading (see for
569 instance Price and Devlin, 2003). Several previous studies evidenced that LvOT
570 activity is sensitive to task properties and, among others, stimulus presentation
571 duration was identified as one likely cause of inconsistencies in the literature (Mano
572 et al., 2013; McNorgan, Chabal, O'Young, Lukic and Booth, 2015; Schuster,
573 Hawelka, Richlan, Ludersdorfer and Hutzler, 2015; Yang and Zevin, 2014). More
574 specifically, studies with long presentation durations (ranging from 600 ms to 2000
575 ms) reported higher activation for pseudowords compared to words in LvOT (Binder,
576 Medler, Desai, Conant and Liebenthal, 2005; Mechelli, Gorno-Tempini and Price,
577 2003; Kronbichler et al., 2004; Schurz et al., 2010). Conversely, studies which
578 presented the stimuli for substantially shorter presentation durations (from 100 ms to
579 200 ms) found similar levels of LvOT activation for word and pseudoword reading
580 (Kronbichler, Schmid, Maurer and Brandeis 2013; Vinckier et al., 2007).
581 Accordingly, the short presentation duration (180 ms) employed in the present study
582 is the most likely explanation for the activation pattern observed in the LvOT.

583 Conversely to our behavioral findings, fMRI results did not evidence brain
584 areas sensitive to lexical properties of parafoveal items (contrasts WW vs. WP and
585 PW vs. PP). This finding is in agreement with a large body of eye tracking and EEG
586 studies which could not find evidence of parafoveally presented words being
587 processed up to access word meaning (see for instance Brothers et al., 2017; Dimigen
588 et al., 2011; Dimigen, Kliegl and Sommer, 2012; Simola et al., 2009). Importantly,

589 though, other studies reported effects of semantic congruency between foveally and
590 parafoveally presented items (Barber et al., 2010; 2011; 2013). More in detail, Barber
591 and colleagues presented sentences in the form of triplets of words, with each foveal
592 word being flanked by the upcoming word in the sentence (right flanker) and
593 preceding word in the sentence (left flanker). Each triad appeared on the screen for a
594 very short time (100 ms - Barber et al., 2010; 2011, 260 ms - Barber et al., 2013) and
595 the main experimental manipulation consisted in a critical triad where an incongruent
596 word was parafoveally presented (right flanker). Keeping in mind that, with a 180 ms
597 presentation duration we could not provide evidence for lexical processing of
598 parafoveal words it seems unlikely that, with a 100 ms presentation duration,
599 parafoveal words could be fully processed (up to accessing word's meaning) in
600 Barber et al., (2010, 2011). A more plausible explanation for Barber and colleagues'
601 findings is that, in these studies, participants could use partial orthographic
602 information to determine the contextual fit of upcoming words (Dimigen et al., 2012).
603 Although later studies reported parafoveal semantic effects in low constraint contexts
604 (see for instance Barber et al., 2013; Stites, Payne & Federmeier, 2017) it is still
605 unclear whether words in the parafovea are fully processed or whether only initial
606 letters are used to confirm contextually anticipated items (Barber et al., 2010).

607 In line with this interpretation we could provide neuroimaging (and
608 behavioral, see above) evidence for initial letters of parafoveally presented words
609 being processed at the sublexical level. More specifically, in the PW condition, the
610 contrast between constraining and unconstraining trigrams showed a cluster of
611 activation in the left supramarginal gyrus. The constraining trigrams manipulation,
612 however, could be located both in the sublexical orthographic and phonological
613 domain. This hypothesis finds support in results from several transcranial magnetic
614 stimulation (TMS) studies which used the supramarginal gyrus as a target region to
615 impair phonological aspects of word processing. More specifically, supramarginal
616 stimulation impaired performance during homophone judgement task (Sliwinska,
617 Khadilkar, Campbell-Ratcliffe, Quevenco and Devlin, 2012), initial sound similarity
618 task and syllables stress assignment task (Romero, Walsh and Papagno, 2006),
619 syllables counting task (Hartwigsen et al., 2010).

620 Orthographic typicality, in contrast, exerts its effects in the LvOT. To
621 illustrate, Woollams, Silani, Okada, Patterson and Price, (2010) investigated effects of
622 orthographic typicality (i.e., *cider* [typical] or *cynic* [atypical]) on brain activation
623 patterns and reported higher activation for orthographically atypical compared to
624 typical strings in posterior parts of the LvOT. Following Woollams et al.'s, (2010)
625 findings, one would conclude that the observed supramarginal activation is not
626 orthographical but phonological in nature.

627 Although the supramarginal region was repeatedly associated with
628 phonological processing (see for instance Binder et al., 2005; Carreiras, Mechelli,
629 Estévez & Price, 2007; Vigneau, Jobard, Mazoyer & Tzourio-Mazoyer, 2005), refined
630 functional parcellations of supramarginal activity showed a more heterogeneous
631 pattern. In a recent study, Oberhuber et al. (2016) identified four functionally distinct
632 regions within the left supramarginal gyrus. Coordinates of the present fMRI results
633 locate the peak of the supramarginal activation in the anterior dorsal portion of the
634 supramarginal gyrus (adSMG). The adSMG is an area which, according to Oberhuber
635 et al. (2016), could be activated when there is ambiguity in the mapping between
636 inputs and outputs but is not involved in phonological processing per se. Whether
637 phonological or executive, the nature of the here reported supramarginal activation
638 will require further investigation.

639
640

641 **5. Conclusions**

642

643 The present study is an initial step toward a better understanding of internal
644 mechanisms of parafoveal preprocessing. We used fMRI to investigate neural
645 correlates ('where') of parafoveal preprocessing and the type of information that can
646 be extracted from a parafoveal word ('what' and 'how'). Previous studies
647 investigating the type of parafoveally extracted information led to controversies, with
648 studies reporting lexico-semantic processing in the parafovea and studies supporting
649 the view that only sublexical information can be parafoveally extracted. The
650 dichotomous, sublexical-lexical distinction however, appears less clear in our results.
651 Behavioral findings provided evidence in favor of both sublexical and lexical
652 processing of parafoveal stimuli, with foveal load being one of the major determinants
653 of the amount of parafoveally extracted information. Pre-lexical processing of
654 parafoveal words initial letters can facilitate parafoveal word recognition as evidenced
655 by the constraining trigrams manipulation. Effects of constraining trigrams, however,
656 were restricted to the most difficult conditions thus questioning the true
657 generalizability of the present findings to more natural reading situations. Replicating
658 our findings in a more ecologically valid setting as well as including pseudowords
659 starting with constraining trigrams are important avenues for future research.

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