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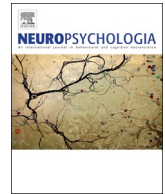
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An electrophysiological investigation of orthographic spatial integration in reading

Joshua Snell^{a,*}, Gabriela Meade^b, Martijn Meeter^c, Phillip Holcomb^d, Jonathan Grainger^a

^a Laboratoire de Psychologie Cognitive, Aix-Marseille University & CNRS, France

^b Joint Doctoral Program in Language and Communicative Disorders, San Diego State University & University of California, San Diego, United States

^c Department of Educational Sciences, Vrije Universiteit Amsterdam, the Netherlands

^d Department of Psychology, San Diego State University, San Diego, United States

ABSTRACT

During reading, word recognition speed is influenced by the amount of orthographic overlap with surrounding words. The nature of this phenomenon is not understood: some theories attribute it to low-level visual operations (i.e., parafoveal feature detectors influencing foveal letter detectors), whereas other theories assume that orthographic processing (i.e., letter position coding and word activation) occurs across multiple words in parallel. To arbitrate between these theories, we used electroencephalography to reveal the time course of orthographic spatial integration in a lexical decision task. Foveal target words were flanked on each side by parafoveal words, manipulated across three conditions: repetition flankers (e.g. *rock rock rock*), unrelated flankers (*step rock step*) and a no-flanker condition. Linear mixed-effect models were constructed to analyze EEG data on a trial-by-trial basis. Word recognition was worse in the unrelated flanker condition than in the repetition and no-flanker conditions. This behavioral pattern was accompanied by increased negativity in the N250 and N400 windows, associated with the activation of sub-lexical and lexico-semantic representations, respectively. Crucially, the absence of effects prior to 200 ms post-stimulus onset provides evidence against the involvement of low-level visual processes. We conclude that orthographic spatial integration is driven by parallel processing of multiple words, which leads to the activation of a larger set of sub-lexical nodes and more difficult processing at the lexical level when those words are orthographically unrelated.

1. Introduction

One of the main endeavors of reading research has been to determine how processing of letter strings leads to word recognition. This has led to sophisticated accounts of single word recognition (e.g., Grainger, 2008, for a review). However, given that words are rarely viewed in isolation, a complete account of the word recognition process must take into consideration the ways in which the recognition of a given word is influenced by surrounding words. The present study addresses this characteristic of the reading process. Specifically, electroencephalography (EEG) is employed with the aim of understanding how word recognition is influenced by letters from surrounding words.

Recent lines of research have demonstrated that information about the identity and relative position of letters is integrated across words. For instance, lexical decisions about target words (e.g., *'rock'*) are made faster and more accurately when those targets are flanked by orthographically related stimuli (e.g., *'ro rock ck'*) compared to unrelated stimuli (*'st rock ep'*) (Dare and Shillcock, 2013; Grainger et al., 2014;

Snell et al., 2017; Snell, Bertrand, Meeter & Grainger, 2018a; Snell, Bertrand & Grainger, 2018b). Such so-called orthographic parafoveal-on-foveal¹ effects have not only been established in target word recognition tasks, but also in natural (sentence) reading: readers spend less time viewing words that are orthographically related to upcoming words (Inhoff et al., 2000; Dare and Shillcock, 2013; Angele et al., 2013; Snell et al., 2017). Indeed, the similarity of patterns across different settings suggests that this phenomenon does not concern single word recognition specifically, but is a general feature of reading (Snell and Grainger, 2018).

However, there is still no consensus about the cognitive mechanisms involved. Some researchers have argued that the locus of orthographic parafoveal-on-foveal effects is at an early stage of visual processing. For example, Angele et al. (2013) have proposed that foveal letter detectors are connected to parafoveal feature detectors, thereby driving parafoveal-foveal integration effects. Others have argued that orthographic information may be integrated at later stages of (sub-)lexical processing. As outlined by Grainger et al. (2014) and Snell et al. (2017; 2018a; 2018b), the Open-Bigram model of word recognition (Grainger and van

* Corresponding author.

E-mail address: Joshua.Snell@hotmail.com (J. Snell).

¹ In the present context, the term “parafoveal-on-foveal” does not specifically refer to an influence from information outside the five degrees of visual angle that are attributed to the region of sharp, central vision (the fovea). Rather, we use the term to refer to the influence from surrounding words on recognition of the fixated word, regardless of what portions of these words fall inside or outside the fovea.

Heuven, 2003) assumes parallel processing of letters from multiple words. When surrounding words are orthographically dissimilar, this will lead to the activation of a larger set of sub-lexical nodes (specifically, bigrams, which code for the identity and relative position of letters) than when surrounding words are orthographically related. This in turn prompts activation of a larger set of lexical candidates and consequently slower word recognition (see Snell, van Leipsig, Grainger & Meeter, 2018c, for the implementation of this process in a computational model).²

The key difference between these two accounts is that the former assigns a key role to the interface between features and letters (i.e., the process of recognizing single letters), whereas the latter assumes that effects unfold at the interface between letters and words (i.e., encoding the relative positions of letters in order to activate word representations). As such, these two accounts point to different temporal loci for orthographic parafoveal-foveal integration (see Section 1.1). Therefore, electroencephalography may well provide the perfect tool for discerning the nature of this phenomenon. Indeed, the high temporal resolution of event-related potentials (ERPs) has already provided ample insight into the time course of the recognition of isolated words (Holcomb, O'Rourke and Grainger, 2002; Grainger et al., 2006; Hauk et al., 2006; Holcomb and Grainger, 2006; Petit et al., 2006; Dufau et al., 2008; Grainger and Holcomb, 2009; Massol et al., 2010; Dufau et al., 2015; Meade et al., 2018), and has established a cascade of ERP components that can be linked to the onset and interplay of various cognitive stages involved in reading; from the earliest stages of visual processing up to the levels of lexical and semantic access. Below, we briefly summarize these ERP components. Subsequently, we will specify our hypotheses concerning the time course of the spatial integration of orthographic information, as reflected in ERPs.

1.1. ERP components of visual word recognition

As reviewed by Grainger and Holcomb (2009), ERP investigations of single word reading have revealed at least three key components: N/P150, N250 and N400. The first of these, the N/P150, is a domain-unspecific bipolar component, consisting of a more positive deflection over anterior sites and a concurrent negative deflection over posterior sites. This component is associated with processing at the level of visual features. More specifically, the N/P150 is thought to reflect mapping of visual features onto abstract representations (e.g., letters), a process that takes place in the time frame of approximately 90–200 ms after stimulus onset (Grainger and Holcomb, 2009). Evidence for the relevance of this component to the domain of reading was obtained with the masked priming paradigm (e.g., Forster and Davis, 1984), which tests lexical decisions about target words as a function of prime words that are briefly presented (and likely go unnoticed) prior to the onset of the target. Increased visual similarity between the target and prime stimuli led to smaller amplitude N/P150s, indicative of reduced processing difficulty (Petit et al., 2006).

Following the rationale of Angele et al. (2013)'s account of orthographic parafoveal-on-foveal effects (i.e., that letter detectors are influenced by parafoveal feature detectors), the N/P150 component elicited by a target word

² Going further still, one could argue that parafoveal information might impact the post-lexical stage of decision-making, such that decisions are influenced by the experienced convergence of independently processed target and flanking stimuli. A set of unrelated stimuli may be evaluated as being 'more complex', thereby biasing the reader to make a nonword response. However, countering this conception is the fact that orthographic parafoveal-on-foveal effects are typically not observed in pseudoword target trials (e.g., Snell et al., 2018b), where unrelated flankers would also be expected to be make the stimulus 'more complex'. Additionally, this account would not cover parafoveal-on-foveal effects observed in the realm of sentence reading. This account is therefore not considered further.

should be affected by its orthographic relatedness to flanking stimuli.³ Indeed, other estimations of the time window associated with single letter recognition, such as the 130–190 ms interval specified by Bann and Herdman (2016), largely overlap with the N/P150. Taking the upper bound of this interval, the phenomenon should manifest itself prior to 200 ms post-stimulus onset according to this account.

The N/P150 is followed by a negative-going peak around 250 ms. This N250 component has a widespread scalp distribution, but is usually strongest over anterior sites. Indicative of its involvement in visual word recognition, the component is more negative if a target word is preceded by an orthographically unrelated prime, compared to a repetition prime (Grainger and Holcomb, 2009). Importantly, the N250 is not affected by manipulations of similarity in prime-target pairs consisting of pictures or single letters (Eddy et al., 2006; Petit et al., 2006). On the other hand, N250 effects do occur when manipulating the orthographic relatedness of pseudoword prime-target pairs. That the use of (word-like) multiple-letter strings is a prerequisite for N250 effects to occur, indicates that this component reflects mapping of activated sublexical representations (e.g., letters, bigrams) onto whole-word form representations (Grainger and Holcomb, 2009).

Finally, the negative-going posterior-oriented N400 is influenced by lexico-semantic level factors. The classic finding is that words elicit smaller amplitude N400s when preceded by semantically related primes compared to unrelated primes (e.g., Bentin et al., 1985; Holcomb, 1988; Kutas and Federmeier, 2011, for a review). More relevant to the present study, N400 amplitude also increases as a function of the difficulty of word recognition. Words that have more orthographic neighbors typically elicit larger amplitude N400s than those with fewer neighbors, potentially due to stronger competition from an increased number of activated lexical representations (e.g., Vergara-Martínez and Swaab, 2012). In line with Grainger and Holcomb (2009), such findings suggest that the N400 represents the ease of mapping activated word identities onto higher-level semantic representations.

1.2. The present study

In the present study, the approach to discerning the nature of orthographic parafoveal-on-foveal effects consists of drawing an analogy from temporal information integration, as seen in the masked priming paradigm, to spatial information integration, as observed in the flanker paradigm (e.g., Snell et al., 2018a). We report an experiment that tested, by means of a lexical decision task, the processing of briefly presented target words that were flanked either by the same words ('rock rock rock'; the repetition flanker condition), by unrelated control words of the same frequency ('step rock step'; the unrelated flanker condition) or by nothing ('rock'; the no-flanker condition).

The methodological focus of this paper is on time course analyses of the EEG signal elicited by target stimuli across these three flanker conditions. Voltage differences across conditions were analyzed at every 10 ms timestep, which allowed us to determine precisely at what point in time processing of the target is impacted by its orthographic relatedness to surrounding stimuli and, based on this, to infer the mechanisms involved.

There were two possible scenarios. Angele et al. (2013)'s account states that letter detectors are influenced by parafoveal feature detectors and therefore predicts that the electrophysiological signals in the

³ One might contend this presumption in light of Dufau et al. (2008)'s finding that N/P150 effects of prime-target featural overlap disappear when the prime and target are not presented at the exact same location. However, that study suffered from a shortcoming: as primes were shifted one letter relative to the target, target letter processing likely suffered from forward masking even in the case of a repetition prime (e.g., in the case of 'rock', the prime's 'o' would have preceded the target's 'r', the prime's 'c' would have preceded the target's 'o', and the prime's 'k' would have preceded the target's 'c'). The flanker paradigm does not suffer from this potential shortcoming.

repeated versus unrelated flanker conditions should start to differ at an early timepoint (< 200 ms). Our own account (e.g., Grainger et al., 2014; Snell et al., 2017; 2018a; 2018b) states that sub-lexical (bigram) nodes are activated by the target as well as parallel-processed flankers. Activation of a larger set of activated sub-lexical nodes in the unrelated flanker condition would be reflected by greater N250 amplitude in the unrelated flanker condition compared to the repetition flanker condition. A subsequent larger N400 amplitude in the unrelated flanker condition would reflect the activation of a larger set of lexical competitors, and thus a more difficult word recognition process.

Comparisons against the no-flanker condition were carried out as an exploratory investigation of the effects of flanker presence. Compared to the no-flanker condition, we expected the unrelated flanker condition to again elicit more negative deflections in the N250 window as the result of the activation of a greater set of sub-lexical nodes. Additionally, increased N250 and N400 amplitudes were expected as the result of an increase in processing difficulty when resources are shared between the flanker and the target compared to when the target is presented alone (e.g., Meade et al., 2018; Brouwer et al., 2017).

2. Methods

2.1. Participants

We recruited 24 participants (F = 13) in the age range of 18–28 years old from the Aix-Marseille University. All participants reported to be native French speakers, non-dyslexic, right-handed, and to have normal or corrected-to-normal vision. Participants received monetary compensation and gave informed consent to their participation in accordance with the Institutional Review Board of Aix-Marseille University. In the analyses, three participants were excluded due to lost EEG data as a result of experimenter error.

2.2. Stimuli and design

We retrieved 80 four-letter word targets (M log-frequency = 5.50 Zipf) and 80 four-letter pseudoword targets from the French Lexicon Project database (Ferrand et al., 2010). Stimuli contained no diacritics. For each target, we retrieved an orthographically unrelated stimulus with the same length, frequency, and lexical status from the database. These unrelated stimuli were used as unrelated flankers.

The experiment comprised three experimental flanker conditions (*repetition, unrelated, no-flanker*). Pseudoword trials were implemented using the same flanker manipulations, but as pseudoword stimuli were merely used to induce the task, target lexicality was not considered an experimental factor and pseudowords were not analyzed. All participants saw all targets in all flanker conditions, meaning there were 480 trials per participant in total (including pseudowords). These were presented in random order.

2.3. Procedure

Participants were seated in a comfortable office chair in a dimly lit room. Prior to the experiment, participants received task instructions from the experimenter and visually on the screen.

The trial procedure is shown in Fig. 1. Stimuli were shown in black

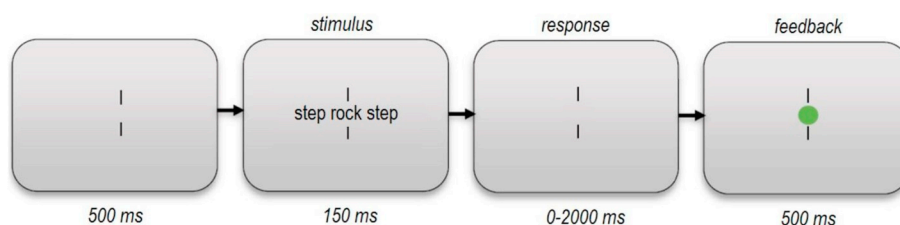


Fig. 1. Trial procedure. The size of stimuli relative to the screen is exaggerated in this example.

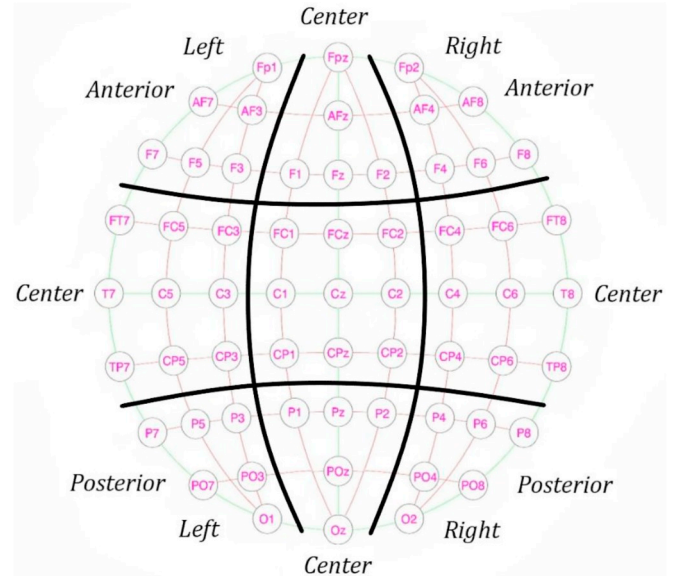


Fig. 2. 64 Scalp electrode sites divided into a 3 × 3 grid.

(mono font, size 12) on a luminance-neutral gray background. Each trial started with a 500 ms fixation display consisting of two centrally positioned vertical fixation bars. This display was followed by a 150 ms stimulus display with the target being positioned in between the two fixation bars. Flankers were separated from the target by a single character space. The stimulus display was followed by the fixation display allowing participants a maximum of 2000 ms to respond with a right- or left-handed trigger button to indicate ‘word’ or ‘pseudoword’, respectively. Upon the participant’s response (or the 2000 ms time-out), a centrally positioned green or red fixation dot was presented for 500 ms to indicate that the response was correct or incorrect, respectively.

The experiment was implemented with OpenSesame (Mathôt et al., 2012). Stimuli were presented on a 1024 × 768 pixel 75 Hz CRT monitor about 100 cm from the participant’s eyes, so that each letter in the display subtended 0.30 degrees of visual angle.

Three breaks were offered during the experiment. The 480 experimental trials were preceded by 12 practice trials. The entire experiment lasted approximately 25 min.

2.4. EEG recording and analysis

Participants were fitted with an elastic cap with 64 electrodes. A reference signal was recorded from an electrode on the left mastoid, while recordings from electrodes below the left eye and on the outer canthi of both eyes were used to detect blinks and horizontal eye movements, respectively. EEG was sampled with a Biosemi ActiveTwo system at a rate of 2048 Hz, but subsequently down-sampled to 512 Hz. Each epoch began 100 ms before stimulus onset (used for baseline correction), ended 600 ms after stimulus onset, and was filtered between 0.1 and 15 Hz (following Meade et al., 2018, and other previous work). Trials contaminated by artifacts within this window (detected with blink-detection algorithms and manual verification (Matlab

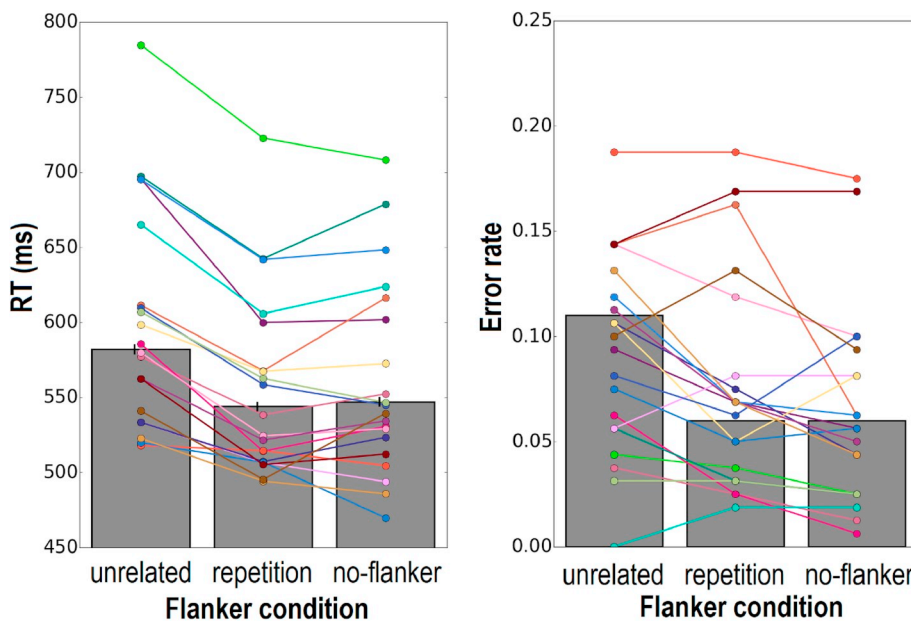


Fig. 3. Average RTs (left panel) and error rate (right panel) per flanker condition for word trials. Individual participants' means are presented in a unique color used in both panels. Black vertical bars represent standard errors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

EEGLAB package; Delorme and Makeig, 2004) and a $|75| \mu\text{V}$ threshold; 13% of trials on average) were excluded from all analyses, as were trials with incorrect responses. Channels with consistent artifacts across trials were replaced using spherical spline interpolation (Perrin et al., 1989).

Two types of analyses were performed: first, to differentiate between the theories outlined in the Introduction, we performed time course analyses that consisted of contrasting conditions with one another in every 10 ms timestep of the interval between the baseline and 600 ms post-stimulus onset. This allowed for a temporally fine-grained inspection of the onset of processes involved in the spatial integration of orthographic information. Within each trial and electrode, potential differences were averaged across every 10 ms timestep. This yielded a three-dimensional data matrix with potential differences per trial, electrode and timepoint. A linear mixed-effect model (LMM), including items and participants as random effects (Baayen, 2008) and flanker condition as factor, was run for each timepoint and for each electrode. The model thus performed 70×64 contrasts, each on a number of data points equal to the total number of trials. The model included by-item and by-participant random intercepts but no random slopes, as the model did not converge under this maximal random structure for a subset of the analyses.⁴

Second, we analyzed distinct time-windows corresponding to the N150, N250 and N400 components. Here, data was averaged within the intervals of interest (90–180 ms, 175–250 ms and 250–450 ms for the N150, N250 and N400 respectively (following masked priming studies as discussed by Grainger and Holcomb (2009)) within each trial and for each individual electrode. Each trial thus yielded 64 data points per component. Each component was analyzed with a single LMM encompassing data from all electrodes. These models tested for distributional effects by assigning a spatial coordinate to each electrode according to a 3×3 grid (Fig. 2), such that the mean amplitude measured at each electrode was tested as a function of three independent variables and

⁴ Whether or not a maximal random effects structure should be preferred is an ongoing debate. Crucially, prior studies employing similar flanker conditions have shown that models with random slopes do not provide a significantly better fit than models without random slopes (Snell and Grainger, 2018), and that there are high correlations between the random slopes and intercepts when slopes are included (in the 0.8–1.0 range; Snell et al., 2018b). We therefore reckon that simpler models with random intercepts but without random slopes are appropriate here. Thus, the resulting model syntax as implemented in R was as follows: $\mu\text{V} \sim \text{condition} + (1|\text{participant}) + (1|\text{item})$.

their interactions: flanker condition, laterality (*left, center, right*) and anteriority (*anterior, center, posterior*). We refer to these models as the Distributional Effects Models (DEMs). Separate DEMs were run to test for effects of flanker relatedness (isolating the repetition and unrelated flanker conditions; Section 3.2.2) and effects of flanker presence (isolating the unrelated and no-flanker conditions; Section 3.2.3).

To visualize effects observed in each window, we obtained separate LMM solutions for each individual electrode (hence without the spatial factors) and plotted the resulting *t*-values across the scalp using interpolated topographic maps.

3. Results

3.1. Response times and errors

Trials with an RT beyond 2.5 SD from the grand mean (2.22% of trials) were excluded from the analyses of RTs and errors. Trials with an incorrect response (7.83%) were excluded from the RT analyses.

The behavioral data were analyzed with LMM models that included by-participant and by-item random intercepts as well as random slopes. We report *b*-values, standard errors (SEs) and *t*-values (RTs) or *z*-values (errors), with $|t|$ and $|z|$ beyond 1.96 deemed significant (Baayen, 2008).

The individual and average RTs per condition are plotted in Fig. 3. RTs to words were significantly longer in the presence of unrelated flankers compared to repetition flankers ($b = 37.00$, $SE = 4.37$, $t = 8.47$) and no flankers ($b = 33.41$, $SE = 3.89$, $t = 8.59$). No difference was observed between the repetition flanker condition and no-flanker condition ($b = 3.64$, $SE = 3.61$, $t = 1.01$), in line with the finding of Snell and Grainger (2018). A similar pattern was observed in the error rate, with more errors in the unrelated flanker condition than in the repetition flanker condition ($b = 0.64$, $SE = 0.27$, $z = 2.33$) and no-flanker condition ($b = 0.77$, $SE = 0.26$, $z = 2.96$), while the repetition flanker condition and no-flanker condition were again similar ($b = 0.14$, $SE = 0.30$, $z = 0.45$).

3.2. Electrophysiological data

ERPs for each condition at electrode sites Fz, Cz and POz are plotted in Fig. 4.

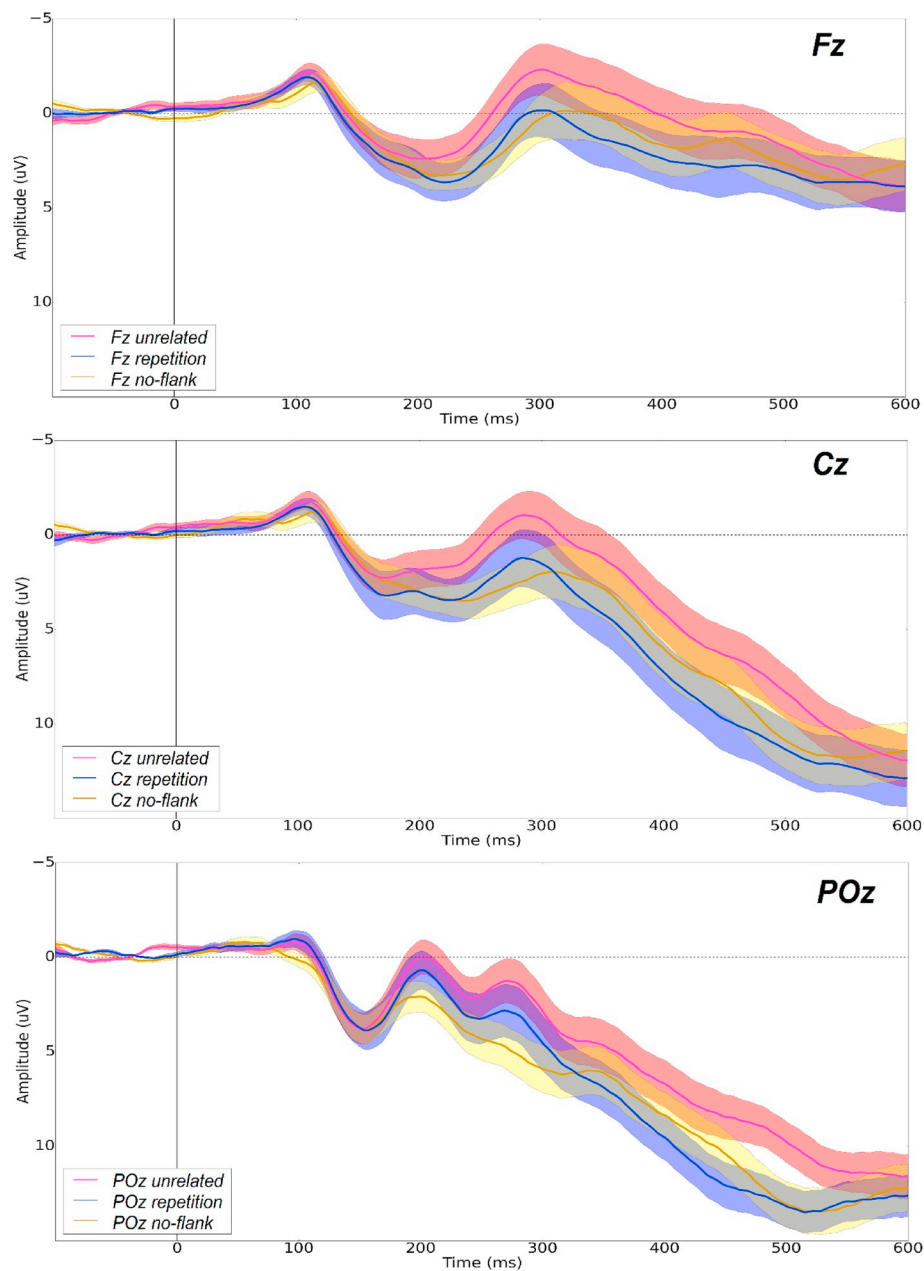


Fig. 4. ERPs per condition, at Fz (top panel), Cz (middle panel), and POz (bottom panel). Mean amplitude is plotted in the up direction. Shaded areas around the curves represent standard errors.

3.2.1. Time course analyses

Prior to all analyses, trials in which the potential difference of the electrode at the timepoint of interest was beyond 2.5 SD from the grand mean (2.60% of trials on average) were discarded. Analyses are plotted in Figs. 5 and 6. For the sake of readability, we did not plot analyses of all 64 electrodes, but rather of one electrode per each of the nine cells, as delineated in Fig. 2.

As can be seen in Fig. 5, significant differences between the unrelated and repetition flanker conditions began around 200 ms and continued beyond 500 ms. Deflections were more negative in the unrelated flanker condition. Importantly, and in line with previous descriptions of the N250 and N400 (Section 1.1), effects appeared to be larger at anterior sites around 250 ms and larger at posterior sites around 450 ms.

When contrasting the unrelated flanker condition against the no-flanker condition, an even clearer difference was observed around the N250 window (Fig. 6). Words elicited larger negativities when flanked

by unrelated flankers than when viewed in isolation. The effect was significant throughout the N400 window, where it was strongest across posterior sites.

One may take note of the multiple-comparisons problem, which entails that the chance of encountering false positives increases as the number of contrasts being carried out increases. Crucially, therefore, it must be observed in Fig. 5 that the intervals of significance are sustained for considerable amounts of time (> 100 ms) and are preceded and followed by trends toward significance. These aspects of the data indicate that the observed effects are not type I errors (e.g., Guthrie and Buchwald, 1991). Nonetheless, as our filtering procedures might have increased auto-correlation of the data across time (thus potentially elongating spurious effects under assumption of the null hypothesis), we performed a temporal cluster-based permutation test using data from electrode Cz. Within each iteration of a $N = 10,000$ Monte Carlo simulation, we determined the largest cluster of adjacent timepoints with a significant difference ($|t| > 1.96$) within all pairs of conditions

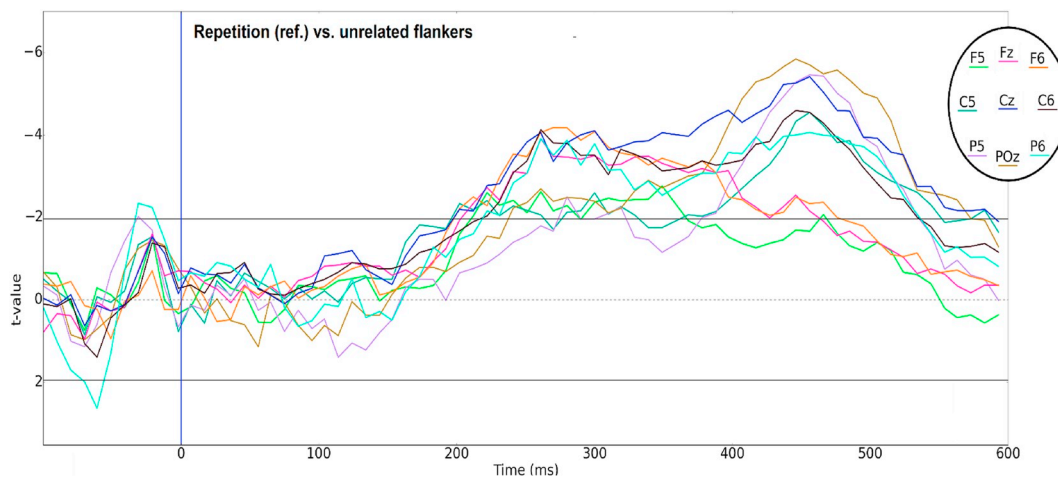


Fig. 5. Contrast of the Repetition (ref.) vs. Unrelated flanker condition, across the baseline to 600 ms post target onset interval. The significance thresholds are indicated by the black horizontal lines at $t = |1.96|$.

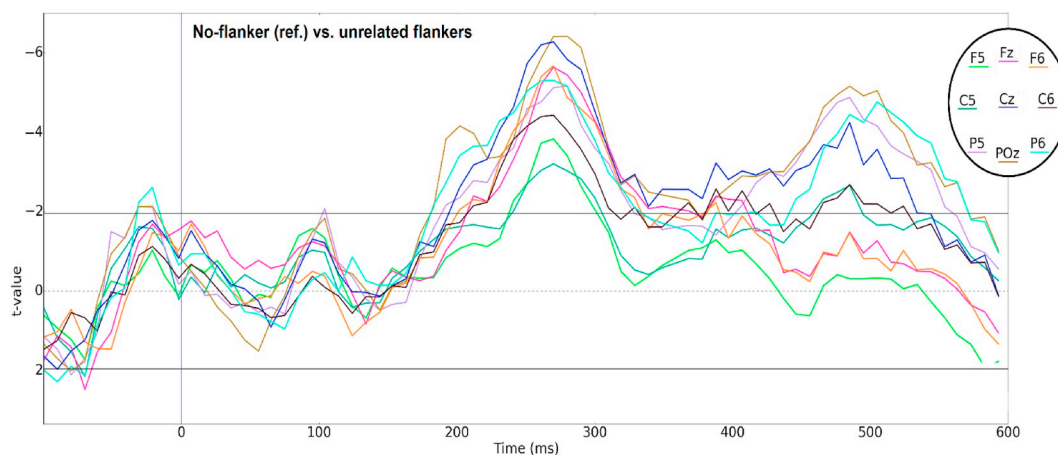


Fig. 6. Contrast of the No-flanker (ref.) vs. Unrelated flanker condition, across the baseline to 600 ms post target onset interval. The significance thresholds are indicated by the black horizontal lines at $t = |1.96|$.

Flanker relatedness

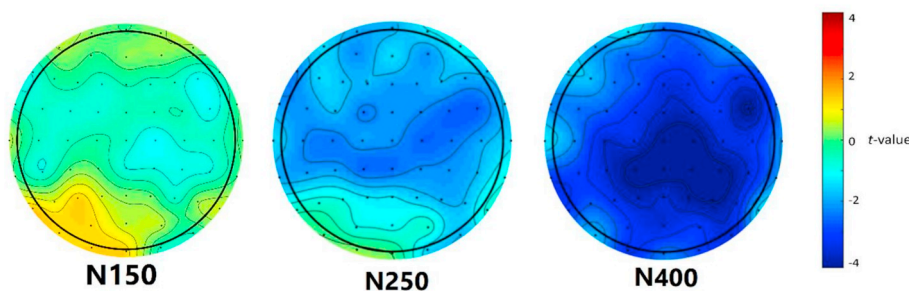


Fig. 7. t -values across the scalp, illustrating effects of flanker relatedness (ref.: repetition flankers) in the N150, N250 and N400 windows.

after randomly assigning condition labels to participants' timepoint-specific individual means. The average cluster size after 10,000 iterations was 0.4, with the largest cluster being 7 (i.e., a 70 ms interval of significance). Hence, according to our Monte Carlo simulation, there would be virtually no chance of finding our 300 ms interval of significance (i.e., cluster size 30) under assumption of the null hypothesis ($p < 1 \cdot 10^{-5}$).

3.2.2. DEMs: flanker relatedness

Isolating the repetition and unrelated flanker conditions to test for

distributional effects of flanker relatedness, we observed no significant effects in the N150 window. Significant main effects were observed in the N250 and N400 windows (Fig. 7; Table 1). In line with the research outlined in Section 1.1, a significant interaction between flanker relatedness and anteriority indicated that the N250 effect was strongest at anterior sites (Table 1). No such spatial distribution was observed in the N400 window. Neither an interaction of flanker relatedness and laterality, nor a three-way interaction of flanker relatedness, laterality, and anteriority was observed in any window.

Table 1
Contrasts of Unrelated vs. Repetition flankers (ref.: Repetition flankers) in our three windows of interest. Significant values are shown in bold.

		<i>b</i>	<i>SE</i>	<i>t</i>
N150	Intercept	0.06	0.44	0.14
	Flanker relatedness	-0.16	0.13	-1.23
	Relatedness × Anteriority	0.18	0.10	1.91
	Relatedness × Laterality	0.01	0.10	0.12
	Three-way interaction	-0.07	0.07	-0.96
N250	Intercept	2.85	0.70	4.07
	Flanker relatedness	-0.99	0.15	-6.55
	Relatedness × Anteriority	0.33	0.11	2.89
	Relatedness × Laterality	0.06	0.12	0.51
	Three-way interaction	-0.10	0.09	-1.09
N400	Intercept	0.13	0.88	0.15
	Flanker relatedness	-1.27	0.16	-7.89
	Relatedness × Anteriority	0.01	0.12	0.10
	Relatedness × Laterality	-0.10	0.12	-0.80
	Three-way interaction	0.02	0.09	0.19

3.2.3. DEMs: flanker presence

Isolating the unrelated and no-flanker conditions, we found no effects of flanker presence in the N150 window (Fig. 8; Table 2). A posterior effect, with more negativity in the presence of unrelated flankers, was observed in the N250 and N400 windows, as reflected by the significant interaction between flanker presence and anteriority in these windows (Table 2). The effect was also stronger over the right hemisphere sites in the N400 window, as indicated by the interaction between flanker presence and laterality.

4. Discussion

The present study provides the first electrophysiological examination of orthographic parafoveal-on-foveal effects in a flanker paradigm. We show that such effects onset in the time window of the N250, a component associated with the mapping of activated sub-lexical representations (e.g., letters, bigrams) onto whole-word form representations (Grainger and Holcomb, 2009). We argue that the greater negativity in the presence of unrelated flankers is caused by the activation of a larger set of sub-lexical nodes. This in turn translates into a larger set of activated lexical competitors (characterized by more negative deflections in the N400 window), and consequently increased lexical processing difficulty.

The absence of flanker relatedness effects prior to 200 ms (Fig. 5) speaks against theories that posit that orthographic spatial integration unfolds at levels of low-level visual processing. Specifically, Angele et al. (2013) have argued that foveal letter detectors may be connected to, and influenced by, parafoveal feature detectors. As such, the recognition of foveal letters would be biased by parafoveally perceived features even if attention were confined to the foveal word. The crux of

Table 2
Contrasts of Unrelated vs. No-flankers (ref.: No-flankers) in our three windows of interest. Significant values are shown in bold.

		<i>b</i>	<i>SE</i>	<i>t</i>
N150	Intercept	0.10	0.41	0.26
	Flanker presence	0.06	0.13	0.50
	Presence × Anteriority	-0.10	0.10	-1.01
	Presence × Laterality	0.03	0.10	0.31
	Three-way interaction	-0.04	0.07	-0.50
N250	Intercept	2.81	0.62	4.53
	Flanker presence	-0.57	0.15	-3.78
	Presence × Anteriority	-0.26	0.11	-2.27
	Presence × Laterality	-0.11	0.12	-0.98
	Three-way interaction	-0.03	0.09	-0.36
N400	Intercept	0.04	0.88	0.05
	Flanker presence	-0.80	0.16	-4.97
	Presence × Anteriority	-0.34	0.12	-2.82
	Presence × Laterality	-0.29	0.12	-2.36
	Three-way interaction	0.15	0.09	1.60

such theorizing is to reconcile orthographic parafoveal-on-foveal effects with the serial processing perspective, which assumes that processing is confined to single words. This scenario—which, as we see it, would indeed be the only sensible scenario if serial processing were true—clearly assigns the locus of effects to the stage of low-level visual processing (letter detection). Therefore, the absence of effects in time windows associated with letter detection (e.g., 90–200 ms; Grainger and Holcomb, 2009; 130–190 ms; Bann and Herdman, 2016) in the present study disfavors the only viable account from a serial processing perspective. Instead, the present findings converge with recent observations that processing at the level of orthographic representations occurs for multiple words in parallel (e.g., Snell, Mathôt, Mirault & Grainger, 2018c).

Interestingly, although the repetition flanker condition and no-flanker condition yielded similar RTs (Fig. 3), the EEG data make clear that these two conditions differ from the unrelated flanker condition for different reasons. While the effect of flanker relatedness on the N250 was stronger over anterior sites, the effect of flanker presence had a more posterior locus (evidenced by the opposite directions of interaction effects with the Anteriority factor, as reported in Tables 1 and 2). This dichotomy coincides with the recent claim of Snell and Grainger (2018) that parafoveal words impact foveal word processing in at least two distinct ways. They observed that flankers influence foveal word processing both through the spatial integration of orthographic information and through shifting some attentional resources away from the fovea. This suggests that the effects observed in Fig. 8 are not only orthographic, but also attentional in nature. This can be validated, for instance, in a flanker paradigm that implements spatial cues (e.g., Posner, 1980), with the prediction that such cues should modulate the effects of flanker presence (depicted in Fig. 8) to a greater degree than

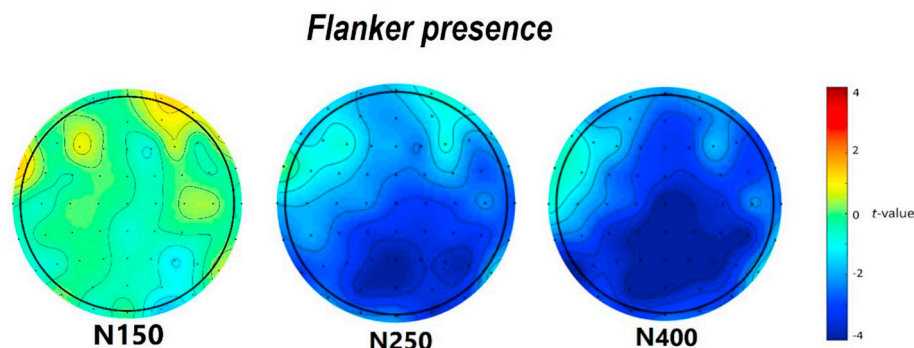


Fig. 8. *t*-values across the scalp, illustrating effects of flanker presence (ref.: No-flankers, panel) in the N150, N250 and N400 windows.

the effects of flanker relatedness (depicted in Fig. 7).

Finally, with respect to avenues for future research, we note the important developments being made with respect to the co-registration of eye movements and EEG during sentence reading (e.g., Dimigen et al., 2011; Niefind and Dimigen, 2016; Degno et al., 2019). This line of research has shown that ERPs can be effectively time-locked to fixation onsets, meaning that the orthographic parafoveal-on-foveal effects that were observed in sentence reading (Inhoff et al., 2000; Dare and Shillcock, 2013; Angele et al., 2013; Snell et al., 2017) can be inspected in a way similar to the present study. Comparing electrophysiological patterns established in sentence reading to those reported here will further help in determining to which extent ‘artificial’ paradigms such as the flanker task can be employed to infer the mechanisms involved in reading—a question that has been raised in recent work (Snell and Grainger, 2018).

In sum, in the present paper we have shed light on the nature of orthographic parafoveal-on-foveal effects. Our analyses indicate that such effects unfold approximately 200 ms post-stimulus onset. We conclude that parafoveal and foveal words jointly activate sub-lexical nodes, leading to the activation of a larger set of lexical candidates and more difficult word recognition when the words are dissimilar.

CRedit authorship contribution statement

Joshua Snell: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. **Gabriela Meade:** Data curation, Formal analysis, Methodology, Writing - review & editing. **Martijn Meeter:** Investigation, Methodology, Supervision, Writing - review & editing. **Phillip Holcomb:** Methodology. **Jonathan Grainger:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing - review & editing.

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