



Processing of parafoveally presented words. An fMRI study

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ABSTRACT

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

1. Introduction

While we read we do not only process the currently fixated word, but information is also extracted from upcoming – not yet fixated – words. This process is known as parafoveal preprocessing. To date, a large amount of research has focused on investigating the timeline (‘when’) and type (‘what’) of parafoveally accessed information (see Schotter et al., 2012 for a review). Concurrently, cognitive models of visual word recognition used this (mostly behavioral) data in the attempt to explain ‘how’ parafoveal word recognition is carried out in terms of cognitive operations. Importantly, however, studies focusing on internal mechanisms (‘where’) of parafoveal preprocessing are scarce. The study of ‘where’ could prove relevant in order to gain a deeper understanding of the ‘what’ and ‘how’ of parafoveal preprocessing (Carreiras, Armstrong, Perea and Frost, 2014). Furthermore, detailed anatomical information offers an opportunity for unique advance in developing more biologically plausible models of natural reading (Carreiras et al., 2014). The aim of the present study was to use functional magnetic resonance imaging (fMRI) to investigate neural correlates (‘where’) of parafoveal preprocessing during reading and the type of information that can be extracted from a parafoveal word (‘what’ and ‘how’).

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

Typically, ET studies recorded the eye movements of participants while they read sentences that had various linguistic or non-linguistic features manipulated (Schotter et al., 2012). Eye movement behavior can then be analyzed in relation to stimulus properties and used to infer cognitive processes underlying parafoveal preprocessing (Rayner, 1998). Although there is little doubt that proficient readers are able to extract and process information from upcoming words (McConkie and Rayner, 1975; Rayner, 1975), the type of such information (e.g., sublexical, lexico-semantic) is still a controversial topic. To illustrate, whereas it is widely accepted that sublexical (i.e., orthographic or phonological) information can be extracted from the parafoveal word (Balota and Rayner, 1983; Chanceaux and Grainger, 2012; Chanceaux et al., 2012; Dare and Shillcock, 2013; Grainger et al., 2014; Henderson et al., 1995; Rayner et al., 1978; Rayner et al., 1980; Tiffin-Richards and Schroeder, 2015, for

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reviews see Brothers et al., 2017; Schotter et al., 2012), evidence for parafoveal lexical processing is sparse (Hohenstein et al., 2010; Tsai et al., 2012; White et al., 2008; Yan et al., 2009).

On a similar line of research, several studies attempted to investigate which type of information can be extracted from parafoveally presented words by means of electroencephalography (EEG). These studies focus on parafoveal-on-foveal effects (POF, Kennedy et al., 2002). In brief, POF effects occur when properties of the - not yet fixated - word $n+1$ affect the processing of the currently fixated word (word n). Accordingly, EEG experiments would time-lock the analysis of event-related potentials (ERPs) to the point in time when processing of word n begins (e.g., stimulus onset of or fixation onset on word n). The time course and morphology of the ERPs could then be analyzed in relation to the psycholinguistic properties of word $n+1$. Thanks to the millisecond resolution of the EEG signal, these studies contributed to our understanding of ‘when’ parafoveal information becomes accessible (see Kliegl et al., 2012). However, as far as it concerns the specific issue of the type of information that can be extracted from the parafoveal words, EEG studies do not offer clear-cut answer to the controversies that emerged in the ET literature (see above). More specifically, whereas several studies reported effects of parafoveal semantic congruency on ERPs (Baccino and Manunta, 2005; Barber et al., 2010; Barber et al., 2011; Barber et al., 2013; López-Pérez, Dampuré, Hernández-Cabrera, and Barber, 2016), others could not replicate these findings (Dimigen et al., 2011; Simola et al., 2009).

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

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

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

At the behavioral level, the aim was to replicate classical lexical decision findings. More specifically, one would predict a processing benefit (i.e., faster reaction times, lower error rates) for foveally presented words as compared to foveally presented pseudowords (Cattell, 1886; Rayner, 1998). Moreover, it will be interesting to see whether lexical properties of parafoveal stimuli will affect behavioral performance, which would be indicative that parafoveal stimuli are processed at the lexical level. Last, in line with findings from the eye movement literature (Gagl et al., 2014;

Hand et al., 2012; Rayner et al., 1982) we expected parafoveally presented words which contained constraining trigrams to induce a higher word-likeness estimate (thus reflected in a higher number of “YES” responses) as compared to those which contained unconstraining trigrams.

At the neural level we expected lexical properties of foveal items to induce activation within brain areas evidenced by a recent meta-analysis summarizing results of 36 neuroimaging studies for word and pseudo-word reading (Taylor et al., 2013). More specifically Taylor et al. (2013) identified a mainly left-lateralized network that included (among others) the occipitotemporal cortex, the anterior fusiform and middle temporal gyrus, the inferior parietal cortex and the inferior frontal gyrus. With regard to our sublexical manipulation, we can only speculate about brain activation induced (if any) by the processing of parafoveal stimuli. It is now a commonly accepted view that the reading network encompasses two paths towards visual word recognition, that is a dorsal and a ventral pathway (see Carreiras et al., 2014; Price, 2012 for reviews). The dorsal pathway has been associated with sublexical processing (i.e., the processing of small units for visual word recognition such as the process of grapheme-phoneme conversion). The ventral pathway has been characterized as lexico-semantic route and is involved in whole-word recognition through activation of lexical nodes in an orthographic lexicon. Following this dual-route perspective, one would assume lexical access of parafoveally presented words to activate areas along the ventral lexico-semantic route. Conversely, one could expect the constraining trigrams manipulation to induce activity within the dorsal sublexical route.

2. Materials and methods

2.1. Participants

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

2.2. Experimental procedure

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

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

Participants were instructed to press a green button whenever they could recognize a word, independently whether foveally or parafoveally

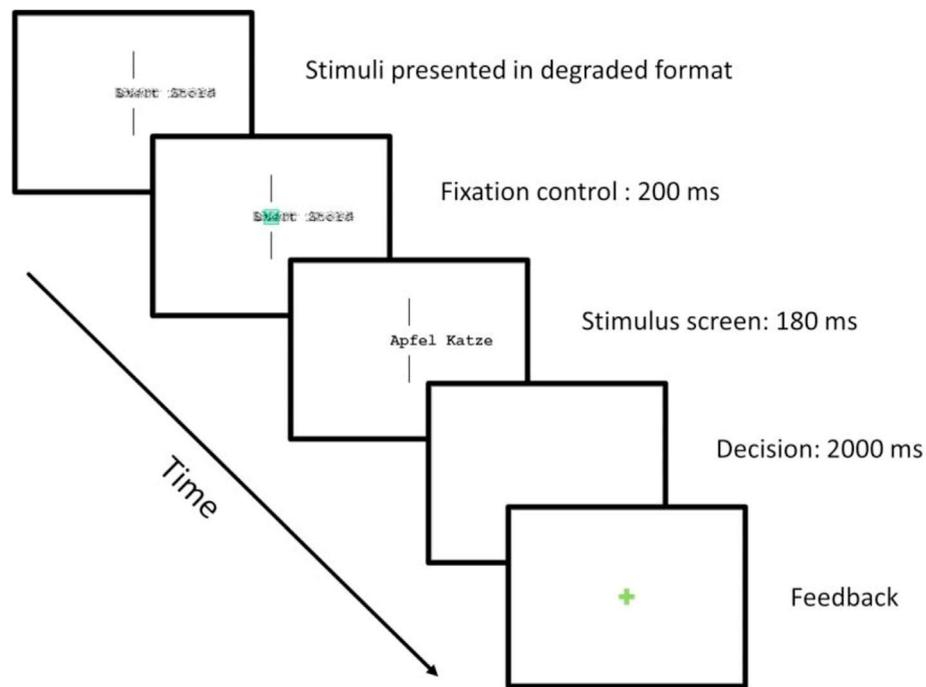


Fig. 1. Schematic representation of stimuli and task. Each trial started with stimuli being presented in a visually degraded format. A fixation of 200 ms between two vertically aligned bars triggered stimulus appearance. Stimuli remained on the screen for 180 ms. Followed a blank screen of 2000 ms where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

presented (conditions: WW, WP, PW). Only in the case of two pseudowords (condition PP) they were instructed to press a red button. At the end of each trial, a visual feedback in the form of a green or red cross indicated the correctness of the response. Before the beginning of the experiment, the participants were familiarized with the task in a short training session (40 trials) performed outside the scanner. Each experimental session was divided in four runs of 125 trials each (about 9–10 min per run). The overall experiment lasted about 1 h.

2.3. Stimuli

Stimuli were presented in a bold, monospaced font via a mirror on an MR-compatible LCD screen (NordicNeuroLab, Bergen, Norway) with a refresh rate of 60 Hz and a resolution of 1024 × 768 pixels. Four experimental conditions of 100 trials each were presented in a pseudorandomized order and intermixed with one hundred null-events (no stimuli appeared on the screen). In each trial two stimuli simultaneously appeared on the screen (see Fig. 1), one foveally and one parafoveally. The stimulus pair covered a total width of 5° of visual angle and extended from 0.9° left of the fixation control up to 4.1° to the right of the fixation control (each stimulus covered 2.3° of visual angle). The four experimental conditions were: foveal word and parafoveal word (WW), foveal word and parafoveal pseudoword (WP), foveal pseudoword and parafoveal word (PW) and foveal and parafoveal pseudoword (PP). For the

sublexical manipulation we manipulated the initial trigram of parafoveally presented words (conditions WW and PW). This resulted in conditions WW and PW having half of the parafoveally presented words containing a constraining trigram, and half an unconstraining trigram (50 trials each). A constraining trigram was defined as a unique three-letters-sequence at the beginning of a word as compared to all 5-letter nouns in the CELEX database (Baayen et al., 1993). The unconstraining trigrams had a mean frequency of 3.04 (difference: $t(198) = 14.22$).

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

2.4. fMRI

Functional and structural neuroimaging data were collected with a Siemens Magnetom Trio 3 T Scanner (Siemens AG, Erlangen, Germany) using a 12-channel head-coil. Functional images consisted of a T2*-weighted gradient echo EPI sequence (TR 2250 ms, TE 30 ms, matrix 64 × 64, FOV 192 mm, flip angle 70°). Within the TR thirty-six slices with a slice thickness of 3 mm and a slice gap of 0.3 mm were acquired. In addition to the functional images, a gradient echo field map (TR 488 ms, TE 1 = 4.49 ms, TE 2 = 6.95 ms) and a high resolution (1 × 1 × 1 mm) structural scan with a T1-weighted MPRAGE sequence were acquired

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)

^a Note: First bigram frequency.

^b Note: Average bigram frequency.

from each participant. Scanning proceeded in 4 runs separated by short breaks. Each run had a variable number of scans that depended on the participants' viewing behavior and the number of required calibration procedures (ranging from 204 to 563 scans, $M = 257$ scans).

2.5. Eye tracking

Eye movements were recorded monocularly from the right eye with an SR Research (Ontario, Canada) EyeLink CL system (sampling rate: 1 kHz) in the long-range setup. The camera was mounted on the head side of the scanner bore at a distance of 90 cm from the participant's head and 120 cm from the LCD screen. A 3 points calibration routine was administered at the beginning of each run. The average tracking error was kept below 0.5° of visual angle. The calibration routine was repeated every time the fixation control at the beginning of a trial (see Fig. 1) failed. Stimulus presentation was controlled by the Experiment Builder software (SR Research Ltd., Canada).

2.6. Accuracy rate and reaction time analysis

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

2.7. fMRI data preprocessing and analysis

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

Statistical analysis was performed in a two-stage mixed effects model. In a participant-specific first level model, the onsets of the stimuli were modeled by a canonical hemodynamic response function with no time and dispersion derivatives. The movement parameters derived from the realignment step during preprocessing were modeled as covariates of no interest. The functional data in these first level models were highpass filtered with a cut-off of 128 s and corrected for autocorrelation by an AR(1) model (Friston et al., 2002). In order to investigate effects of lexicality on brain activation patterns, the parameter estimates reflecting signal change for each individual condition (WW, WP, PW, PP) versus baseline (which consisted of the inter-stimulus intervals, the null-events, and the eye tracker recalibration procedures) were calculated in the context of a GLM (Henson, 2003). These participant-specific contrast images were used for the second-level random effect analysis. Differences between conditions were examined by *t*-tests thresholded at a voxel-level (height) of $p < .001$ (uncorrected) and a cluster-level (extent) of $p < .05$ (corrected for multiple comparisons using the false discovery rate).

A similar procedure was adopted to calculate effects of the

constraining trigrams manipulation on brain activation patterns. First-level contrast images were estimated for those condition where we manipulated the constraint imposed by the trigrams (wW_C, wW_U, pW_C, pW_U). These participant-specific contrast images were used for the second-level random effect analysis. Differences between conditions were examined by *t*-tests thresholded at a voxel-level (height) of $p < .001$ (uncorrected) and a cluster-level (extent) of $p < .05$ (corrected for multiple comparisons using the false discovery rate).

3. Results

3.1. Behavioral results

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

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

3.2. Neural correlates of the lexicality effect

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

The results from the contrast WW > PP are shown in Fig. 3 (blue tones) and details of all clusters of activation are given in Table 2A. The largest cluster was observed in the left middle occipital cortex encompassing left angular gyrus and precuneus. Other large clusters were observed in the bilateral occipito-temporal cortex and in the middle frontal gyrus. Additionally we observed smaller clusters of activation in the left putamen, right caudate and in the right somatosensory cortex.

Results from the reversed contrast (i.e., PP > WW) are shown in Fig. 3 (red tones) and details of all clusters are given in Table 2B. This contrast evidenced a main cluster of activation in the left supramarginal gyrus extending horizontally over the intraparietal sulcus and postcentral gyrus. In the right hemisphere we observed a similar (but less extensive) cluster. Furthermore, we observed bilateral activation of the insular regions as well as activation in the paracingulate cortex. Minor clusters of activation for this contrast were in the left and right thalamus.

3.3. Neural correlates of the parafoveal lexicality effect

In order to investigate the parafoveal lexicality effect we focused on the contrast between conditions that had comparable foveal lexical information but differed in the parafoveal lexical information (i.e., WW vs.

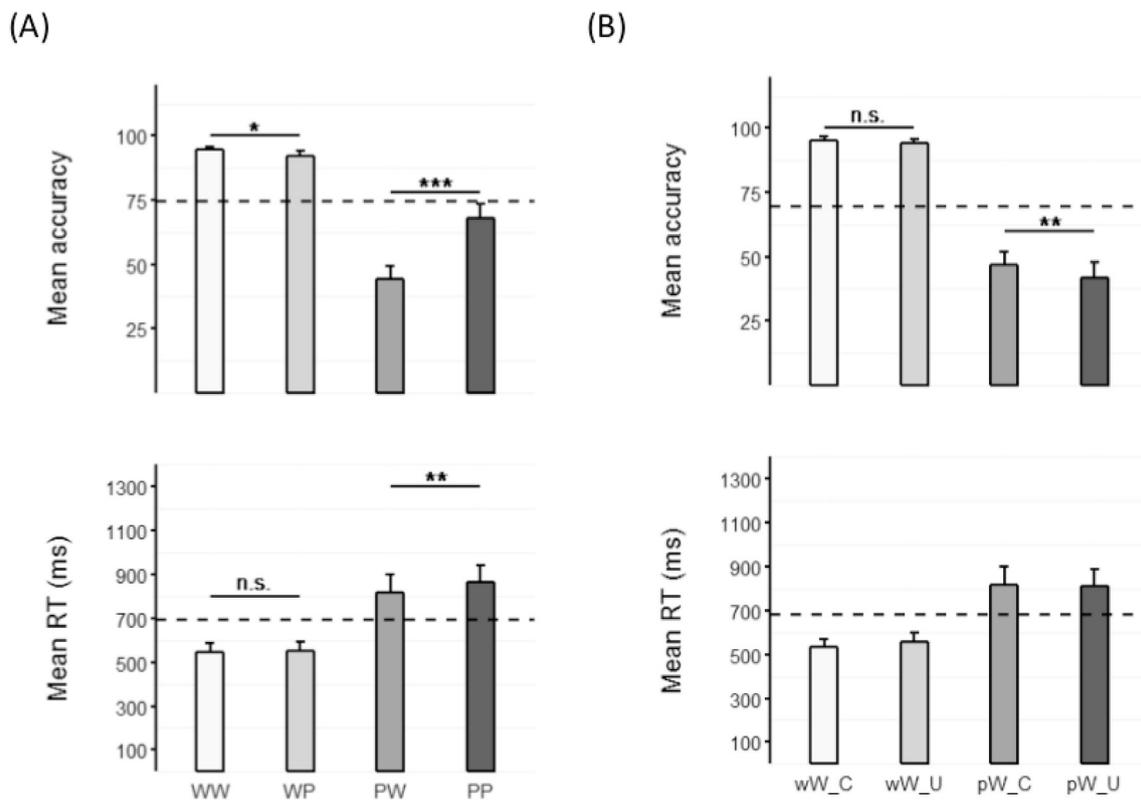


Fig. 2. Behavioral results. (A) Mean accuracy rates (percent correct) and reaction times (RTs) in the four experimental conditions. (B) Mean accuracy and reaction times (RTs) for constraining and unconstraining trigrams conditions. Error bars represent 95% confidence intervals. Dashed lines represent mean accuracy rates and mean reaction times across conditions. Significant differences between conditions are marked with asterisks: * $p < .5$, ** $p < .01$, *** $p < .001$. 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.

WP and PW vs. PP). Interestingly, none of the four possible combinations (i.e., $WW > WP$, $WP > WW$, $PW > PP$, $PP > PW$) evidenced significant clusters of activation. This result speaks against lexical processing of parafoveally presented words.

3.4. Neural correlates of the constraining trigram manipulation

To investigate effects of constraining trigrams on brain activation patterns we focused on the conditions which contained parafoveally presented words (WW and PW). We compared conditions which contained constraining trigrams to those containing unconstraining trigrams (i.e., wW_C vs. wW_U and pW_C vs. pW_U). The contrasts wW_C > wW_U, wW_U > wW_C and pW_U > pW_C did not evidence significant clusters of activation. The contrast pW_C > pW_U revealed a significant cluster of activation in the left supramarginal gyrus (ISMG; $-39, -34, 43$; $Z = 4.84$; 152 voxels). That is, constraining trigrams induced higher activation in the ISMG as compared to unconstraining trigrams (see Fig. 4).

4. Discussion

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

4.1. Behavioral findings

Expectedly, conditions with foveally presented words induced shorter reaction times and higher accuracy rates as compared to conditions with foveally presented pseudowords (Cattell, 1886; Rayner, 1998). Conversely, effects of lexicality in the parafovea showed a less clear pattern of results. Contrasts between word word (WW) and word pseudoword (WP) conditions evidenced a significant effect in accuracy rates, but not in reaction times. Moreover, performance in the pseudoword word (PW) condition was at chance level, indicative that, in this condition, participants were not able to recognize parafoveally presented words. Because performance was at chance level in the PW condition we reasoned that the relatively high accuracy rate (67.5%) observed in the pseudoword pseudoword (PP) condition can hardly be explained in terms of parafoveal pseudowords being fully processed. Instead, a more likely explanation for this finding is that participants were more inclined toward a “no” response when unable to correctly identify parafoveally presented stimuli.

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

In the present study, however, the amount of information extracted

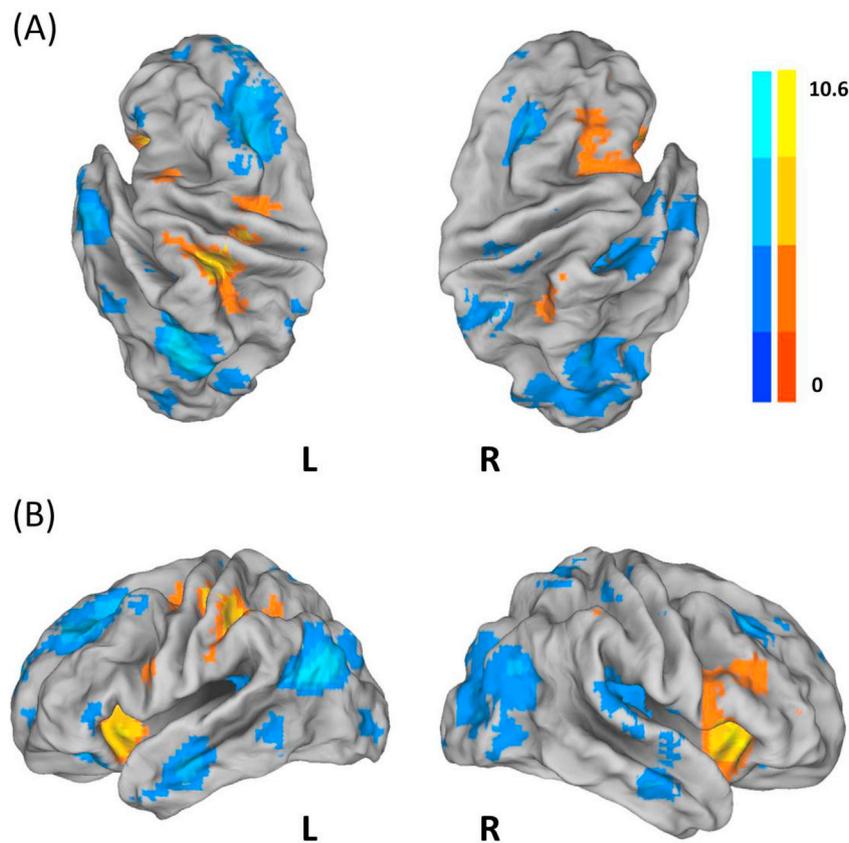


Fig. 3. Contrasts of interest. Surface rendering of the WW > PP (blue tones) and PP > WW (red tones) contrasts, (A) dorsal view rotated inwards by 45° (B) lateral view. L, left; R, right.

from parafoveal stimuli was affected by the difficulty of the foveal stimulus. In line with the foveal load hypothesis (Henderson and Ferreira, 1990; Payne et al., 2016), less information was acquired parafoveally when foveal processing was difficult. To illustrate, when foveal stimuli were high frequency nouns, parafoveal information could be extracted up to the lexical level. Accordingly, one might speculate that lower accuracy rates in the WP as compared to WW condition could be explained with parafoveal difficulty modulating concurrent foveal processing (i.e., parafoveal on foveal effect, POF).

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

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

At this point, it is important to note, that the existence of POF effects is a highly controversial topic in the eye tracking literature (Rayner, 2009). According to Rayner (2009), POF effects arise due to mislocated fixations (Drieghe et al., 2008) and are often observed when a large corpus of data is taken into account (see Kliegl et al., 2006; Kliegl, 2007). Conversely, with more constraining paradigms, POF effects were almost exclusively observed when orthographically illegal non-words were parafoveally presented (Drieghe, 2011; Drieghe et al., 2005) or when foveal and parafoveally presented words were semantically related (see Payne et al., 2016). As far as it concerns the present study, all pseudowords were orthographically legal non-words and stimulus pairs shared

no semantic relationships. To conclude, lower accuracy rates in the WP condition as compared to the WW condition indicate parafoveal lexical processing. This effect, however, must be interpreted with caution given that it finds no support in our neuroimaging findings (see below).

In summary, foveal load significantly contributed to the amount of parafoveally extracted information (see also Payne et al., 2016). In conditions with low foveal load (i.e. WW and WP) parafoveal information could be extracted up to the lexical level. Conversely, in the conditions where foveal stimuli were more difficult to process (i.e. PW and PP), only pre-lexical information could be extracted from the parafovea. Furthermore, behavioral evidence confirmed the special role that words' initial letters play during parafoveal preprocessing (Rayner et al., 1982). Former studies, which also found an effect of the initial trigrams (Gagl et al., 2014; Hand et al., 2012), interpreted the effect in accordance to the lexical constraint hypothesis proposed by Lima and Inhoff (1985). The lexical constraint hypothesis assumes that parafoveally processed word-initial letters are used in accessing the word's meaning. Moreover, the advantage for constraining over unconstraining initial trigrams stems out of the fact that constraining trigrams will pre-activate smaller lexical neighborhoods (e.g., Hawelka et al., 2013). To illustrate, whereas the three letters sequence “*dwa*” can only pre-activate the word “*dwarf*”, the sequence “*ang*” will pre-activate words like “*angle*”, “*anger*”, “*angel*”. The difference in the number of potential lexical candidates activated by the initial letters of a word can result in the processing benefit observed in the present as well as other studies (Gagl et al., 2014; Hand et al., 2012).

4.2. Neuroimaging findings

Neural underpinnings of the lexicality effects (contrast between WW and PP conditions) largely overlapped with a network of brain regions evidenced by a recent meta-analysis of word and pseudoword reading experiments (Taylor et al., 2013). It is important to note, however, that in

Table 2

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.

Cluster	Label	Number of Voxels	Z	MNI coordinates		
				x	y	z
(A) WW > PP						
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						
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

left ventral occipitotemporal cortex (LvOT) the activation profile observed in the present study does not conform to Taylor et al. (2013) findings. More in detail, Taylor et al. (2013) reported higher activation for pseudowords than words in the LvOT whereas, for the same area, we did not find differences across conditions. This result nicely fits the ongoing debate concerning levels of activation within the LvOT during word and pseudoword reading (see for instance Price and Devlin, 2003).

Several previous studies evidenced that LvOT activity is sensitive to task properties and, among others, stimulus presentation duration was identified as one likely cause of inconsistencies in the literature (Mano et al., 2012; McNorgan, Chabal, O'Young, Lukic and Booth, 2015; Schuster et al., 2015; Yang and Zevin, 2014). More specifically, studies with long presentation durations (ranging from 600 ms to 2000 ms) reported higher activation for pseudowords compared to words in LvOT (Binder et al., 2005; Mechelli et al., 2003; Kronbichler et al., 2004; Schurz et al., 2010). Conversely, studies which presented the stimuli for substantially shorter presentation durations (from 100 ms to 200 ms) found similar levels of LvOT activation for word and pseudoword reading (Kronshabel et al., 2013; Vinckier et al., 2007). Accordingly, the short presentation duration (180 ms) employed in the present study is the most likely explanation for the activation pattern observed in the LvOT.

Conversely to our behavioral findings, fMRI results did not evidence brain areas sensitive to lexical properties of parafoveal items (contrasts WW vs. WP and PW vs. PP). This finding is in agreement with a large body of eye tracking and EEG studies which could not find evidence of parafoveally presented words being processed up to access word meaning (see for instance Brothers et al., 2017; Dimigen et al., 2011; Dimigen et al., 2012; Simola et al., 2009). Importantly, though, other studies reported effects of semantic congruency between foveally and parafoveally presented items (Barber et al., 2010, 2011; 2013). More in detail, Barber and colleagues presented sentences in the form of triplets of words, with each foveal word being flanked by the upcoming word in the sentence (right flanker) and preceding word in the sentence (left flanker). Each triad appeared on the screen for a very short time (100 ms - Barber et al., 2010, 2011, 260 ms - Barber et al., 2013) and the main experimental manipulation consisted in a critical triad where an incongruent word was parafoveally presented (right flanker). Keeping in mind that, with a 180 ms presentation duration we could not provide evidence for lexical processing of parafoveal words it seems unlikely that, with a 100 ms presentation duration, parafoveal words could be fully processed (up to accessing word's meaning) in Barber et al. (2010, 2011). A more plausible explanation for Barber and colleagues' findings is that, in these studies, participants could use partial orthographic information to determine the contextual fit of upcoming words (Dimigen et al., 2012). Although later studies reported parafoveal semantic effects in low constraint contexts (see for instance Barber et al., 2013; Stites et al., 2017) it is still unclear whether words in the parafovea are fully processed or whether only initial letters are used to confirm contextually anticipated items (Barber et al., 2010).

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

Orthographic typicality, in contrast, exerts its effects in the LvOT. To illustrate, Woollams, Silani, Okada, Patterson and Price (2011) investigated effects of orthographic typicality (i.e., cider [typical] or cynic [atypical]) on brain activation patterns and reported higher activation for orthographically atypical compared to typical strings in posterior parts of the LvOT. Following Woollams et al.'s (2011) findings, one would conclude that the observed supramarginal activation is not orthographical but phonological in nature.

Although the supramarginal region was repeatedly associated with phonological processing (see for instance Binder et al., 2005; Carreiras

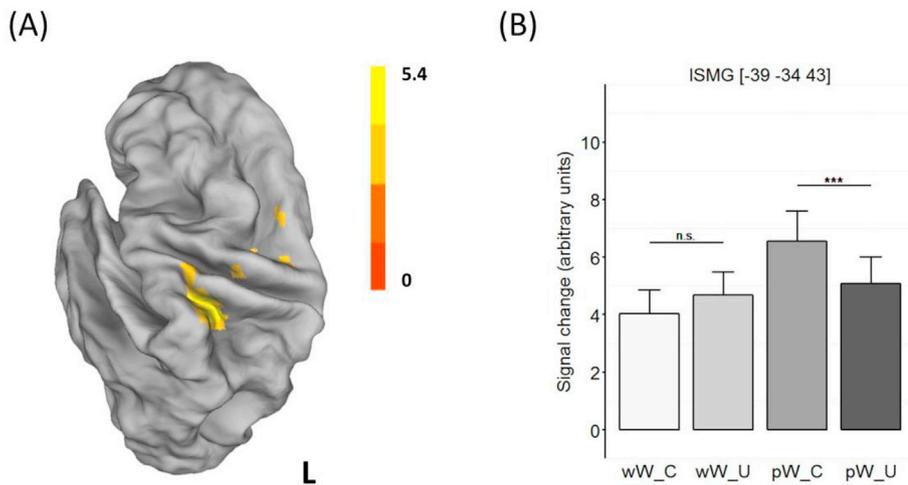


Fig. 4. Neural correlates of constraining trigrams. Surface rendering of the pW_C > pW_U, (A) dorsal view rotated inwards by 45°. L, left (B) Bar plots represent signal change estimates (in arbitrary units). Error bars represent 95% confidence intervals. Significant differences between conditions are marked with asterisks: *** $p < .001$. MNI coordinates for individual ROI reported between []. ISMG, left supramarginal gyrus. wW_C, constraining trigrams condition WW; wW_U, unconstraining trigrams condition WW; pW_C, constraining trigrams condition PW; pW_U, unconstraining trigrams condition PW.

et al., 2007; Vigneau et al., 2005), refined functional parcellations of supramarginal activity showed a more heterogeneous pattern. In a recent study, Oberhuber et al. (2016) identified four functionally distinct regions within the left supramarginal gyrus. Coordinates of the present fMRI results locate the peak of the supramarginal activation in the anterior dorsal portion of the supramarginal gyrus (adSMG). The adSMG is an area which, according to Oberhuber et al. (2016), could be activated when there is ambiguity in the mapping between inputs and outputs but is not involved in phonological processing per se. Whether phonological or executive, the nature of the here reported supramarginal activation will require further investigation.

5. Conclusions

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

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References

- Baayen, R.H., Piepenbrock, R., van H, R., 1993. The {CELEX} Lexical Data Base on {CD-ROM}.
- Baccino, T., Manunta, Y., 2005. Eye-fixation-related potentials: insight into parafoveal processing. *J. Psychophysiol.* 19 (3), 204–215. <https://doi.org/10.1027/0269-8803.19.3.204>.

- Balota, D.A., Rayner, K., 1983. Parafoveal visual information and semantic contextual constraints. *J. Exp. Psychol. Hum. Percept. Perform.* 9 (5), 726.
- Barber, H.A., Donamayor, N., Kutas, M., Munte, T., 2010. Parafoveal N400 effect during sentence reading. *Neurosci. Lett.* 479 (2), 152–156. <https://doi.org/10.1016/j.neulet.2010.05.053>.
- Barber, H.A., Ben-Zvi, S., Bentin, S., Kutas, M., 2011. Parafoveal perception during sentence reading? an ERP paradigm using rapid serial visual presentation (RSVP) with flankers. *Psychophysiology* 48 (4), 523–531.
- Barber, H.A., van der Meij, M., Kutas, M., 2013. An electrophysiological analysis of contextual and temporal constraints on parafoveal word processing. *Psychophysiology* 50 (1), 48–59. <https://doi.org/10.1111/j.1469-8986.2012.01489.x>.
- Bendahman, L.A., Vitu, F., Grainger, J., 2010. Ultra-fast processing of printed words? *Perception* 39 (S), 147.
- Binder, J.R., Medler, D.A., Desai, R., Conant, L.L., Liebenthal, E., 2005. Some neurophysiological constraints on models of word naming. *Neuroimage* 27 (3), 677–693.
- Brothers, T., Hoversten, L.J., Traxler, M.J., 2017. Looking back on reading ahead: No evidence for lexical parafoveal-on-foveal effects. *J. Mem. Lang.* 96, 9–22.
- Carreiras, M., Mechelli, A., Estévez, A., Price, C.J., 2007. Brain activation for lexical decision and reading aloud: two sides of the same coin? *J. Cognit. Neurosci.* 19 (3), 433–444.
- Carreiras, M., Armstrong, B.C., Perea, M., Frost, R., 2014. The what, when, where, and how of visual word recognition. *Trends Cognit. Sci.* 18 (2), 90–98.
- Cattell, J.M., 1886. The time it takes to see and name objects. *Mind* 11 (41), 63–65.
- Chanceaux, M., Grainger, J., 2012. Serial position effects in the identification of letters, digits, symbols, and shapes in peripheral vision. *Acta Psychol.* 141 (2), 149–158.
- Chanceaux, M., Vitu, F., Bendahman, L., Thorpe, S., Grainger, J., 2012. Word processing speed in peripheral vision measured with a saccadic choice task. *Vis. Res.* 56, 10–19.
- Dare, N., Shillcock, R., 2013. Serial and parallel processing in reading: investigating the effects of parafoveal orthographic information on nonisolated word recognition. *Q. J. Exp. Psychol.* 66 (3), 487–504.
- Dimigen, O., Sommer, W., Hohlfield, A., Jacobs, A.M., Kliegl, R., 2011. Coregistration of eye movements and EEG in natural reading: analyses and review. *J. Exp. Psychol. Gen.* 140 (4), 552.
- Dimigen, O., Kliegl, R., Sommer, W., 2012. Trans-saccadic parafoveal preview benefits in fluent reading: a study with fixation-related brain potentials. *Neuroimage* 62 (1), 381–393.
- Drieghe, D., 2011. Parafoveal-on-foveal Effects on Eye Movements during reading.
- Drieghe, D., Brysbaert, M., Desmet, T., 2005. Parafoveal-on-foveal effects on eye movements in text reading: does an extra space make a difference? *Vis. Res.* 45 (13), 1693–1706.
- Drieghe, D., Rayner, K., Pollatsek, A., 2008. Mislocated fixations can account for parafoveal-on-foveal effects in eye movements during reading. *Q. J. Exp. Psychol.* 61 (8), 1239–1249.
- Friston, K., Glaser, D., Henson, R., Kiebel, S., Phillips, C., Ashburner, J., 2002. Classical and Bayesian inference in neuroimaging: applications. *Neuroimage* 16 (2), 484–512. <https://doi.org/10.1006/nimg.2002.1091>.
- Gagl, B., Hawelka, S., Richlan, F., Schuster, S., Hutzler, F., 2014. Parafoveal preprocessing in reading revisited: evidence from a novel preview manipulation. *J. Exp. Psychol. Learn. Mem. Cognit.* 40 (2), 588.
- Grainger, J., Mathôt, S., Vitu, F., 2014. Tests of a model of multi-word reading: effects of parafoveal flanking letters on foveal word recognition. *Acta Psychol.* 146, 35–40.
- Hand, C.J., O'Donnell, P.J., Sereno, S.C., 2012. Word-initial letters influence fixation durations during fluent reading. *Front. Psychol.* 3.
- Hartwigsen, G., Baumgaertner, A., Price, C.J., Koehnke, M., Ulmer, S., Siebner, H.R., 2010. Phonological decisions require both the left and right supramarginal gyri. *Proc. Natl. Acad. Sci. Unit. States Am.* 107 (38), 16494–16499.

- Hawelka, S., Schuster, S., Gagl, B., Hutzler, F., 2013. Beyond single syllables: the effect of first syllable frequency and orthographic similarity on eye movements during silent reading. *Lang. Cognit. Process.* 28 (8), 1134–1153.
- Henderson, J.M., Ferreira, F., 1990. Effects of foveal processing difficulty on the perceptual span in reading: implications for attention and eye movement control. *J. Exp. Psychol. Learn. Mem. Cognit.* 16 (3), 417.
- Henderson, J.M., Dixon, P., Petersen, A., Twilley, L.C., Ferreira, F., 1995. Evidence for the use of phonological representations during transsaccadic word recognition. *J. Exp. Psychol. Hum. Percept. Perform.* 21 (1), 82.
- Henson, R., 2003. Analysis of fMRI Time Series: Linear Time-invariant Models, Event-related fMRI and Optimal Experimental Design.
- Hohenstein, S., Laubrock, J., Kliegl, R., 2010. Semantic preview benefit in eye movements during reading: a parafoveal fast-priming study. *J. Exp. Psychol. Learn. Mem. Cognit.* 36 (5), 1150.
- Kennedy, A., Pynte, J., Ducrot, S., 2002. Parafoveal-on-foveal interactions in word recognition. *Q. J. Exp. Psychol.: Section A* 55 (4), 1307–1337.
- Keuleers, E., Brysbaert, M., 2010. Wuggy: a multilingual pseudoword generator. *Behav. Res. Meth.* 42 (3), 627–633.
- Kliegl, R., 2007. Toward a perceptual-span theory of distributed processing in reading: a reply to Rayner, Pollatsek, Drieghe, Slattery, and Reichle (2007). *J. Exp. Psychol. Gen.* 136 (3), 530.
- Kliegl, R., Nuthmann, A., Engbert, R., 2006. Tracking the mind during reading: the influence of past, present, and future words on fixation durations. *J. Exp. Psychol. Gen.* 135 (1), 12.
- Kliegl, R., Dambacher, M., Dimigen, O., Jacobs, A.M., Sommer, W., 2012. Eye movements and brain electric potentials during reading. *Psychol. Res.* 76 (2), 145–158.
- Kronbichler, M., Hutzler, F., Wimmer, H., Mair, A., Staffen, W., Ladurner, G., 2004. The visual word form area and the frequency with which words are encountered: evidence from a parametric fMRI study. *Neuroimage* 21 (3), 946–953.
- Kronschabel, J., Schmid, R., Maurer, U., Brandeis, D., 2013. Visual print tuning deficits in dyslexic adolescents under minimized phonological demands. *Neuroimage* 74, 58–69.
- Lawrence, M.A., 2011. Ez: Easy Analysis and Visualization of Factorial Experiments. Computer Software Manual[R Package Version 3.0-0].
- Lima, S.D., Inhoff, A.W., 1985. Lexical access during eye fixations in reading: effects of word-initial letter sequence. *J. Exp. Psychol. Hum. Percept. Perform.* 11 (3), 272.
- López-Peréz, P., Dampurè, J., Hernández-Cabrera, J., Barber, H., 2016. Semantic parafoveal-on-foveal effects and preview benefits in reading: evidence from fixation related potentials. *Brain Lang.* 162, 29–34.
- Mano, Q.R., Humphries, C., Desai, R.H., Seidenberg, M.S., Osmon, D.C., Stengel, B.C., Binder, J.R., 2012. The role of left occipitotemporal cortex in reading: reconciling stimulus, task, and lexicality effects. *Cerebr. Cortex* 23 (4), 988–1001.
- McConkie, G.W., Rayner, K., 1975. The span of the effective stimulus during a fixation in reading. *Attention, Perception, & Psychophysics* 17 (6), 578–586.
- McNorgan, C., Chabal, S., O'young, D., Lukic, S., Booth, J.R., 2015. Task dependent lexicality effects support interactive models of reading: a meta-analytic neuroimaging review. *Neuropsychologia* 67, 148–158.
- Mechelli, A., Gorno-Tempini, M.L., Price, C.J., 2003. Neuroimaging studies of word and pseudoword reading: consistencies, inconsistencies, and limitations. *J. Cognit. Neurosci.* 15 (2), 260–271.
- Oberhuber, M., Hope, T.M.H., Seghier, M.L., Parker Jones, O., Prejawa, S., Green, D.W., Price, C.J., 2016. Four functionally distinct regions in the left supramarginal gyrus support word processing. *Cerebr. Cortex* 26 (11), 4212–4226.
- Payne, B.R., Stites, M.C., Federmeier, K.D., 2016. Out of the corner of my eye: foveal semantic load modulates parafoveal processing in reading. *J. Exp. Psychol. Hum. Percept. Perform.* 42 (11), 1839.
- Price, C.J., 2012. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *Neuroimage* 62 (2), 816–847.
- Price, C.J., Devlin, J.T., 2003. The myth of the visual word form area. *Neuroimage* 19 (3), 473–481.
- Rayner, K., 1975. The perceptual span and peripheral cues in reading. *Cognit. Psychol.* 7 (1), 65–81.
- Rayner, K., 1998. Eye movements in reading and information processing: 20 years of research. *Psychol. Bull.* 124 (3), 372.
- Rayner, K., 2009. Eye movements and attention in reading, scene perception, and visual search. *Q. J. Exp. Psychol.* 62 (8), 1457–1506.
- Rayner, K., McConkie, G.W., Ehrlich, S., 1978. Eye movements and integrating information across fixations. *J. Exp. Psychol. Hum. Percept. Perform.* 4 (4), 529.
- Rayner, K., McConkie, G.W., Zola, D., 1980. Integrating information across eye movements. *Cognit. Psychol.* 12 (2), 206–226.
- Rayner, K., Well, A.D., Pollatsek, A., Bertera, J.H., 1982. The availability of useful information to the right of fixation in reading. *Attention, Perception, & Psychophysics* 31 (6), 537–550.
- Romero, L., Walsh, V., Papagno, C., 2006. The neural correlates of phonological short-term memory: a repetitive transcranial magnetic stimulation study. *J. Cognit. Neurosci.* 18 (7), 1147–1155.
- Schotter, E., Angele, B., Rayner, K., 2012. Parafoveal processing in reading. *Atten. Percept. Psychophys.* 74 (1), 5–35. <https://doi.org/10.3758/s1314-011-0219-2>.
- Schurz, M., Sturm, D., Richlan, F., Kronbichler, M., Ladurner, G., Wimmer, H., 2010. A dual-route perspective on brain activation in response to visual words: evidence for a length by lexicality interaction in the visual word form area (VWFA). *Neuroimage* 49 (3), 2649–2661.
- Schuster, S., Hawelka, S., Richlan, F., Ludersdorfer, P., Hutzler, F., 2015. Eyes on words: a fixation-related fMRI study of the left occipito-temporal cortex during self-paced silent reading of words and pseudowords. *Sci. Rep.* 5.
- Simola, J., Holmqvist, K., Lindgren, M., 2009. Right visual field advantage in parafoveal processing: evidence from eye-fixation-related potentials. *Brain Lang.* 111 (2), 101–113.
- Sliwinska, M.W., Khadilkar, M., Campbell-Ratcliffe, J., Quevenco, F., Devlin, J.T., 2012. Early and sustained supramarginal gyrus contributions to phonological processing. *Front. Psychol.* 3.
- Stites, M.C., Payne, B.R., Federmeier, K.D., 2017. Getting ahead of yourself: parafoveal word expectancy modulates the N400 during sentence reading. *Cognit. Affect Behav. Neurosci.* 17 (3), 475–490.
- Taylor, J.S.H., Rastle, K., Davis, M.H., 2013. Can Cognitive Models Explain Brain Activation during Word and Pseudoword reading? a Meta-analysis of 36 Neuroimaging Studies.
- Team, R.C., 2013. R: A Language and Environment for Statistical Computing.
- Tiffin-Richards, S.P., Schroeder, S., 2015. Children's and adults' parafoveal processes in German: phonological and orthographic effects. *J. Cognit. Psychol.* 27 (5), 531–548.
- Tsai, J.L., Kliegl, R., Yan, M., 2012. Parafoveal semantic information extraction in traditional Chinese reading. *Acta Psychol.* 141 (1), 17–23.
- Vigneau, M., Jobard, G., Mazoyer, B., Tzourio-Mazoyer, N., 2005. Word and non-word reading: what role for the visual word form area? *Neuroimage* 27 (3), 694–705.
- Vinckier, F., Dehaene, S., Jobert, A., Dubus, J.P., Sigman, M., Cohen, L., 2007. Hierarchical coding of letter strings in the ventral stream: dissecting the inner organization of the visual word-form system. *Neuron* 55 (1), 143–156.
- White, S.J., Bertram, R., Hyönä, J., 2008. Semantic processing of previews within compound words. *J. Exp. Psychol. Learn. Mem. Cognit.* 34 (4), 988.
- Woollams, A.M., Silani, G., Okada, K., Patterson, K., Price, C.J., 2011. Word or word-like? Dissociating orthographic typicality from lexicality in the left occipito-temporal cortex. *J. Cognit. Neurosci.* 23 (4), 992–1002.
- Yan, M., Richter, E.M., Shu, H., Kliegl, R., 2009. Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bull. Rev.* 16 (3), 561–566.
- Yang, J., Zevin, J., 2014. The impact of task demand on visual word recognition. *Neuroscience* 272, 102–115.