Parafoveal-on-foveal repetition effects in sentence reading: A co-registered eye-tracking and electroencephalogram study

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Parafoveal-on-foveal repetition effects in sentence reading: A co-registered eye-tracking and electroencephalogram study

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Abstract
When reading, can the next word in the sentence (word $n + 1$) influence how you read the word you are currently looking at (word n)? Serial models of sentence reading state that this generally should not be the case, whereas parallel models predict that this should be the case. Here we focus on perhaps the simplest and the strongest Parafoveal-on-Foveal (PoF) manipulation: word $n + 1$ is either the same as word n or a different word. Participants read sentences for comprehension and when their eyes left word n, the repeated or unrelated word at position $n + 1$ was swapped for a word that provided a syntactically correct continuation of the sentence. We recorded electroencephalogram and eye-movements, and time-locked the analysis of fixation-related potentials (FRPs) to fixation of word n. We found robust PoF repetition effects on gaze durations on word n, and also on the initial landing position on word n. Most important is that we also observed significant effects in FRPs, reaching significance at 260 ms post-fixation of word n. Repetition of the target word n at position $n + 1$ caused a widely distributed reduced negativity in the FRPs. Given the timing of this effect, we argue that it is driven by orthographic processing of word $n + 1$, while readers were still looking at word n, plus the spatial integration of orthographic information extracted from these two words in parallel.

KEYWORDS
eye-movements, fixation-related-potentials, parafoveal-on-foveal effects, parallel processing, reading

1 | INTRODUCTION

When readers move their eyes along a line of text while reading for meaning, can the word locate immediately to the right of the currently fixated word ($n + 1$)[1] influence the processing of the fixated word (n)? This is the question asked by studies of so-called parafoveal-on-foveal (PoF) influences on reading behavior, and the answer to that question is still hotly debated. That is because the question is of utmost theoretical importance, with current theories of eye-movement control and reading diverging with respect to the answer they offer. Sequential attention shift models, such as E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998) initially

[1]That is the next word in the sentence for languages read from left-to-right.

predicted that there should be no such PoF effects, at least not lexically driven effects.[2] Moreover, parallel processing models, such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005), Glenmore (Reilly & Radach, 2006), and OB1-reader (Snell, van Leipsig, Grainger, & Meeter, 2018), naturally predict that such effects should be observable.

A number of studies investigating PoF influences in reading manipulated the frequency of word $n + 1$ and measured the impact of that manipulation on the time spent reading word n before the eyes left that word with a progressive saccade. Several analyses of eye-movement corpus data have revealed an influence of the frequency of word $n + 1$ on the time spent looking at word n before the eyes leave that word (Kennedy & Pynte, 2005; Kennedy, Pynte, & Ducrot, 2002; Kliegl, Nuthmann, & Engbert, 2006). However, laboratory sentence reading studies have typically failed to find such PoF frequency effects (see Drieghe, 2011, for a summary of the evidence). Moreover, manipulations of the orthographic regularity of word $n + 1$ have shown clear effects on the processing of word n (Inhoff, Starr, & Shindler, 2000; Pynte, Kennedy, & Ducrot, 2004), possibly due to attention being attracted by such manipulation.

More directly relevant for the present work are the investigations of orthographic PoF effects by Dare and Shillcock (2013) and Angele, Tran, and Rayner (2013).[3] Here, the orthographic overlap between word n and $n + 1$ was manipulated using the gaze-contingent boundary paradigm (Rayner, 1975). Both of these studies included a repetition manipulation that was contrasted with an unrelated word at position $n + 1$. Thus, for example, participants read the following word sequence "The store had a coat coat that week," and when their eyes left the first occurrence of "coat" with a progressive saccade, the second occurrence was changed to "sale," and participants had the impression they had read the normal sentence "The store had a coat sale that week." This repetition condition was compared with "The store had a coat milk that week," with the word "milk" changing to "sale" as readers' eyes left the word coat. gaze durations (GD) on word n were found to be significantly shorter when $n + 1$ was the same word compared with a different word. Furthermore, these PoF effects did not depend on the exact repetition of words n and $n + 1$, since orthographically related nonwords (Angele et al., 2013; Dare & Shillcock, 2013) and words (Snell, Vitu, & Grainger, 2017) generate similar amounts of facilitation.

Angele et al. (2013) interpreted the PoF effects that they observed as reflecting preattentive spatial integration of the visual features associated with words n and $n + 1$, that occurs prior to the sequential orthographic processing of word $n + 1$ once attention has shifted to that word. Grainger, Mathôt, and Vitu (2014) interpreted these effects, as well as effects of orthographic overlap obtained with the flanker paradigm (Dare & Shillcock, 2013; Grainger et al., 2014), as reflecting the spatial integration of orthographic information that is processed in parallel across multiple words. They proposed a model in which letter identities spanning several words are processed in parallel and integrated into a single channel for orthographic processing (see also Grainger, Dufau, & Ziegler, 2016; and see Snell, Leipsig, et al., 2018, for an implementation of spatial integration processes in a computational model of eye-moments and reading). In this way, orthographic information associated with neighboring words can influence the processing of the currently fixated word, but visual and attentional constraints ensure that the currently fixated word will generally dominate processing and be correctly identified.

In the present study, we co-registered eye-movements and electroencephalogram (EEG) in order to test these two interpretations of behavioral PoF repetition effects. Such co-registration enables time-locking of EEG analyses to t desired moment during text reading, such as when the readers' eyes fixate a designated critical word. The averaged EEG is then referred to as a fixation-related potential (FRP) as opposed to the more common even-related potential (ERP) that is time-locked to stimulus onset (Baccino & Manunta, 2005; Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Simola, Holmqvist, & Lindgren, 2009).[4] Prior studies using FRPs to investigate parafoveal processing during reading have successfully observed parafoveal preview effects (Degno et al., 2019; Dimigen, Kliegl, & Sommer, 2012; Kornrumpf, Niefind, Sommer, & Dimigen, 2016; Niefind & Dimigen, 2016). Parafoveal preview effects are obtained by manipulating the stimulus at a given location in a sentence prior to the eyes moving to that location. The stimulus then becomes the target word at that location, and the stimulus presented prior to that is called the parafoveal preview. Parafoveal preview effects in FRPs were found to be strongest with valid previews (i.e., the preview is the same word as the target word that it is replaced by) relative to different types of invalid previews in the different studies. Invalid previews were found to induce more negative-going FRPs starting as early as 120–140 ms post-fixation of the target word in the studies of Degno et al. (2019) and Niefind and Dimigen (2016), with effects continuing into the N400 time-window. Another line of FRP research has examined the impact of repeating words in lists of otherwise unrelated words (Hutzler et al., 2007,

[2]We note, however, that in the face of growing evidence for PoF effects, serial attention shift models have been adapted in order to account for both sublexical (e.g., Angele, Tran, & Rayner, 2013) and lexical PoF effects (e.g., Schotter, 2018). We return to this issue in the Discussion.

[3]See Inhoff, Radach, Starr, and Greenberg (2000), and Vitu, Brysbaert, and Lancelin (2004) for earlier investigations.

[4]Here we focus on studies measuring FRPs and we return to discuss related work using the flanker RSVP paradigm in the Discussion.

2013). Targets were the last word in the sequence, and repetition of that word earlier in the sequence generated a reduced negativity starting between 200 and 250 ms post-fixation of the target word. Hutzler et al. (2013) also examined the impact of an X-string preview (vs. valid preview) on these repetition effects and found that the effects were significantly delayed with an X-string preview.

However, the focus of the present study is on PoF effects in FRPs, as a means to investigate skilled readers' ability to process information in parallel across two adjacent words. Two early FRP investigations of PoF effects (Baccino & Manunta, 2005; Simola et al., 2009) presented either two words or a word and a nonword simultaneously, and participants had to successively fixate the two stimuli and judge if they were semantically related or not. Both studies reported an effect of the lexical status of the stimulus at position $n + 1$ on FRPs time-locked to fixation of word n. When stimuli were presented uniquely in the right visual field (Baccino & Manunta, 2005) then an effect of semantic relatedness was observed, while no effect of semantic relatedness was found in the Simola et al. study. Another kind of semantic PoF effect was reported by Kretzschmar, Bornkessel-Schlesewsky, and Schlesewsky (2009) in a more natural sentence reading paradigm. These authors examined the influence of the predictability of the final word in a sentence given the preceding context. For example, a sentence beginning with "The opposite of black is …" could be completed with either "white," "yellow," or "nice." FRPs time-locked to the last fixation before the final word (i.e., on the penultimate word) revealed an increased N400 amplitude in the condition where the final word was neither predictable nor semantically related (i.e., "nice" in the example).

A number of later FRP investigations of PoF effects examined the influence of parafoveal word frequency on the processing of the fixated word. Niefind and Dimigen (2016) reported a PoF frequency effect that was significant between 130 and 140 ms post-fixation of word n. Low-frequency parafoveal words generated more positive-going waveforms at two right-frontal electrode sites. However, this study involved reading lists of unrelated words and might not be entirely representative of natural sentence reading. In this respect, it is important to note that studies investigating effects of PoF frequency on FRPs during sentence reading have failed to find evidence for such effects (Degno et al., 2019; Kretzschmar, Schlesewsky, & Staub, 2015). More directly related to the present work, Dimigen et al. (2012) tested conditions where word $n + 1$ was the same as word n (i.e., PoF repetition), a semantically related word, or an unrelated word, and only found effects of this manipulation once the eyes had moved to word $n + 1$, albeit quite rapidly after that (about 80 ms). As noted above, however, this FRP study used lists of words rather than normal sentences. Moreover, in the PoF manipulation, it was word n that changed across conditions rather than word $n + 1$. Degno et al. (2019) also examined the impact of the different parafoveal preview conditions they tested (string of Xs, string of letters, valid preview) on FRPs time-locked to fixation of the pretarget word (i.e., an examination of PoF effects). They found robust PoF effects in both eye movement measures and FRPs when contrasting the X-string preview condition with the two orthographic preview conditions. Moreover, the two orthographic conditions (letter string, valid preview) did not differ significantly in the eye movement data although they did differ in the FRP data. Combined with the failure to find a PoF frequency effect, Degno et al. concluded that their results provided little evidence for lexical processing in the parafoveal.

In the present study, we pursued the search for PoF effects in FRPs, prompted by some recent results obtained in our lab using the flanker paradigm (Snell, Meade, Meeter, Holcomb, & Grainger, 2019). The Snell et al. study examined flanker repetition effects (flankers could either be the same word as the central target or a different word) in ERPs time-locked to the simultaneous onset of the target and two flankers (one to the left, one to the right). Target and flankers remained on the screen for 150 ms, hence limiting the possibility of participants fixating the flanker stimuli before they disappeared. Snell et al. (2019) found significant effects of target-flanker repetition starting around 200 ms post-stimulus onset and continuing into the N400 time-window. Repeated flankers caused reduced negativity in the ERPs compared with unrelated flankers. The timing of the flanker repetition effect is in line with Grainger et al.'s (2014) explanation of flanker effects as reflecting spatial integration of sublexical orthographic information.

In the present study, we implemented a simple PoF repetition manipulation (word $n + 1$ is the same as word n or a different word) in a sentence reading experiment with co-registration of EEG and eye-movements. We expected to observe a pattern of FRPs that resembles the ERPs reported by Snell et al. (2019). In particular, we expected to see effects emerging in the FRPs in a time-window that has traditionally been associated with sublexical orthographic processing and the mapping of such information onto whole-word identities. This time-window, estimated on the basis of extensive research on single-word recognition (e.g., Holcomb & Grainger, 2006; see Grainger & Holcomb, 2009, for a review) is linked to the N250 ERP component seen in our prior research. This component, peaking around 250 ms poststimulus onset, is the first ERP component that we could unambiguously associate with orthographic processing lying beyond the lower-level mapping of visual features onto letter identities. Feature-level processing was associated with an earlier N/P150 ERP component, peaking around 150 ms poststimulus onset. This allows us to make the following contrasting predictions for PoF repetition effects. According to preattentive feature-level processing interpretations of these effects (Angele et al., 2013; Degno et al., 2019), PoF repetition effects should already be observable in a time-window roughly corresponding to the N/P150 ERP component. According to sublexical orthographic processing interpretations (Grainger et al., 2014; Snell et al., 2019), PoF repetition effects should be first observable in a time-window that roughly corresponds to the N250 ERP component seen in our prior single-word reading research.

2 | METHOD

2.1 | Participants

Forty participants (33 female) were recruited at Aix-Marseille University (Marseille, France). They were all native French speakers and received either course credit or monetary compensation (€10/hour). Four participants were initially excluded due to experimenter error. Two more were removed due to excessive artifacts (see artifact rejection procedure below) such that they did not have at least 35 artifact-free trials per condition. The remaining 34 participants reported normal or correct-to-normal vision and ranged in age from 18 to 28 years ($M = 22.3$, $SD = 2.84$). They were naïve to the purpose of the experiment and signed an informed consent form before starting the experiment. Ethics approval was obtained from the *Comité de Protection des Personnes* SUD-EST IV (No. 17/051), and this research was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

2.2 | Design & stimuli

We constructed 200 sentences in French, each containing between 6 and 11 words ($M = 7.39$; $SD = 1.01$). The sentences had an average length of 42.16 characters (including spaces; $SD = 6.29$) and the average frequency of all words in the sentences was 5,233 occurrences per million which is equivalent to 6.71 Zipf (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). Word frequencies were the film subtitle frequencies of the Lexique2 database (New, Pallier, Brysbaert, & Ferrand, 2004). We manipulated the nature of the parafoveal word ($n + 1$) that was present at that location before the eyes left word n. Word $n + 1$ could either be the same word as word n or a completely unrelated word paired in length and in frequency (see Table 1). In both cases, the words were an illegal continuation of the sentence, and once participants' eyes crossed an invisible boundary between words n and $n + 1$, the word at location $n + 1$ was changed into a word that formed a syntactically correct continuation of the sentence. The target words (n) and their repetition had an average frequency of 4.84 Zipf ($SD = 1.25$), and the unrelated words had an average of frequency of 4.82 Zipf ($SD = 1.25$). These two sets of frequencies did not differ significantly ($p = .32$). We used a Latin-Square design with participants divided into two groups such that all sentences were tested in the two conditions across the groups, but were seen only once per participant, with 100 sentences assigned to each condition per participant. The sentences were presented in a different random order for each participant. The complete list of stimuli is provided in Appendix B.

2.3 | Apparatus

Stimuli were displayed using OpenSesame (Mathôt, Schreij, & Theeuwes, 2012)[5] with each sentence occupying a single line. Eye movements were recorded with an EyeLink 1,000 system (SR Research, Mississauga, ON, Canada) with a high spatial resolution (0.01°) and a sampling rate of 1,000 Hz. Viewing was binocular, but only the right eye was monitored. The sentences were displayed on a 20-inch ViewSonic CRT monitor with a refresh rate of 85 Hz and a screen resolution of 1,024 × 768 pixels (30 × 40 cm). Stimuli were presented in lower case 24-point monospaced font (droid sans mono; the default monospaced font in OpenSesame) and the text was presented in black on a grey background. Participants were seated 86 cm from the monitor, such that every three characters equaled approximately 1° of visual angle. A chin-rest was used to minimize head movements.

The scalp electrical activity was recorded with the ActiveTwo BioSemi system from a 64-electrode head cap (Electro-Cap Inc.) and positioned according to the 10–20 international system. Two additional electrodes (CMS/DRL) were used as an online reference (for a complete description, see Schutter, Leitner, Kenemans, & van Honk, 2006). The montage included 10 midline sites and 27 sites over each hemisphere. Four additional electrodes were used to monitor eye movements and blinks (two placed at lateral canthi and two below the eyes), and two additional electrodes were used for an offline re-referencing (placed behind the ears on the mastoid bone). Continuous EEG was digitized at 1,024 Hertz.

The EyeLink and BioSemi systems were jointly controlled using OpenSesame on the master computer which sent triggers to the EyeLink through an ethernet cable and to the BioSemi software via the parallel port. We used optocouplers (The Black Box Toolkit V2, The Black Box Toolkit Ltd., Sheffield, UK)

[5]All scripts (OpenSesame and R) and data are available at: https://osf.io/caqj9/?view_only=d3821d9e2f3846f09e785f35990c708b.

TABLE 1 Average values for the first-pass eye movement measures for each condition

	Fixation durations (ms)		Saccade probabilities		Landing position (0–1)
Condition	FFD	GD	Skip	Refixation	ILP
Repetition	209 (1.01)	240 (1.61)	0.010 (0.01)	0.19 (0.01)	0.335 (0.01)
Different	212 (1.02)	247 (1.74)	0.010 (0.01)	0.20 (0.01)	0.318 (0.01)

Note: Values between parentheses represent 95% CIs. FFD, first fixation durations), GD (gaze durations), ILP (initial landing position).

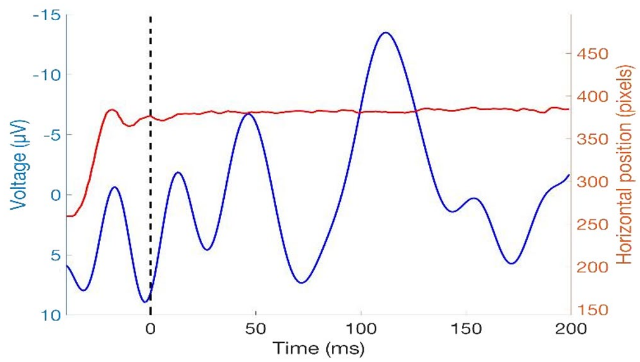

FIGURE 1 Example of one raw co-registration from EEG and Eye Tracking systems. Blue curve represents the EEG values from FPZ channel for participant n°3 and trial n°3. The red curve represents the horizontal position of the participant's gaze. The dotted line indicates the trigger for time-locking the FRP analyses

to synchronize the triggers with a delay of less than 5ms. The synchronization of the triggers enabled a tight coupling of the eye-movement and EEG data as illustrated in Figure 1.

2.4 | Procedure

At the beginning of the experiment, the participants' eye position was calibrated using a 3-point calibration line. Each trial involved the presentation of one sentence. The trial started with a drift correction dot located 112 pixels to the right of the left edge of the display. Participants were instructed to focus on this dot, which would trigger the onset of the sentence stimulus, with the starting point of the sentence being located to the right of the drift correction dot. Since our sentences had different lengths, the distance between the fixation point and the beginning of the sentence was randomly determined. Participants were instructed to silently read for meaning each sentence from left to right. An invisible boundary was defined precisely midway between the target word n and word $n + 1$ in order to change the word at position n + 1 when readers' eyes moved from word n to word $n + 1$ (see Figure 2). When participants were looking at the target word (in red in Figure 2), word $n + 1$ could either be the same word as n or a different word (in blue in Figure 2). When participants moved their eyes from word n to word $n + 1$, the word at position $n + 1$ was changed into a syntactically correct continuation of the sentence. At the end of the sentence, another boundary was defined such that the sentence disappeared when the eyes crossed that boundary. Next, on 25% of trials participants were shown a question in order to maintain vigilance. We used simple questions with a yes/no answer (e.g., Sentence: "Votre petit chat est noir/Your small cat is black"; Question: "Est-ce que le chat est blanc?/Is the cat white?") and participants responded by pressing one of the two buttons on a gamepad they held in their lap. The correct answer was randomly "yes" for half of the questions. After the task, participants were asked whether they were aware of the changes and how often. Most participants reported being aware of the changes, with an average self-reported awareness of 40%.

2.5 | Preprocessing

2.5.1 | Preprocessing of eye movement data

The raw data were preprocessed by EyeLink algorithms that detect saccades, fixations, and eye-blinks. We excluded trials on which blinks occurred during the fixation of the target word (0.32%), and we only analyzed first-pass reading measures. That is, trials, where the target word was skipped during first-pass reading, were removed from the fixation duration analyses. The resulting output was then analyzed using scripts written in R data analysis software.

2.5.2 | Preprocessing of EEG data

We used the *EEGLAB* toolbox (version 14.1.2b; Delorme & Makeig, 2004) for MATLAB (version 2018b; The MathWorks) to preprocess the EEG data. In preparation for independent components analysis (ICA), the EEG data were initially downsampled to 500 Hz, re-referenced to the averaged mastoids,[6] and synchronized to the eye-tracking data using the EYE-EEG toolbox (Dimigen et al., 2011), then filtered between 2.5 and 100 Hz. Blinks, as detected by the eye-tracker, were removed

[6] Analyses using an average electrode reference are reported in Appendix A

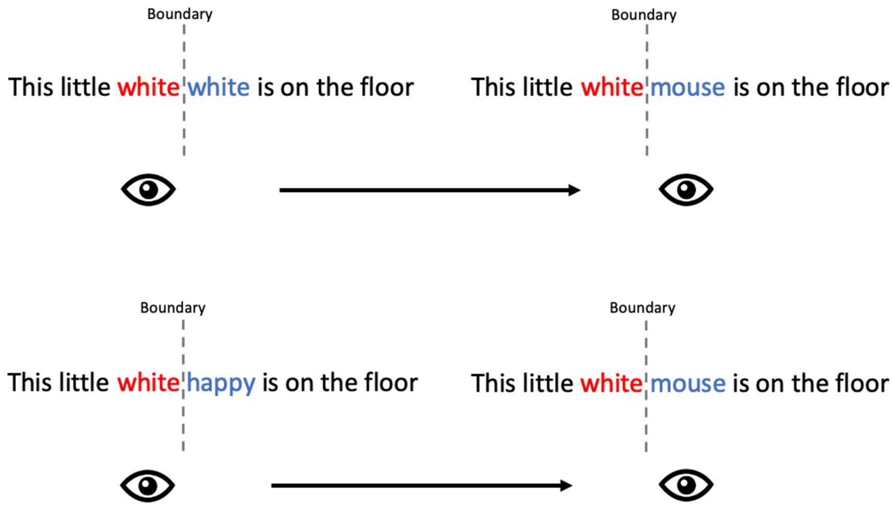

FIGURE 2 Schematic of the boundary paradigm used in the present study. The vertical dashed lines represent the invisible boundary between words n and $n + 1$ that enables control over the word that is presented at location $n + 1$, with the word changing to become a correct continuation of the sentence as the participants' eyes cross this boundary (moving from left to right in the Figure). The top line represents the condition where $n + 1$ is initially the same word as n and the bottom line represents the condition where $n + 1$ is a different word (but matched in length and frequency)

from the continuous data with a 50 ms pad before and after. Based on blinks and other ocular artifacts, 22.65% of trials were removed. ICA was trained on this data set which over-weighted presaccadic potentials per the procedure in Dimigen (2018). ICA otherwise used the default settings in EEGLAB.

Separately, each data set was filtered between 0.1 and 40 Hz. The ICA weights from the corresponding training set were then applied to this set. The automatic component rejection was conducted according to the procedure set forth in Plöchl, Ossandon, and König (2012) as implemented in the EYE-EEG toolbox using the default threshold of 1.1. An average of 1.6 components corresponding to ocular artifacts were removed per participant. Following the component rejection, the data were separated into epochs of −100 to 800 ms post-onset of the fixation on the target word n, as well as for word $n + 1$. Epochs were then baseline corrected using the 100ms prefixation baseline. An additional 8.76% of trials were removed due to residual EEG artifacts. This left 4,664 total trials included in the final analysis of the EEG time-locked to word n.

2.6 | Analyses

2.6.1 | EEG analyses

We conducted a mass-univariate analysis using the cluster-mass permutation test in the Mass Univariate ERP Toolbox (Groppe, Urbach, & Kutas, 2011) in MATLAB. This test was run on the t-statistic for the difference between the averaged ERPs to the repetition and non-repetition conditions (different—repeated) for all 64 scalp electrodes. The time window for the test was 0–550 ms, and 2,500 permutations were used.

2.6.2 | Eye movement analyses

For each eye movement measure (first fixation duration (FFD), gaze duration (GD), skipping rate, refixation rate, initial landing position [ILP]), we used LME analyses (for FFD, GD, and ILP) and GLME (for skipping and refixation rates) with main effects of condition (repeated parafoveal word, different parafoveal word), and included random intercepts for participants and items. All measures corresponded to first-pass reading. The averages values and 95% CIs were computed using R. All LMEs/GLMEs were implemented using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) also in R (R Core Team, 2013), and were compared using a likelihood ratio test using the *ANOVA* function in R. This test compares a full model fit with all parameters to a simplified one fit without the parameter to be tested to estimate whether that parameter provides an improvement in goodness of fit to the data greater than sampling error. Duration values (in ms) were inverse-transformed (−1,000/duration) prior to analysis.

3 | RESULTS

3.1 | Accuracy

The average accuracy for the comprehension questions was 88.32% (*SD* = 6.34).

3.2 | Fixation-related potentials

The results of the cluster-mass permutation test time-locked to the fixation on word *n* revealed one large negative cluster, meaning that ERP amplitude was significantly reduced in the repeated word condition relative to the different word conditions. This cluster spans from about 256 ms post-fixation on word n to the end of the analyzed epoch (550 ms). The cluster, with the exception of the antero-frontal AF8 electrode, can be divided into two sub-clusters. The first spans about 260–410 ms with its peak mass at 370 ms, and the second from 416 to 550 ms with its peak mass at 460 ms and a local minimum at 510 ms before a secondary peak mass at 550 ms. The distribution is quite widespread but is strongest over central-posterior and posterior sites. Figure 3 shows the grand average FRPs time-locked to onset of fixation on word *n* at five representative electrode sites (Fz, Cz, Pz, CP3, CP4), and Figure 4 shows the results of the cluster-mass permutation test.

3.3 | Eye movements

From the eye-tracking data, we measured the fixation durations, saccades probabilities (refixations and skips), and landing position, all with respect to the target word *n*. There was a total of 5,668 observations in the data set.

3.3.1 | Effects of boundary change awareness

Given that all participants reported noticing the boundary change, and given the evidence that parafoveal processing is sensitive to boundary change awareness (White, Rayner, & Liversedge, 2005), we entered the estimated percentage of trials on which this occurred as a continuous variable in the LME analysis in order to test for an influence of this factor on PoF repetition effects. The estimated mean percentage detection of a boundary change was 40.85% (*range* = 10%–80%;

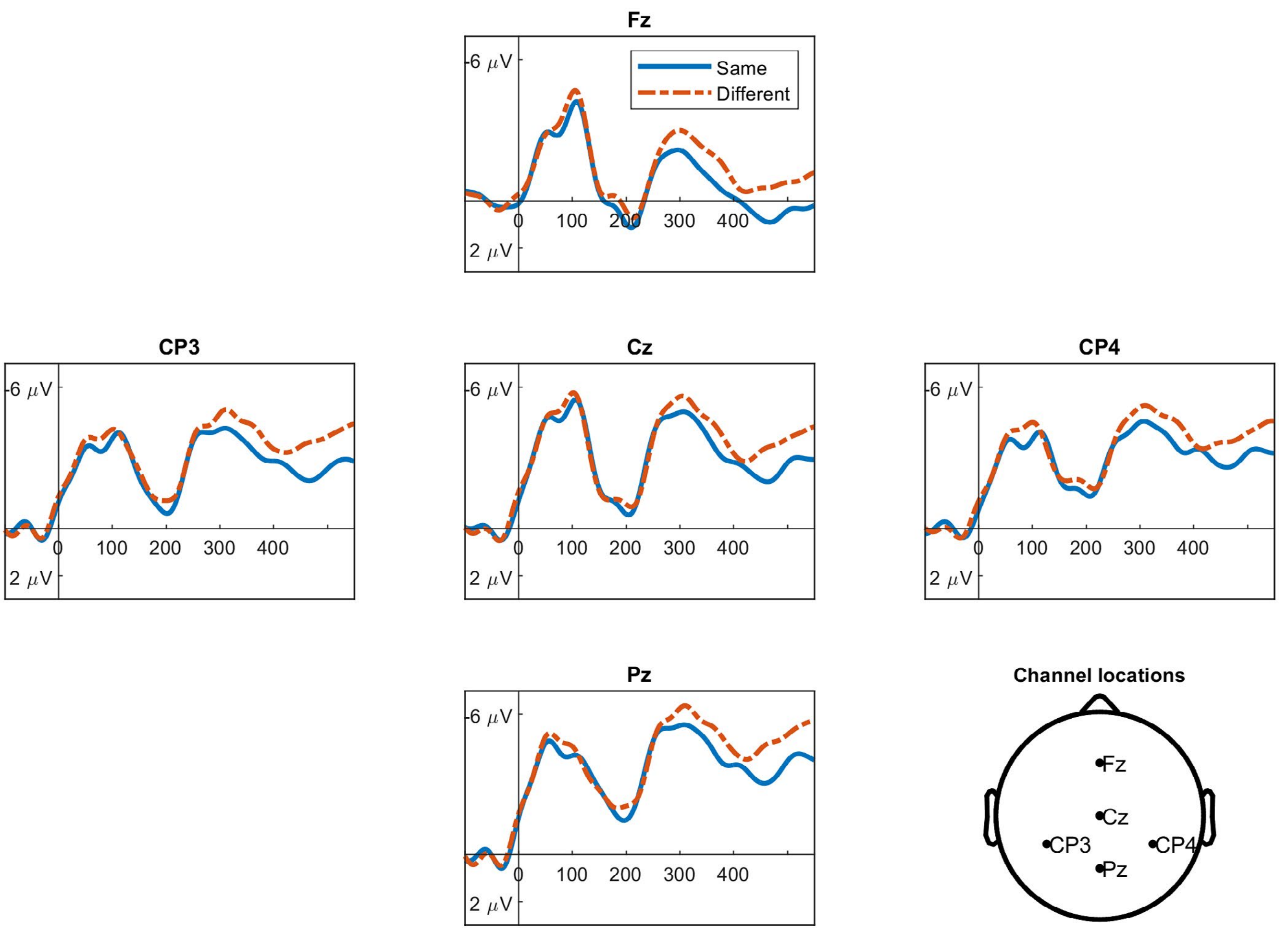

FIGURE 3 Grand average Fixation-Related Potentials (FRPs) at five representative electrode sites (Fz, Cz, Pz, CP3, CP4). FRPs are time-locked to the onset of fixation on word *n* (time 0 on the X axis), and averaged as a function of the nature of the following word $n + 1$ (repeated—solid blue line - or different words—dashed red line). It should be noted that once the eyes move from *n* to $n + 1$ (at around 250 ms) the stimuli in the two conditions are identical (word $n + 1$ is changed to the same word that is a syntactically correct continuation of the sentence in both conditions)

SD = 21.11%), and this did not interact with PoF repetition in any of our analyses. Since there were no significant interactions with boundary change detection, we removed this variable from the main analyses in order to simplify the statistical models.

3.3.2 | Fixation durations

We analyzed FFD, which represents the duration of the fixation immediately following the first forward saccade into the target word and GD, which is the sum of all first-pass fixations on the target word. Prior to analysis, we excluded 1.83% of the data for durations with values beyond 2.5 *SD* from the grand mean (FFD = 2.38%, GD = 1.28%). The mean duration values (in ms) per experimental condition are reported in Table 1. The PoF repetition effect was not significant on FFD, $p = .068$, but was significant in the GD, $p < .01$.

3.3.3 | Fixation probabilities

We analyzed FFD, which represents the duration of the fixation immediately following the first forward saccade into the target word and GD, which is the sum of all first-pass fixations on the target word. Prior to analysis, we excluded 1.83% of the data for durations with values beyond 2.5 *SD* from the grand mean (FFD = 2.38%, GD = 1.28%). The mean duration values (in ms) per experimental condition are reported in Table 1. The PoF repetition effect was not significant on FFD, $p = .068$, but was significant in the GD, $p < .01$.

3.3.4 | Initial landing position

We analyzed PoF repetition effects on the probability of skipping word *n*, and the probability of refixating this word (after excluding trials where word *n* was skipped—that is, first-pass refixations only). The resulting average probabilities per experimental condition are reported in Table 1. Regression probabilities are not reported because of the potential impact of the display change upon leaving word *n* on the probability of returning to fixate that word. There was no significant effect of Repetition on refixation rates, $p = .37$, or skipping rates, $p = .15$.

4 | DISCUSSION

The present study investigated PoF repetition effects during sentence reading, while jointly recording eye-movement behavior and scalp electrical activity (EEG). This co-registration enabled analysis of FRPs that were time-locked to fixation of the target word *n*. We used the boundary technique (Rayner, 1975) to manipulate the upcoming word in the sentence ($n + 1$), while participants were looking at word *n*. The word at location $n + 1$ could either be the same as the target word (the repetition condition) or a different word (the control condition), both of which were illegal continuations of the sentence. As soon as readers' eyes left word *n*, the word at location $n + 1$ was changed to become a syntactically and semantically correct continuation of the sentence. Our theoretical framework (Grainger et al., 2014; Snell, Leipsig, et al., 2018) predicted that PoF repetition effects should be observable in a time-window associated with sublexical orthographic processing of the target word. The results from prior work in our lab using the flanker paradigm (Snell et al., 2019) found repetition flanker effects starting around 200 ms post-stimulus (target + flankers) onset, which corresponds roughly with the N250 component seen in masked priming studies and associated with the mapping of sublexical orthographic representations onto whole-word orthographic representations (Grainger & Holcomb, 2009).

Replicating Dare and Shillcock (2013) and Angele et al. (2013), we found highly robust PoF repetition effects on GD on word *n*. We also found a significant effect of PoF repetition on the ILP on word *n*, with the eyes landing further to the right when the parafoveal word was a repetition. This is evidence that PoF repetition facilitated processing of word *n* even before readers' eyes have fixated word *n*. This facilitation would then lead to a less cautious saccade targeting strategy—that is, aim closer to the center of the upcoming word. This finding is in line with prior reports of word frequency and internal word structure influencing ILPs on words, with landing positions moving closer to the word center with high-frequency words, and closer to the beginning of words when the most informative information is located there (e.g., Hyönä, Yan, & Vainio, 2018).

Most important, however, is that we also observed effects in FRPs that became significant in a cluster-based permutation test at 260 ms post-fixation of word *n* (see Figure 4). Repetition of the target word *n* at position $n + 1$ caused a reduced negativity in the FRPs. A comparison of these FRP repetition effects (see Figure 3) with the flanker ERP repetition effects reported in Snell et al. (2019) reveals a striking similarity. The bulk of both effects can be seen in a negative-going component that onsets around 200–250 ms post-stimulus/fixation onset and that continues into the N400 time-window, and in both studies these effects have a widespread scalp distribution. This further corroborates our claim that effects seen in the flanker paradigm (without eye movements) are driven by mechanisms that largely overlap with those driving PoF effects as observed in sentence reading with eye movements. Furthermore, we note a striking resemblance between the present results and the ERP sentence

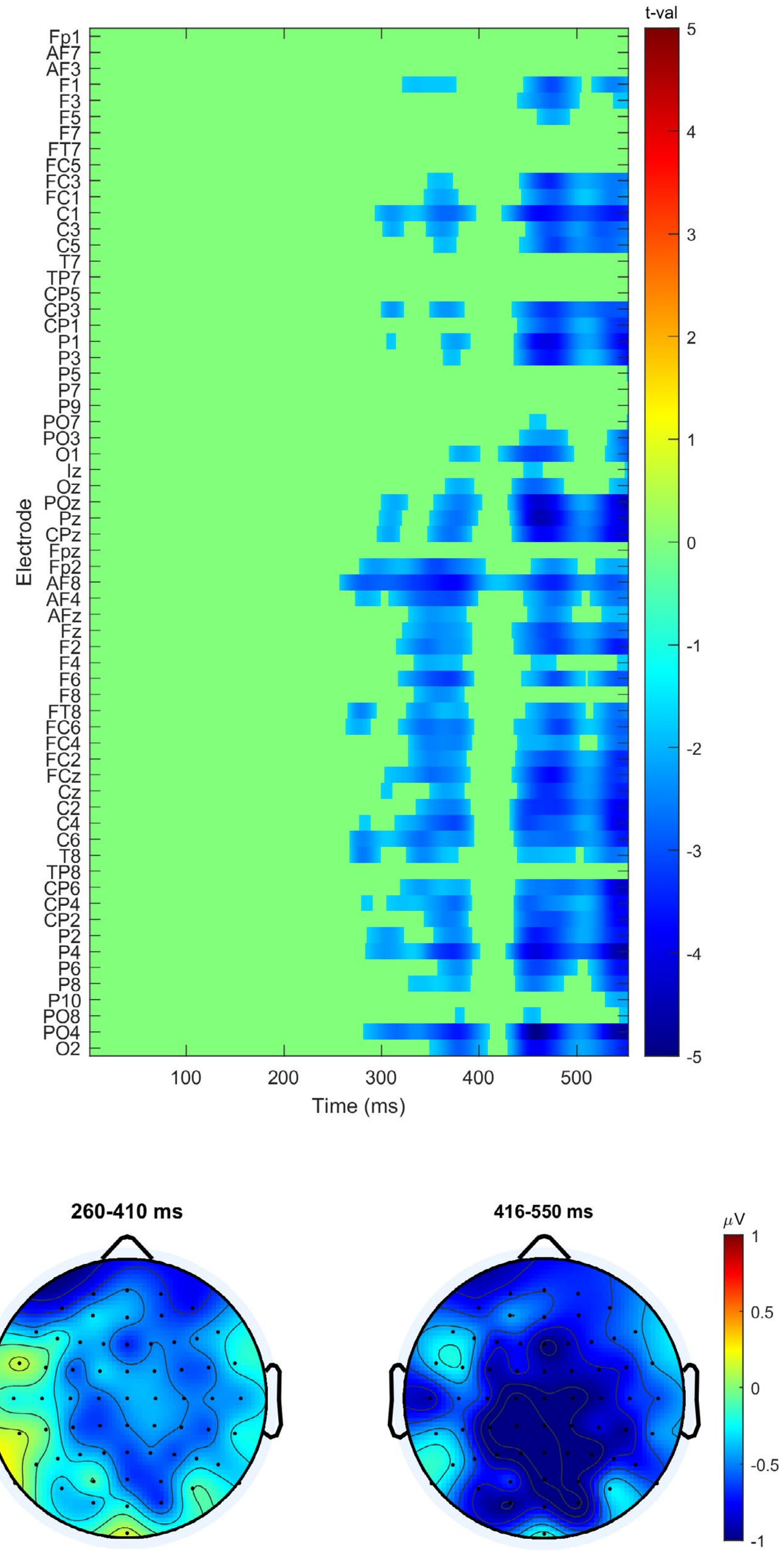

FIGURE 4 Results of the cluster-based permutation test on word *n*. Top: *t* values for electrode × time point pairs forming part of a significant cluster. All values not part of a significant cluster are set to zero. Bottom: mean scalp topographies of different minus repeated word conditions for 260–410 ms and 416–550 ms post-fixation of word *n*

superiority effect reported by Wen, Snell and Grainger (2019). In that study, briefly presented (200 ms followed by a pattern mask) four-word sequences could either form a correct sentence or an ungrammatical scrambled version of the same words. Participants had to identify one word at a postcued location. ERPs time-locked to onset of the word sequence revealed reduced negativity for the correct sentences that became significant around 270 ms post-sequence onset and was most prominent in a negative-going component that peaked just after 300 ms. The first cluster was estimated to occur between 274 and 410 ms (vs. 260–410 ms in the present study), and the corresponding scalp map revealed the same widespread distribution as in the present work. The Snell et al. (2019) flanker study also revealed a similar pattern of ERP effects, with flanker repetition first having an influence in a time-window spanning 175–250 ms. Closer inspection of these finding reveals, however, that the effect of flanker relatedness only started to become significant after 200 ms, and that the peak of the ERP component showing the bulk of this effect is around 300 ms at electrode Cz. One interesting possibility, that we will only briefly mention here given its tentative nature, is that what looks like an early N400 effect in the Snell et al. (2019), Wen, Snell, and Grainger (2019), and the present study (see Figure 3), might, in fact, reflect a combination of the N250 and N400 components seen in our masked priming research (see Grainger & Holcomb, 2009, for a review). Increasing prime duration is known to eliminate the N250 effect but does not impact on the peak latency of the N400 (Holcomb & Grainger, 2007). It is possible that the availability of information in parallel across simultaneously presented words is the key factor in generating an ERP component that would more directly reflect the mapping of sublexical information extracted in parallel from these words onto word identities.

The present study provides important complementary information relative to the findings revealed by prior investigations of PoF effects measured with FRPs during sentence reading. Kretzschmar et al. (2009) reported evidence that semantic information extracted from the parafoveal word can impact on FRPs time-locked to the foveal word. Moreover, the results of Degno et al. (2019) pointed to a relatively low-level locus of PoF effects. Furthermore, prior demonstrations of PoF frequency effects (i.e., an effect of word $n + 1$ frequency, while processing word n: Niefind & Dimigen, 2016) were obtained with lists of words, while sentence reading experiments failed to find such an effect (Degno et al., 2019; Kretzschmar et al., 2015). The present results point to orthographic processing as the starting point of PoF repetition effects, without, however, providing evidence that processing in the parafovea can extend to lexical and semantic levels of processing, although our results do not exclude this possibility. We reasoned, on the basis of our prior work on single-word reading (Grainger & Holcomb, 2009), that if PoF repetition effects were driven by preattentive visual processing (Angele et al., 2013; Degno et al., 2019), then the effect should emerge early in the FRPs, around 150ms post-fixation onset. The emergence of the effect around 250ms in the present study is more in line with our orthographic processing account of PoF repetition effects (Grainger et al., 2014; Snell et al., 2019).[7]

[7]It is important to note that an additional analysis of the FRP data with an average electrode reference replacing the linked mastoid reference, also failed to reveal any early PoF repetition effect (see Appendix A).

Importantly, our results are in line with prior investigations using ERPs to investigate PoF effects and parafoveal processing in general (e.g., parafoveal preview effects), while controlling for eye movements by artificial reading paradigms. The "one-word-at-a-time" RSVP technique has perhaps been the most widely used paradigm in electrophysiological investigations of sentence reading (see Kutas & Federmeier, 2011, for a review). It has, however, been criticized for its lack of resemblance to natural reading, and notably for the fact that the potential for parallel processing of words is excluded in this paradigm. An extension of this technique, the flanker RSVP paradigm, remedies this specific problem while continuing to enable a valuable control over stimulus presentation time. In this paradigm, each sentence is presented as the successive presentation of word triads, taking the first three words in the sentence to begin with, and then moving the presentation window one word forward for the next sequence, and so forth until the end of the sentence. Thus, a sentence like "the cat sat on the mat" is presented as "the cat sat," "cat sat on," "sat on the," "on the mat." Participants are instructed to keep their gaze on the central word and presentation times are typically very brief (e.g., 100 ms; Barber, van der Meij, & Kutas, 2013). This technique has systematically revealed that the nature of words at the rightmost position in the triad (parafoveal words) impacts on ERPs, and in particular, the N400 component. Thus, the semantic compatibility of words at this position modulates N400 amplitude (Barber, Doñamayor, Kutas, & Münte, 2010; Barber et al., 2013; Li, Niefind, Wang, Sommer, & Dimigen, 2015; Payne & Federmeier, 2017; Stites, Payne, & Federmeier, 2017). These results, plus the results of Snell et al. (2019) obtained with a simple flanker paradigm, suggest that parallel processing of words is possible, and that this involves not only early orthographic processing but also higher-level syntactic and semantic processing (see also Snell, Declerck, & Grainger, 2018; Wen et al., 2019).

As argued by Schotter (2018), one means for serial models, such as EZ-Reader, to accommodate such findings is to assume that attention can be shifted to word $n + 1$ much more rapidly than was previously assumed. This could arise when the processing of word n is faster than usual, when the word is high frequency and/or highly predictable given the prior context (Reichle, Rayner, & Pollatsek, 2003). Given that we tested low-constraint sentences in the present study, we decided to examine this possibility by including the frequency of word n as a covariate in our analysis of GD. The prediction was that our PoF repetition effect should be driven by the most frequent target words (n). In a post hoc LME analysis, however, target word frequency (log10 occurrences per million) was not found to interact with the PoF repetition effect for any of our eye-tracking measurements (models were fit with a condition × word frequency interaction effect, fixed effects for word frequency and condition, and random effects for participants and items. We nevertheless acknowledge that our interpretation of the present findings in terms of sublexical orthographic effects is not incompatible with more recent versions of serial models. The current debate between serial and parallel accounts of eye-movements and reading is more focused on whether or not higher-level properties of words (semantics, syntax) can be processed in parallel (for a recent discussion see Snell & Grainger, 2019, and associated commentaries: Schotter & Payne, 2019; White, Boynton, & Yeatman, 2019). The key conclusion with respect to the present findings is that PoF repetition effects cannot simply be dismissed as the result of preattentive feature-level processing of the parafoveal word (Angele et al., 2013; Degno et al., 2019). Finally, we also acknowledge that the relatively high-level of awareness of the boundary change in our study (see Section 3.3.1) might have impacted on the present findings, even although we failed to find an interaction between this variable and the PoF repetition effect on GD (but see Angele, Slattery, & Rayner, 2016, and White et al., 2005, for evidence for an impact of boundary change detection on parafoveal processing). In response to this, we are currently investigating orthographic PoF effects in sentence reading without using a boundary manipulation (e.g., The detective examined the *dark* mark on the floor).

In sum, combining a simple but strong experimental manipulation (PoF repetition) and a large number of sentences per condition and participant ($N = 100$) we found clear evidence that the nature of the word at position $n + 1$ impacts on processing of the word at position n. Repeating word n at position $n + 1$ compared with an unrelated word at that position caused a reduced negativity in FRPs becoming significant at 260 ms post-fixation of word n and being most prominent in a negative-going component peaking around 300 ms. These findings minimally imply that orthographic processing of word $n + 1$ had commenced before readers looked at that word, and this orthographic processing influenced on-going processing of word n. This is clear evidence that PoF effects can be found in a relatively natural reading context, and therefore that parallel processing might be an inherent characteristic of ordinary everyday reading.

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REFERENCES

Angele, B., Slattery, T., & Rayner, K. (2016). Two stages of parafoveal processing during reading: Evidence from a display change detection task. *Psychonomic Bulletin & Review*, *23*, 1241–1249. https://doi.org/10.3758/s13423-015-0995-0

Angele, B., Tran, R., & Rayner, K. (2013). Parafoveal–foveal overlap can facilitate ongoing word identification during reading: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 526. https://doi.org/10.1037/a0029492

Baccino, T., & Manunta, Y. (2005). Eye-fixation-related potentials: Insight into parafoveal processing. *Journal of Psychophysiology*, *19*, 204–215. https://doi.org/10.1027/0269-8803.19.3.204

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, *37*, 379–384. https://doi.org/10.3758/BF03192707

Barber, H. A., Doñamayor, N., Kutas, M., & Münte, T. (2010). Parafoveal N400 effect during sentence reading. *Neuroscience Letters*, *479*, 152–156. https://doi.org/10.1016/j.neulet.2010.05.053

Barber, H. A., van der Meij, M., & Kutas, M. (2013). An electrophysiological analysis of contextual and temporal constraints on parafoveal word processing. *Psychophysiology*, *50*, 48–59. https://doi.org/10.1111/j.1469-8986.2012.01489.x

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48.

Dare, N., & Shillcock, R. (2013). Serial and parallel processing in reading: Investigating the effects of parafoveal orthographic information on nonisolated word recognition. *The Quarterly Journal of Experimental Psychology*, *66*, 487–504. https://doi.org/10.1080/17470218.2012.703212

Degno, F., Loberg, O., Zang, C., Zhang, M., Donnelly, N., & Liversedge, S. P. (2019). Parafoveal previews and lexical frequency in natural reading: Evidence from eye movements and fixation-related potentials. *Journal of Experimental Psychology: General*, *148*, 453–474. https://doi.org/10.1037/xge0000494

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dimigen, O. (2018). Optimized ICA-based removal of ocular EEG artifacts from free viewing experiments. *BioRxiv*, https://doi.org/10.1101/446955

Dimigen, O., Kliegl, R., & Sommer, W. (2012). Trans-saccadic parafoveal preview benefits in fluent reading: A study with fixation-related brain potentials. *NeuroImage*, *62*, 381–393. https://doi.org/10.1016/j.neuroimage.2012.04.006

Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, A. M., & Kliegl, R. (2011). Coregistration of eye movements and EEG in natural reading: Analyses and review. *Journal of Experimental Psychology: General*, *140*, 552. https://doi.org/10.1037/a0023885

Drieghe, D. (2011). Parafoveal-on-foveal effects on eye movements during reading. In S. Liversedge, I. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 839–855). Oxford, UK: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199539789.013.0046

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, *112*, 777. https://doi.org/10.1037/0033-295X.112.4.777

Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Sciences*, *20*, 171–179. https://doi.org/10.1016/j.tics.2015.12.008

Grainger, J., & Holcomb, P. J. (2009). Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass*, *3*, 128–156. https://doi.org/10.1111/j.1749-818X.2008.00121.x

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 Psychologica*, *146*, 35–40. https://doi.org/10.1016/j.actpsy.2013.11.014

Groppe, D. M., Urbach, T. P., & Kutas, M. (2011). Mass univariate analysis of event-related brain potentials/fields I: A critical tutorial review. *Psychophysiology*, *48*, 1711–1725. https://doi.org/10.1111/j.1469-8986.2011.01273.x

Holcomb, P. J., & Grainger, J. (2006). On the time-course of visual word recognition: An ERP investigation using masked repetition priming. *Journal of Cognitive Neuroscience*, *18*, 1631–1643.

Holcomb, P. J., & Grainger, J. (2007). Exploring the temporal dynamics of visual word recognition in the masked repetition priming paradigm using event-related potentials. *Brain Research*, *1180*, 39–58. https://doi.org/10.1016/j.brainres.2007.06.110

Hutzler, F., Braun, M., Vo, M. L. H., Engl, V., Hofmann, M., Dambacher, M., … Jacobs, A. M. (2007). Welcome to the real world: Validating fixation-related brain potentials for ecologically valid settings. *Brain Research*, *1172*, 124–129. https://doi.org/10.1016/j.brainres.2007.07.025

Hutzler, F., Fuchs, I., Gagl, B., Schuster, S., Richlan, F., Braun, M., & Hawelka, S. (2013). Parafoveal X-masks interfere with foveal word recognition: Evidence form fixation-related potentials. *Frontiers in Systems Neuroscience*, *7*, 33. https://doi.org/10.3389/fnsys.2013.00033

Hyönä, J., Yan, M., & Vainio, S. (2018). Morphological structure influences the initial landing position in words during reading Finnish. *The Quarterly Journal of Experimental Psychology*, *71*, 122–130. https://doi.org/10.1080/17470218.2016.1267233

Inhoff, A. W., Radach, R., Starr, M., & Greenberg, S. (2000). Allocation of visuo-spatial attention and saccade programming during reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 221–246). Amsterdam, Netherlands: North-Holland. https://doi.org/10.1016/B978-008043642-5/50012-7.

Inhoff, A. W., Starr, M., & Shindler, K. L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics*, *62*, 1474–1484. https://doi.org/10.3758/BF03212147

Kennedy, A., & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research*, *45*(2), 153–168. https://doi.org/10.1016/j.visres.2004.07.037

Kennedy, A., Pynte, J., & Ducrot, S. (2002). Parafoveal-on-foveal interactions in word recognition. *The Quarterly Journal of Experimental Psychology Section A*, *55*, 1307–1337. https://doi.org/10.1080/02724980244000071

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, *135*, 12. https://doi.org/10.1037/0096-3445.135.1.12

Kornrumpf, B., Niefind, F., Sommer, W., & Dimigen, O. (2016). Neural correlates of word recognition: A systematic comparison of natural reading and rapid serial visual presentation. *Journal of Cognitive Neuroscience*, *28*, 1374–1391. https://doi.org/10.1162/jocn_a_00977

Kretzschmar, F., Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2009). Parafoveal versus foveal N400s dissociate spreading activation from contextual fit. *NeuroReport*, *20*, 1613–1618. https://doi.org/10.1097/WNR.0b013e328332c4f4

Kretzschmar, F., Schlesewsky, M., & Staub, A. (2015). Dissociating word frequency and predictability effects in reading: Evidence from coregistration of eye movements and EEG. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 1648. https://doi.org/10.1037/xlm0000128

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, *62*, 621–647. https://doi.org/10.1146/annurev.psych.093008.131123

Li, N., Niefind, F., Wang, S., Sommer, W., & Dimigen, O. (2015). Parafoveal processing in reading Chinese sentences: Evidence from event-related brain potentials. *Psychophysiology*, *52*, 1361–1374. https://doi.org/10.1111/psyp.12502

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*, 314–324. https://doi.org/10.3758/s13428-011-0168-7

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers*, *36*, 516–524. https://doi.org/10.3758/BF03195598

Niefind, F., & Dimigen, O. (2016). Dissociating parafoveal preview benefit and parafovea-on-fovea effects during reading: A combined eye tracking and EEG study. *Psychophysiology*, *53*, 1784–1798. https://doi.org/10.1111/psyp.12765

Payne, B. R., & Federmeier, K. D. (2017). Pace yourself: Intraindividual variability in context use revealed by self-paced event-related brain potentials. *Journal of Cognitive Neuroscience*, *29*, 837–854. https://doi.org/10.1162/jocn_a_01090

Plöchl, M., Ossandon, J. P., & König, P. (2012). Combining EEG and eye tracking: Identification, characterization, and correction of eye movement artifacts in electroencephalographic data. *Frontiers in Human Neuroscience*, https://doi.org/10.3389/fnhum.2012.00278

Pynte, J., Kennedy, A., & Ducrot, S. (2004). The influence of parafoveal typographical errors on eye movements in reading. *European Journal of Cognitive Psychology*, *16*, 178–202. https://doi.org/10.1080/09541440340000169

R Core Team. (2013). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*, 65–81. https://doi.org/10.1016/0010-0285(75)90005-5

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*, 125. https://doi.org/10.1037/0033-295X.105.1.125

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, *26*, 445–526. https://doi.org/10.1017/S0140525X03000104

Reilly, R. G., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research*, *7*, 34–55. https://doi.org/10.1016/j.cogsys.2005.07.006

Schotter, E. R. (2018). Reading ahead by hedging our bets on seeing the future: Eye tracking and electrophysiology evidence for parafoveal lexical processing and saccadic control by partial word recognition. *Psychology of Learning and Motivation*, *68*, 263–297.

Schotter, E. R., & Payne, B. R. (2019). Eye movements and comprehension are important to reading. *Trends in Cognitive Sciences*, *23*, 811–812. https://doi.org/10.1016/j.tics.2019.06.005

Schutter, D. J., Leitner, C., Kenemans, J. L., & van Honk, J. (2006). Electrophysiological correlates of cortico-subcortical interaction: A cross-frequency spectral EEG analysis. *Clinical Neurophysiology*, *117*, 381–387. https://doi.org/10.1016/j.clinph.2005.09.021

Simola, J., Holmqvist, K., & Lindgren, M. (2009). Right visual field advantage in parafoveal processing: Evidence from eye-fixation-related potentials. *Brain & Language*, *111*, 101–113. https://doi.org/10.1016/j.bandl.2009.08.004

Snell, J., Declerck, M., & Grainger, J. (2018). Parallel semantic processing in reading revisited: Effects of translation equivalents in bilingual readers. *Language, Cognition & Neuroscience*, *33*, 563–574. https://doi.org/10.1080/23273798.2017.1392583

Snell, J., & Grainger, J. (2019). Readers are parallel processors. *Trends in Cognitive Sciences*, *23*, 537–546. https://doi.org/10.1016/j.tics.2019.04.006

Snell, J., Meade, G., Meeter, M., Holcomb, P. J., & Grainger, J. (2019). An electrophysiological investigation of orthographic spatial integration in reading. *Neuropsychologia*, *129*, 276–283. https://doi.org/10.1016/j.neuropsychologia.2019.04.009

Snell, J., van Leipsig, S., Grainger, J., & Meeter, M. (2018). OB1-reader: A model of word recognition and eye movements in text reading. *Psychological Review*, *125*, 969. https://doi.org/10.1037/rev0000119

Snell, J., Vitu, F., & Grainger, J. (2017). Integration of parafoveal orthographic information during foveal word reading: Beyond the sub-lexical level? *The Quarterly Journal of Experimental Psychology*, *70*, 1984–1996. https://doi.org/10.1080/17470218.2016.1217247

Stites, M. C., Payne, B. R., & Federmeier, K. D. (2017). Getting ahead of yourself: Parafoveal word expectancy modulates the N400 during sentence reading. *Cognitive, Affective, & Behavioral Neuroscience*, *17*, 475–490. https://doi.org/10.3758/s13415-016-0492-6

Van Heuven, W. J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *The Quarterly Journal of Experimental Psychology*, *67*, 1176–1190. https://doi.org/10.1080/17470218.2013.850521

Vitu, F., Brysbaert, M., & Lancelin, D. (2004). A test of parafoveal-on-foveal effects with pairs of orthographically related words. *European Journal of Cognitive Psychology*, *16*, 154–177. https://doi.org/10.1080/09541440340000178

Wen, Y., Snell, J., & Grainger, J. (2019). Parallel, cascaded, interactive processing of words during sentence reading. *Cognition*, *189*, 221–226. https://doi.org/10.1016/j.cognition.2019.04.013

White, A. L., Boynton, G. M., & Yeatman, J. D. (2019). You can't recognize two words simultaneously. *Trends in Cognitive Sciences*, *23*, 812–814. https://doi.org/10.1016/j.tics.2019.07.001

White, S. J., Rayner, K., & Liversedge, S. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic, Bulletin & Review*, *12*, 891–896. https://doi.org/10.3758/BF03196782

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APPENDIX A

ERP results obtained using an average electrode reference

A reviewer pointed out that the absence of an early PoF repetition effect could be due to our use of a linked mastoid reference. The location of the mastoid electrodes could impact on effects generated in ventral occipital cortex, known to be involved in orthographic processing. Indeed, Li et al. (2015) found early parafoveal preview effects that prior studies (Barber et al., 2010, 2013) had failed to observe. They demonstrated that their early effects only emerged when using an average reference and not with a linked mastoid reference. To check for a potential early effect on posterior electrode sites, we reprocessed our data using an average reference of all 64 scalp electrodes instead of the linked mastoids. Apart from this, the processing steps were the same as described in Section 2.5.2. Li et al. (2015) identified a region of interest (ROI) comprised of four occipitotemporal electrodes (PO9, PO7, PO8, PO10). The system employed for this study does not have electrodes at the PO9 and P10 sites, so we instead used the electrodes PO7, O1, O2, and PO8 as our ROI. We ran repeated-measures ANOVAs with our PoF repetition factor for this ROI in three consecutive 100 ms time-windows from target word onset to 300 ms. There were no significant effects of PoF repetition at our ROI in these three time-windows (see Figure A1): 0–100 ms ($F(1, 33) = 1.826$, $p = .19$, *partial eta squared* = 0.052, Bakeman, 2005); 100–200 ms ($F(1, 33) = 0.111$, $p = .74$, *partial eta squared* = 0.003); 200–300 ms ($F(1, 33) = 0.115$, $p = .74$, *partial eta squared* = 0.003).

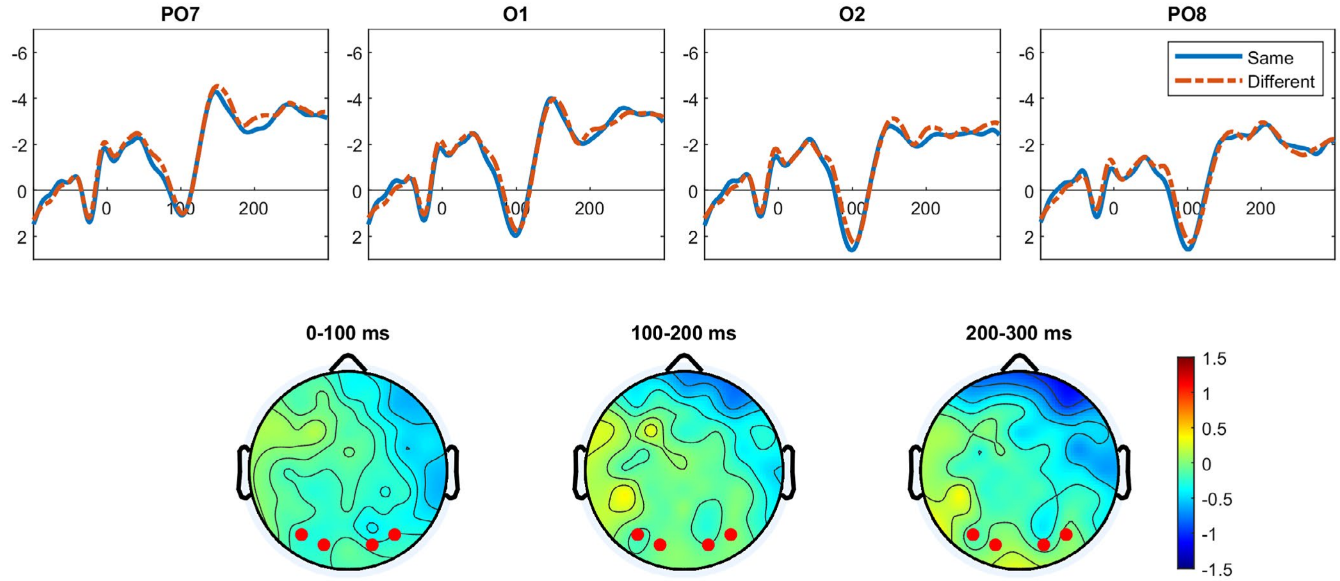

FIGURE A1 Top. Grand average waveforms for four occipital electrode sites in the same and different word $n + 1$ conditions obtained with an average electrode reference. Bottom. Scalp topographies of the PoF repetition effect in three consecutive time-windows. Red dots reflect the location of the ROI electrodes plotted above. The Y axis and difference (color) scales are in microvolts, and the X axis scale in milliseconds

APPENDIX B

The 200 sentences tested in the present study

The word n + 1 is the word that was present at the location immediately to the right of the target word prior to the eyes moving to that location. For example, in the first sentence, prior to presenting the word "dans" as the regular continuation of the sentence "Je me sers du café …," the word "rues" was present at that location.

Stimuli	Target (*n*)	*n* + 1
Je me sers du café dans un verre	café	rues
Elie fait souvent rigoler les gens	souvent	simples
Alain a trouvé un gros truc en creusant	gros	fous
Ta mère voudrait replacer le meuble	voudrais	pouvions
Elle avait donné sa poupée adorée à son ami	poupée	habits
La petite fouine mord vite dans la forêt	mord	abat
Je voudrais une nouvelle tablette en novembre	nouvelle	gentille
Jean va au grand bazar tous les jours	grand	juste
Tu manges de la bonne purée tous les soirs	bonne	petit
Le gentil médecin examine ton doigt	médecin	rapport
La poule picore des grosses graines de maïs	grosses	mauvais
Ce coq avale une limace marron le dimanche	limace	coyote
Il faut que je veuille meubler mon studio cet hiver	veuille	sachant
Ils mangent des grandes huîtres au restaurant	grandes	dernier
Le facteur avait trois bouteilles de lait	avait	aller
Franck élève des jolis chats dans le salon	jolis	plein
Léa avale sa soupe tiède très vite	soupe	aises
Aurélie conduit un nouveau scooter sur le trottoir	nouveau	pleines
Vous êtes toutes minces dans votre groupe	toutes	bonnes
Fred fait une recette secrète le jeudi	recette	formule

Stimuli	Target (*n*)	*n* + 1
Paul mange des bananes froides pour diner	bananes	fichier
Il veut venir faire des travaux	venir	suivi
Je pense que tu dois lire très vite	dois	venu
Les trois fleurs fanées sont dans le vase	fleurs	visite
Ce petit cahier rigolo coute assez cher	cahier	minous
Tu as revu ces chères filles du couvent	chères	pleins
Nous avons déjà joué à ce jeux	déjà	donc
Les jeunes garçons adorent le football	garçons	polices
Cette fille a un gros pied gauche	gros	noir
Arnaud va voir cinq de ses amies	voir	sait
Paul est allé dans le temple	allé	iras
Elles veulent toujours exécuter les ordres	toujours	pourquoi
Il porte un pull noir sur lui	pull	ours
Eliane fait du tricot assise sur son canapé	tricot	blocus
Remi a parfois attaché sa perruque	parfois	surtout
Eric nous mène neuf baguettes de pain	mène	fuma
Vous êtes venus après le spectacle	venus	devez
Nous vous avons souri dans le métro	avons	faire
Demain soir vous irez chez votre mère	vous	elle
Karl fait une vidange précise de sa voiture	vidange	rotules
Igor ira sûrement chercher des pommes vertes	sûrement	pareille
Lucie prépare un énorme gâteau le samedi	énorme	rapide
Mathias regarde la jolie grive en plein vol	jolie	chers
Je joue avec son vieux banjo sur le banc	vieux	folle
Il fait un grand geste de la main droite	grand	juste
Ils chassent les méchants goélands de chez eux	méchants	superbes
Le chat mange une grosse souris devant moi	grosse	jeunes
Mes enfants se ressemblent vraiment beaucoup trop	vraiment	beaucoup
Il te donne une idée pour être sympa	idée	truc
Les deux vieilles gazelles dorment dans le terrier	vieilles	désolées
Demain nous irons crier aux secrétariat	irons	ferez
Les trois brigands farfelus se sont évadés	brigands	implants
Un ange gardien céleste est sur un nuage	gardien	saisons
Regardez cette grande girafe qui dort	grande	folles
Je veux une plante grasse sur mon balcon	plante	tasses
Pour que tu puisses revenir chez nous	puisses	dirions
Elles demandent un plateau de sushi frais ce soir	sushi	ortie
Ils veulent du couscous marocain pour souper	couscous	carences
Paul est un confident rigoureux depuis des années	confident	carapaces
Patrick conduit sa superbe voiture sur le parking	superbe	proches
Hier mon cœur palpitait calmement dans ma poitrine	palpitait	adjugeant
Nous ne savons pas quelles nations choisir	quelles	rapides
Ce tableau est laid mais cher pour la famille	mais	donc
Une grosse dépression engendrera un arrêt maladie	dépression	originales
Je chante avec une robe trop grande	robe	vins
Cette fameuse nuit tous les chats sont gris	nuit	gens

Stimuli	Target (*n*)	*n* + 1
Le feu purifie les plaies salies et infectées	plaies	micros
Cest un beau blouson repassé que nous voulons	blouson	tapette
Un énorme nuage blanc arrive vers nous	nuage	nerfs
Les enfants turbulents deviennent rationnels en grandissant	deviennent	commencera
La lumière du soleil brille fort	soleil	erreur
Cette carte est sur la table basse noire	table	sujet
Il aime les films de super héros courageux	super	longs
Il est certain que trop manger change son corps	manger	oublia
Cette joyeuse danse disco résonne ce soir	danse	codes
Tu as vu une écume dense sur la plage	écume	meute
Ce lourd secret était celui de Barry	était	soyez
Il a tué trois types sur son jeu vidéo	trois	prête
Les nombreuses abeilles chantent en été	abeilles	planques
Mes cheveux longs sont très bruns	sont	aura
Cette jeune femme voulait devenir pilote	voulait	pouvons
Pour cet homme les six coups annoncent le réveil	les	une
Un nouveau printemps luxuriant est toujours agréable	printemps	approches
Les nombreux bons amis sont toujours là	bons	tout
Tu fais des dépistages différents cette semaine	dépistages	camemberts
Selon moi le meilleur logement est là bas	meilleur	finement
Je vois un ouvrage robuste sur le meuble	ouvrage	volcans
Nous ne voulons plus voir cela de notre vie	plus	bien
Une autre rive peut être un meilleur terrain	rive	cerf
Les enfants nagent autour de la bouée	nagent	saisit
Le brave petit poney cavale dans les champs	petit	sûres
Des massives cheminées invendues reste en stock	cheminées	technique
Le fantastique trésor cuivré est pour toi	trésor	crises
Je fais un safari chaque samedi matin	chaque	jolies
Il est simplement parti chercher beaucoup de pain	chercher	entendus
Certains grands oiseaux migrent dès le mois prochain	oiseaux	bonheur
La présence est dorénavant nécessaire pour les réunions	dorénavant	volontiers
Le nouveau chien vous paraitra vraiment gros	paraîtra	sauteras
Je veux voir leurs maris ce soir	leurs	jeune
Je monte dans le train rouge dans une heure	train	films
Je dresse des chevaux propres depuis longtemps	chevaux	retards
On oublie souvent la femme seule à la maison	femme	jours
Tu veux des belles bagues pour ton mariage	belles	autres
Je vais descendre calmement les escaliers	descendre	vaudrions
Elle prend une grande avance sur toi	grande	justes
Nous sommes partis avec huit amis au ski	avec	dans
Vous voulez des tartines grillées le matin	tartines	montures
Le marin navigue bravant les vagues	navigue	imprima
Ma petite souris triste dort beaucoup	souris	navire
Des grandes baleines plongent vers le fond	baleines	langages
Votre ami a des requins albinos dans son aquarium	requins	facteur
Ce petit chapeau devrait te convenir	chapeau	respect

Stimuli	Target (*n*)	*n* + 1
Le bel étalon cavale sur la plage	étalon	stages
Votre nouvel écran tomba au sol	écran	mardi
Nos trois enfants placent des guirlandes	enfants	accords
Il pense que tu devrais décrire la photo	devrais	voyions
Elles doivent partir devant pour nous montrer	partir	appela
Les plantes vertes seront coupées en hiver	vertes	proche
Les pierres précieuses ajoutaient de la valeur	précieuses	supérieure
Ces gros ciseaux coupent du métal	ciseaux	colonie
Ces vifs mouvements arriveront à nous faire tomber	mouvements	chauffeuse
Ils sont déjà assis quand tu arrives	assis	porta
Vous venez de tourner presque trop tôt	tourner	vendras
Tu auras deux mois pour faire ton dossier	deux	vrai
Je mange des frites salées ce midi	frites	dindes
Ils dorment dans une maison isolée au loin	maison	heures
Antoine porte une cravate blanche le lundi	cravate	vivants
Il faut que tu regardes toujours avant de traverser	regardes	donnions
Etienne aime chanter habillé en rock star	chanter	calmera
Vous nous demandez pourquoi il pleut	demandez	mourrons
Je me demande comment pouvons nous rêver	comment	presque
Julie fait des crêpes rondes pour ce soir	crêpes	brosse
Grégoire commande une assiette copieuse de frites	assiette	tensions
La voiture roule entre les camions	roule	causa
Cet oiseau volera durant des heures	volera	fermer
Ton petit fils dormira presque toute la nuit	dormira	excusez
La pomme verte était posée sur la table	était	serez
Le chapeau serait dessus la commode	serait	furent
Il va vendre la petite maison bleue à son frère	petite	seules
Mon gros chameau viendra cette nuit	chameau	grilles
Cette très jolie fenêtre tombera par terre	fenêtre	gamines
Le rideau froissé brûlera dans la chambre	froissé	candide
Mes deux chaussures écraseront les insectes	chaussures	sentiments
Les grandes routes seront bientôt pavées	routes	bureau
Ce gros et gentil ourson ira dans la forêt	gentil	pauvre
Le saumon sauvage remonte la cascade	sauvage	sourdes
Les grands renards roux sont très beaux	roux	vile
Il est dur de différencier concrètement les étoiles	différencier	galoperaient
Ce bon filet mignon fumait dans le four	mignon	bleues
Je prends mon parapluie notamment le week end	parapluie	confiture
Plusieurs intrus repèrent rarement les alarmes	repèrent	conclure
Tes voisins altèrent toujours les plantes du jardin	altèrent	instaure
Le maître suspend souvent les cours du soir	suspend	traquer
Quelques vieilles allumettes craqueront dans le brasier	allumettes	population
Ce vieux bonhomme émouvant vit tout seul	bonhomme	terrasse
Certains dominos intriguent énormément les joueurs	intriguent	contribuer
Vos éviers négligés finiront à la poubelle	négligés	colossal
Aucun des sports permet de maigrir	sports	humain

Stimuli	Target (n)	$n + 1$
Une bonne laine se tricote pendant très longtemps	tricote	sommais
Chaque jeu se caractérise durablement par des règles	caractérise	lessiverait
Mon dessin troublant dérangera certaines personnes	troublant	influente
Ce requin vif finira dessus le bateau des brigands	finira	perdre
Tout le linge sèche sur la corde	linge	noces
Leur chaîne rouillée soutient la structure	rouillée	adjointe
Une grande enveloppe emportera tous les documents	enveloppe	japonaise
Plusieurs mines de charbon ferment cette année	charbon	fatigue
Vos anniversaires sont couramment magistraux en fait	couramment	doublement
Ce valeureux hérisson creusera beaucoup de terriers	hérisson	isoloirs
Certains plateaux rouillent tellement que nous les jetons	rouillent	giflerais
Chacun le sait bien en vérité	sait	voir
Le nouveau catalogue plastifié vous sera livré	catalogue	boulevard
Votre beau sourire rayonne dès le matin	sourire	douches
Il veut cette peinture gothique dans son salon	peinture	cotoyens
Tu utilises tes dictionnaires régulièrement pendant le cours	dictionnaires	interrupteurs
Tu vas à cet aéroport national pour partir	aéroport	vendredi
Cette toute nouvelle machine utilise trois piles	machine	vacance
Passe moi ce marteau robuste pour un instant	marteau	panneau
Il y a un dindon adulte dans le jardin	dindon	psaume
De nombreux sièges rouges seront installés	sièges	palais
Elles lavent cet évier beige depuis ce matin	évier	total
Ils veulent une éponge propre pour nettoyer	éponge	melons
Sa mère est une cuisinière regorgeant de recettes	cuisinière	exceptions
Ma fille sera une top modèle turque dans le film	modèle	chutes
Nous mangeons des céréales plantées hier	céréales	mutantes
Je prends une cuillère ébréchée dans le lave vaisselle	cuillère	vermines
Elle va aux toilettes portatifs du camping	toilettes	souvenirs
Tu demandes le pardon absolu pour tes fautes	pardon	voison
Tu aimes consoler certains de tes amis	consoler	figurais
Cet ancien jeu consiste sûrement à faire le plus haut score	consiste	engendre
Nous devons vous avertir pendant que nous avons le temps	avertir	versons
Il va plonger souvent en hiver	plonger	admirez
Cette antenne transmet soixante secondes par jour	transmet	creusons
Ce document atteste comment vous avez fait vos études	atteste	embrasa
Vous allez farcir trente dindes pour les fêtes	farcir	amasse
Cette salsa endiablée terminera la soirée	endiablée	digestive
Cette femme au regard fuyant partit le lendemain	fuyant	repues
Ton nouvel employé est très efficace dimanche matin	efficace	actuelle
Cet être parfait dérange beaucoup de monde	parfait	dingues
Le scénario original explique pas mal de choses	original	absentes
Ce passage captivant détermine la fin du film	captivant	loufoques