Fast syntax in the brain: ERP evidence from the RPVP paradigm

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Fast syntax in the brain:

ERP evidence from the RPVP paradigm

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Running head: Fast syntax in the brain

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Abstract

In two ERP experiments participants read four-word sequences presented for 200 ms (RPVP paradigm) and were required to decide whether the word sequences were grammatical or not. In Experiment 1, the word sequence consisted of either a grammatically correct sentence (e.g., "*she can sing now*") or an ungrammatical scrambled sequence (e.g., "*sing can now she*"). A reduced N400 effect was obtained in the grammatically correct sequences compared to the ungrammatical sequences. In Experiment 2, the critical comparison was between two types of ungrammatical sequences: transposed-word sequences (e.g., "*you that read wrong*") and control sequences (e.g., "*you that read worry*"). An N400 reduction was observed in the transposed-word sequences relative to the control sequences. We interpret these N400 effects as evidence that an elementary syntactic representation can be rapidly constructed on the basis of parallel processing of word identities and their parts-of-speech.

Key words: ERPs; rapid parallel visual presentation (RPVP); grammaticality judgments; fast syntax

1. Introduction

Event-related potentials (ERPs) have been extensively used to reveal linguistic operations in the brain (for a review, see Swaab, Ledoux, Camblin, & Megan, 2012). In the domain of reading comprehension, the majority of studies have focused on two ERP components, namely, the N400 component (a negative deflection peaking around 400 ms after stimuli onset, discovered by Kutas & Hillyard, 1980) and the P600 component (a positive deflection peaking around 600 ms post-stimulus, discovered by Osterhout & Holcomb, 1992). Using the N400 and P600 components as the neural correlates of semantic and syntactic processing respectively, ERP research insofar has substantially advanced our understanding of how skilled readers retrieve syntactic and semantic information encoded in sentences (for reviews, see Friederici & Weissenborn, 2007; Hagoort, 2009; Kuperberg, 2007; Kutas & Federmeier, 2011; Kutas, Van Petten, & Kluender, 2006; Lau, Phillips, & Poeppel, 2008; Molinaro, Barber, & Carreiras, 2011; Osterhout, McLaughlin, Kim, Greenwald, & Inoue, 2004). It is important to note that the existing ERP findings on reading comprehension are predominantly built on the rapid serial visual presentation (RSVP) paradigm, which uses an incremental word-by-word presentation procedure in order to avoid contamination of ERPs by eye movements. In these RSVP studies, the presentation duration of each word is fixed (e.g., 300 ms), and the ERPs are time-locked to the onset of the foveally fixated words. It is obvious that this passive reading involved in the RSVP paradigm is dramatically different from natural reading (for reviews, see Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Kornrumpf, Niefind, Sommer, & Dimigen, 2016; Metzner, von der Malsburg, Vasishth, & Rösler, 2014). For example, during natural reading the words outside the foveal visual field can be processed as well as the fixated word, and this cannot happen when words are presented in isolation in the RSVP. Due to such methodological limitations, the conventional RSVP studies may not uncover the full cognitive architecture of reading comprehension.

Recent electrophysiological research dedicated to reading has provided complementary approaches to move the field forward. The first promising approach is to measure fixation-related brain potentials (FRPs) rather than ERPs (e.g., Baccino & Manunta, 2005; Degno et al., 2019; Dimigen, Kliegl, & Sommer, 2012; Dimigen et al., 2011; Hutzler et al., 2007; Metzner et al., 2014; Nikolaev, Meghanathan, & van Leeuwen, 2016). In FRP studies, eye movements and the electroencephalogram (EEG) are simultaneously recorded, and the FRPs are time-locked to the first fixation onset of the target stimuli. The most prominent advantage of this approach is that participants can control their eye movements to read experimental stimuli in a way that closely mimics everyday reading. A key finding in the FRP studies is that the amplitude of FRPs is modulated by parafoveal processing (e.g., Baccino & Manunta, 2005; Degno et al., 2019; López-Peréz, Dampuré, Hernández-Cabrera, & Barber, 2016; Mirault, Broqua, Dufau, Holcomb, & Grainger, under review). This finding not only mirrors the parafoveal-on-foveal effect found in the eye-tracking studies (for a review, see Drieghe, 2011), but also unravels neural mechanisms underlying parafoveal processing which cannot be captured by the RSVP studies. However, this FRP approach has potential issues (for a systematic review, see Dimigen et al., 2011). For example, the late components of the previously fixated word may temporally overlap with the early components of the currently fixated word, and this overlap may have an unclear impact if experimental stimuli across conditions trigger systematically different fixation durations.

A second complementary approach is to use the RSVP-with-flanker paradigm, a modified version of the RSVP paradigm. Barber, Doñamayor, Kutas, and Münte (2010) used this RSVP-with-flanker paradigm for the first time to determine whether semantic congruency of the parafoveal words can modulate the ERP response to the fixated word. In this seminal study, the RSVP was used to present sentences, but critically three words were presented at one go, i.e., the currently fixated word at the centre, accompanied by two flankers with the previously fixated word on the left and the next word to be fixated on the right. Unknown to participants, the target words were accompanied by right flankers that were either semantically congruent or incongruent with the preceding context, i.e., the target word "*without*" in "*Tino could not read well without glasses*" was presented with either the congruent flanker "*glasses*" or the incongruent flanker "*mice*" on the right. A reduced N400 was found in the congruent flanker condition compared to the incongruent flanker condition, providing evidence for parafoveal processing at the semantic level. Follow-up studies using the same paradigm observed similar findings of parafoveal processing as evidenced by P2 or N400 effects (Barber, Ben-Zvi, Bentin, & Kutas, 2011; Barber, van der Meij, & Kutas, 2013; Li, Niefind, Wang, Sommer, & Dimigen, 2015; Stites, Payne, & Federmeier, 2017; Zhang, Li, Wang, & Wang, 2015; Zhang, Zhen, Liang, & Mo, 2019). Critically, the ERP parafoveal-on-foveal effect was obtained even if the words with flankers were only presented for 100 ms (e.g., Barber et al., 2013; Li et al., 2015; Stites et al., 2017), indicating that processing of multiple words may occur very rapidly. Admittedly, the RSVP-with-flanker paradigm involves passive reading in principal and still differs from natural reading (Kornrumpf et al., 2016). But this paradigm offers a simple and elegant alternative to investigate ERP correlates of parafoveal processing, which is feasible for EEG labs without an eye-tracker.

Note that the FRP and RSVP-with-flanker studies not only provide methodological innovations for electrophysiological investigations of reading, but also contribute to a fundamental issue addressed in reading research, that is, whether skilled reading involves a strictly one-word-at-a-time serial processing, or the parallel processing of multiple words at the same time (Reichle, Liversedge, Pollatsek, & Rayner, 2009; Snell & Grainger, in press). Although eye-tracking studies have found evidence for parafoveal-on-foveal effects in favour of parallel processing, the serial processing view can survive by arguing that this effect is caused by extra-linguistic factors, such as mislocated fixations (for discussions, see Drieghe, 2011; Schotter, Reichle, & Rayner, 2014; Snell, Declerck, & Grainger, 2018). However, such extra-linguistic explanations cannot account for the parafoveal-on-foveal effect observed in FRP and RSVP-with-flanker studies, and therefore this electrophysiological evidence provides crucial support that foveal and parafoveal word processing can occur in parallel (see Snell, Meade, Meeter, Holcomb, & Grainger, 2019, for further ERP evidence for parafoveal-on-foveal effects using a flanked lexical decision paradigm).

In addition to the FRP and RSVP-with-flanker studies, another methodological advance also sheds light on the debate concerning serial and parallel processing. The rapid parallel visual presentation (RPVP) paradigm was first combined with an investigation of a syntactic sentence superiority effect in Snell and Grainger (2017).[1] In this RPVP study, a sequence of four horizontally aligned words was briefly presented (i.e., 200 ms). The experimental task was to identify one post-cued word within the sequence. Snell and Grainger found that individual words (e.g., *sing*) are easier to identify in a syntactically correct word sequence (e.g., *she can sing now*) compared with a scrambled version of the same words (e.g., *now she sing can*). This behavioural sentence superiority effect has three important implications. First, it demonstrates that simultaneous processing of multiple words is possible, and this parallel processing occurs at a remarkable speed. Second, because the syntactically correct sequences used in this study were not confounded with between-word semantic relatedness or predictability as measured by cloze probability, syntactic representations must be the source of the effect. Importantly, the sentence superiority effect is assumed to reflect the interactive processing operating between sentence-level structures and word identities which allows sentence-level constraints to influence on-going word processing (Grainger & Holcomb, 2009). In a follow-up ERP study, Wen, Snell, and Grainger (2019) sought the neural index of the sentence superiority effect by combining ERP measures with the RPVP paradigm. The logic of that ERP study was straightforward: if the sentence superiority effect is driven by parallel word processing guided by sentence-level constraints, a N400 reduction should be observed in the syntactically correct sequences relative to the scrambled sequences. And the N400 sentence superiority effect is exactly what was found.

One puzzling aspect of the results of Wen et al. (2019) is why no P600 effect was found given that the P600 is the classic ERP component associated with syntactic processing. One possible explanation is that Wen et al. (2019) used a post-cued partial report task instead of the grammaticality judgment task widely used in the P600 literature. There is a general consensus that the P600 effect may be sensitive to the experimental task that is used and that the P600 effect is more likely to be evoked when the task involves an explicit judgment of the sentence content, i.e., grammaticality or acceptability judgments (Kuperberg, 2007). However, in the Wen et al. study, the main task of participants was to identify a single word among the sequence of four words, and it might be differences in difficulty in word identification that was driving the N400 effect (e.g., Grainger & Holcomb, 2009).

To address this unresolved issue, the present study combines the RPVP paradigm with a grammaticality judgment task. The present study set out to test whether the N400 sentence superiority effect can be observed in a grammaticality judgment task with briefly presented sequences of words. Therefore, in Experiment 1 we compared ERP responses to grammatically correct normal word sequences (e.g., *the man can run*) with ungrammatical scrambled sequences of the same words (e.g., *run can man the*) in the RPVP paradigm combined with a grammaticality judgment task. If the N400 sentence superiority effect seen in our prior work (Wen et al., 2019) is driven by sentence-level syntactic processing, then it should also be observable in conditions where participants' only task is to make grammaticality judgments.

2. Experiment 1

2.1 Methods

2.1.1 Participants

Twenty-six native French speakers (21 females; mean age = 22.5 years, SD = 2.6 years) received €20 or or course credit for their participation. All participants reported being right-handed, with normal or corrected-to-normal vision, and with no history of neurological, psychiatric or language impairment. Their average LexTALE_Fr vocabulary score (Brysbaert, 2013) was 90.7, SD = 4.1, and their average self-rated language proficiency score was 9.0, SD = 1.0 (10-point scale, 1 = virtually non-existing, 10 = prefect). Data from an additional two participants were excluded from the analyses due to too many slow drifts in the EEG data.

2.1.2 Materials and Design

We constructed 200 four-word sequences that were grammatically correct. The words in these sequences consisted of two to six letters (average word length = 3.27 letters). The average word frequency in Zipf values was 6.03 , SD = 1.27 (Ferrand et al., 2010; van Heuven, Mandera, Keuleers, & Brysbaert, 2014). A scrambled version of every sequence was constructed by switching word positions, and therefore the scrambled sequences were syntactically incorrect (e.g., a grammatically correct sequence: *the man can run*; the corresponding scrambled sequence: *run can man the*). Two counterbalanced lists were generated to ensure that in each list all the 200 sequences were presented in only one condition (normal or scrambled) and all the sequences were viewed in both conditions across lists with different participants. Participants were randomly assigned to one of the lists.

2.1.3 Procedure

The study was approved by the “Comité de Protection des Personnes SUD-EST IV” (No. 17/051). All participants provided their written informed consent before the experiment started. Participants were seated in a comfortable chair in a dimly-lit, electrically shielded booth. Each participant received a unique pseudo-randomized presentation order of the stimuli with the same condition (normal vs. scrambled) occurring no more than three times in a row. Stimuli were presented on a CRT monitor (18″, 1024×768 pixels, 75 Hz) controlled by OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) using the PsychoPy back-end (Peirce, 2008). Each trial began with a central fixation cross together with two vertical fixation bars presented for 500 ms, followed by only two vertical fixation bars for 300 ms. Next, a sequence of four words was presented for 200 ms, followed by a backward mask with hash marks (see Figure 1 for an illustration of visual events in Experiment 1). Participants had to decide whether the presented sequence was grammatically correct nor not. Feedback was then provided with a green (correct) or red (incorrect) dot presented for 700 ms. The inter-trial interval varied from 600 ms to 700 ms. Participants were instructed to fixate between the fixation bars and minimize blinks, eye-movements, and body movements. Prior to the experiment, 20 practice trials were used to familiarize the participants with the procedure. Short breaks were provided every 40 trials and the whole experiment lasted approximately two hours (including electrode placement and breaks).

2.1.4 EEG Recording and Preprocessing

The electroencephalogram (EEG) was recorded with a 64-channel active-electrode system (Biosemi ActiveTwo) at a sample rate of 1024 Hz. Two additional electrodes near Pz (CMS and DRL) were used for online referencing (Metting van Rijn, Peper, & Grimbergen, 1990; Schutter, Leitner, Kenemans, & van Honk, 2006). Six external electrodes were applied: two placed at left and right mastoids for off-line re-referencing, four placed below and at the outer canthus of each eye to monitor eye movements. The electrode offset was kept below 30 mV.

The preprocessing of the EEG data were conducted using the EEGlab/ERPlab Toolbox (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014). EEG data were re-referenced to the averaged mastoids and high-pass filtered at 0.1 Hz. The continuous data were then segmented into epochs ranging from -100 to 1000 ms after the onset of word sequences. The epochs were baseline-corrected using the pre-stimulus interval (-100 to 0 ms), and low-pass filtered at 30 Hz. Trials with incorrect responses were discarded (16.58% of the data). Epochs contaminated by drifts and muscle activity were manually removed (5.29% of the data). For seven participant, epochs containing ocular artifacts were first corrected using an independent component analysis (ICA) algorithm (Jung et al., 2000), otherwise these participants would have more than 20% of the epochs rejected due to ocular artifacts (Tanner, 2019). Epochs containing ocular artifacts or remaining artifacts after ICA correction were automatically dismissed (6.77% of the data). A minimum of 30 epochs were required per condition for each participant (Thierry & Wu, 2007).

2.1.5 Statistical Analysis

To analyse the behavioural data, we conducted a logistic mixed-effects model for the accuracy rates (Jaeger, 2008) and a linear mixed-effects model for the response times using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2017). Participants and items were included as random effects (Baayen, Davidson, & Bates, 2008), and random slopes were also included in the analysis (Barr, Levy, Scheepers, & Tily, 2013). Reaction times beyond 3.5 standard deviations from the mean of each condition in each participant were discarded as outliers (0.95%).

The ERP data were analysed using the cluster-based random permutation test implemented in FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2010). The cluster-based random permutation approach can effectively control for Type I errors involved in multiple comparisons (for details see Maris & Oostenveld, 2007). The cluster-based random permutation test was used as a data-driven method so that the analysis was conducted from 0 ms to 1000 ms post-stimulus on all 64 electrodes.

2.2 Results

2.2.1 Behavioural Results

Accuracy rates of the grammaticality judgement were significantly higher in the word sequences presented in the normal condition than in the scrambled condition, mean accuracy rates: 87.1% vs. 79.8% respectively, $z = 3.545$, $p < .001$ (see Table 1). Responses to the word sequences presented in the normal condition were faster than to those in the scrambled condition, mean RTs: 848 ms vs. 932 ms respectively, $t = -3.376$, $p < .01$ (see Table 2).

2.2.2 ERP Results

Only correct trials were included in the ERP analysis. ERP amplitude was reduced in the normal condition compared to the scrambled condition from 288 to 499 ms (cluster with $p = .004$, see Figure 2).

2.3 Discussion

Using the RPVP paradigm with a grammaticality judgment task, Experiment 1 observed a reduction in N400 amplitude in the grammatically correct normal word sequences relative to the ungrammatical scrambled sequences. This result successfully replicates the N400 sentence superiority effect found in Wen et al. (2019), which used a post-cued partial report task. In line with previous studies (Snell & Grainger, 2017; Wen et al., 2019), we suggest that this N400 effect reflects parallel processing of multiple words which quickly generates an elementary syntactic representation when this is possible (i.e., in the grammatical sequences). The consistent observations of the N400 sentence superiority effect in Experiment 1 and Wen et al. (2019) further suggest that this effect is unlikely to be task-dependent. However, given that the critical comparison in these two studies involved grammatically correct sequences and ungrammatical scrambled sequences, it is unclear whether this syntactic-driven N400 effect is specific for this contrast. Moreover, this contrast in Experiment 1 involved different behavioural responses. Therefore, in Experiment 2, we devised a means to induce an effect of syntactic structure in the grammaticality judgment task but with the same “ungrammatical” response in the two critical conditions.

3. Experiment 2

Experiment 2 also combines the RPVP paradigm and a grammaticality judgment task. The design of Experiment 2 is motivated by our own recent discovery of the behavioural transposed-word effect. In a grammaticality judgment study, Mirault, Snell, and Grainger (2018) found higher error rates and slower RTs to the transposed-word sequences (e.g., “*you that read wrong*”, transposing two adjacent central words can form a grammatical sequence) compared to the control sequences (e.g., “*you that read worry*”, transposing any two adjacent words still forms an ungrammatical sequence). In line with Snell and Grainger (2017), Mirault et al. (2018) suggested that an initial representation of sentence structure can be quickly generated, and this elementary syntactic representation constrains possible word candidates at each position. The combination of such top-down syntactic constraints with the noisy bottom-up encoding of word order drives the transposed-word effect. Following Mirault et al. (2018), Experiment 2 focuses on the ERP responses to two types of ungrammatical sequences, i.e., the transposed-word sequences and the control sequences. Under the hypothesis that transposed-word effects reflect the partial activation of syntactic structures that suggest the presence of a grammatically correct sequence of words, then we expect to observe a reduced N400 amplitude in the transposed-word condition relative to the control condition. Here, it is important to note that the transposed-word condition that is expected to reduce N400 amplitude should generate the slowest RTs and greatest errors. This is the opposite of Experiment 1 where faster RTs and less errors were observed in the grammatically correct normal sequences that caused a reduced N400.

3.1 Methods

3.1.1 Participants

Twenty-six native French speakers (18 females; mean age = 23.2 years, SD = 2.9 years) received €20 or or course credit for their participation. One participant had also participated in Experiment 1. All participants reported being right-handed, with normal or corrected-to-normal vision, and with no history of neurological, psychiatric or language impairment. Their average LexTALE_Fr vocabulary score (Brysbaert, 2013) was 91.1, SD = 4.4, and their average self-rated language proficiency score was 8.7, SD = 1.3 (10-point scale, 1 = virtually non-existing, 10 = prefect). Data from an additional two participants were excluded from the analyses because of excessive eye blinks or high error rates (>25%).

3.1.2 Materials and Design

We constructed a new set of grammatically correct sequences in order to generate the critical stimuli. 160 four-word sequences were first constructed, and then the last words in those sequences were replaced so as to create the corresponding ungrammatical sequences (e.g., *the* *man can run* vs. *the man can big*). Next, the words at positions 2 and 3 were transposed in all the 160 pairs of sequences. The transposed-word version of grammatically correct sequences was referred to as the transposed-word condition (e.g., *the can man run*), whereas the transposed-word version of ungrammatical sequences was referred to as the control condition (e.g., *the can man big*). The words in all these sequences consisted of two to seven letters (average word length = 4.25 letters). The average word frequency in Zipf values was 5.79, SD = 1.09 (Ferrand et al., 2010; van Heuven et al., 2014). Two counterbalanced lists were created to ensure that in each list all the 160 pairs of sequences were presented in only one condition (transposed-word vs. condition) and all the pairs were viewed in both conditions across lists. Participants were randomly assigned to one of the lists. Because all the critical stimuli in both conditions require No responses, another 160 grammatically correct four-word sequences were included as fillers (e.g., *the guy is tall*) in order to have an equal number of Yes and No responses. The words in the grammatically correct filler sequences matched the words used in the critical stimuli in word length (average word length: 4.25 letters) and frequency (average word frequency in Zipf values = 5.96, SD = 1.19).

3.1.3 Procedure

The procedure was identical to the procedure used in Experiment 1 except for one aspect (see Figure 3 for an illustration of visual events in Experiment 2). The backward mask was not used in Experiment 2 in order to avoid visual event-related potentials generated by the appearance of masks overlapping with the N400 component.

3.1.4 EEG Recording and Preprocessing

The same EEG recording setup and EEG preprocessing pipeline were used for Experiment 2 as in Experiment 1. Trials with incorrect responses were discarded (11.69% of the data). Epochs contaminated by drifts and muscle activity were manually removed (3.39% of the data). For 13 participants, epochs containing ocular artifacts were first corrected using an independent component analysis (ICA) algorithm (Jung et al., 2000), otherwise these participants would have more than 20% of the epochs rejected due to ocular artifacts (Tanner, 2019). Epochs containing ocular artifacts or remaining artifacts after ICA correction were automatically dismissed (4.65% of the data).

3.1.5 Statistical Analysis

In line with Experiment 1, we conducted a logistic mixed-effects model for the accuracy rates, a linear mixed-effects model for the response times, and the cluster-based random permutation test for the ERP data. Reaction times beyond 3.5 standard deviations from the mean of each condition in each participant were discarded as outliers (0.94%). The ERP results from Experiment 1 were used to guide the ERP analysis of Experiment 2. Given that a significant cluster was found within the N400 time window (around 290 to 500 ms) in Experiment 1, we focused on this time window in Experiment 2. The ERP amplitude of this a-priori selected time window was first averaged for each electrode and each condition, and then a cluster-based random permutation test was applied on all 64 electrodes. Therefore, cluster-based random permutation tests in Experiment 2 were conducted over electrode. The logic is that the cluster-based random permutation test can be conservative when using as a pure data-driven approach, and an a-priori region of interest or time window can improve the sensitivity of the analysis (for a similar approach, see Wen, Filik, & van Heuven, 2018).

3.2 Results

3.2.1 Behavioural Results

Consistent with Mirault et al. (2018), accuracy rates were significantly higher in the control condition than in the transposed-word condition, mean accuracy rates: 90.5% vs. 82.4%

respectively, $z = 8.248$, $p < .001$ (see Table 3). In addition, participants were quicker in judging the control sequences as ungrammatical relative to the transposed-word sequences, mean RTs: 1183 ms vs. 1230 ms respectively, $t = -3.481$, $p < .01$ (see Table 4).

3.2.2 ERP Results

Only correct trials were included in the ERP analysis. Testing for an N400 effect in the a-priori time window (290 - 500 ms post-stimulus), the cluster-based permutation tests revealed a significant reduction in N400 amplitude in the transposed-word condition compared to the control condition (cluster with $p = .0382$, see Figure 4). [2]

3.3 Discussion

Experiment 2 used the transposed-word effect seen in grammaticality judgments (Mirault et al., 2018) in order to compare conditions requiring the same “ungrammatical” response. As in Experiment 1, the grammaticality judgment task was combined with the brief presentation conditions of the RPVP paradigm. As expected, an attenuated N400 was observed in the transposed-word condition (e.g., “*you that read wrong*”, transposing the two central words forms a grammatically correct sequence) relative to the control condition (e.g., “*you that read worry*”, transposing any two words still forms an ungrammatical sequence). This result is consistent with the hypothesis that parallel word processing can quickly generate an initial representation of sentence structure, which then constrains possible word candidates at each position (Mirault et al., 2018). Hence the transposed-word effect was attributed to the joint effect of the top-down sentence-level constraints and the noisy bottom-up processing of word order (see also Snell & Grainger, 2019). The results of Experiment 2 therefore extend the findings of Experiment 1 and Wen et al. (2019) by providing another demonstration of a syntactically-driven N400 effect in RPVP generated by a different experimental manipulation.

4. General Discussion

The present study reports two experiments that for the first time combined the RPVP paradigm and a grammaticality judgment task with EEG recordings. Sequences of four words were presented simultaneously for 200 ms and participants were required to decide whether these sequences were grammatical or not. In Experiment 1, the four words consisted of either a grammatically correct normal sentence (e.g., *the man can run*) or an ungrammatical scrambled sequence of the same words (e.g., *run can man the*). The key finding is that a reduction in N400 amplitude was observed in the grammatical sequences compared to the scrambled sequences. This result replicates the N400 sentence superiority effect obtained using a post-cued partial report procedure combined with the same RPVP paradigm (Wen et al., 2019). The present findings therefore suggest that the N400 sentence superiority effect reported by Wen et al. is not a reflection of differences in ease of word identification as a function of surrounding context but most likely reflects the interaction between sentence-level processing and word identification. The general idea is that an elementary syntactic representation of the word sequence can be rapidly activated as a result of parallel word processing, and this syntactic representation then constrains on-going word identification processes via feedback connections. The fact that in the present study we found a very similar reduction in N400 amplitude when participants had to respond to the complete sequence of words rather than a single word, confirms the hypothesised role of syntactic processing in driving the N400 sentence superiority effect.

Crucially, Experiment 2 contrasted two types of ungrammatical sequences, the transposed-word sequences (e.g., *you that read wrong*) and the control sequences (e.g., *you that read worry*). This allowed us to test for effects of syntactic structure in conditions where participants made the same “ungrammatical” response to word sequences. Furthermore, here the transposed-word condition that was predicted to reduce N400 amplitude was the condition that was expected to generate the slowest RTs and highest error rates. Indeed, Experiment 2 replicated the behavioural findings of Mirault et al. (2018) whereby participants made more errors and were slower in judging the transposed-word sequences (e.g., "*you that read wrong*") as ungrammatical compared to the control sequences (e.g., "*you that read worry*"). We predicted a reduced N400 amplitude in the transposed-word condition because this condition was expected to provide evidence in favour of the presence of a correct sentence.

The N400 transposed-word effect was indeed what we observed. To our knowledge, we provide the first neurophysiological demonstration of the transposed-word effect. This effect is analogous to the N400 transposed-letter effect in visual word recognition studies (e.g., Carreiras, Vergara, & Perea, 2007; Vergara-Martínez, Perea, Gómez, & Swaab, 2013), which reflects the coarse coding of letter positions in words (Grainger & Holcomb, 2009; Grainger & Ziegler, 2011). In a similar vein, the N400 transposed-word effect indicates the noisy bottom-up processing of word order as the consequence of "good enough" heuristic mechanisms during sentence reading (Ferreira, Bailey, & Ferraro, 2002; Ferreira & Lowder, 2016; Ferreira & Patson, 2007). The combination of such noisy bottom-up processing with top-down syntactic constraints drives the transposed-word effect.

Taken together, our results are clear-cut. Both experiments observed an N400 effect in conditions where participants were required to make grammaticality judgments about the entire sequence of words. Therefore, we take this N400 effect as a signature of syntactic processing in the brain given that this effect is driven by the processing of word combinations where semantic relatedness was minimized. It is important to note that the N400 effect well proceeds participants' behavioural responses which occurred at least 800 ms after the onset of word sequences. Hence the observed N400 effect is not confounded by behavioural responses or any strategic factors. Furthermore, the N400 effect is not just a processing difficulty effect given that the condition that generated the largest N400 amplitude was the condition that generated the slowest RTs and greatest errors in Experiment 1, while exactly the opposite was true in Experiment 2.

At first glance, the syntactically-driven N400 effect observed in the present study appears at odds with the syntactic P600 effect obtained in the traditional RSVP studies. Given that the N400 effect was obtained in both a post-cued partial report task (Wen et al., 2019) and a grammaticality judgment task (the present study), we reject the task-dependent account to explain the absence of the P600 effect, the well-established neural index of syntactic processing. We would argue that our syntactically-driven N400 effects are fundamentally different from the P600 effect observed in the RSVP studies. In the RSVP studies, when a word is presented to participants, participants have to integrate this word with the prior words in the sentence. However, integration difficulty occurs when encountering syntactic processing obstacles, and an enhanced P600 is typically observed in the critical words that trigger such difficulty, e.g., *eating* is the critical word in the syntactically anomalous sentence *the cat will eating the fish*. It is noteworthy that the RSVP studies not only found a P600 effect elicited by the critical word embedded in the sentences, but also report a N400 effect elicited by the final words of the syntactic-incorrect sentences, e.g., *fish* is the sentence-final word in the previous example (e.g., Hagoort, Brown, & Groothusen, 1993; Osterhout & Mobley, 1995; Osterhout & Nicol, 1999). In addition, the N400 effect may also appear if the critical words appear in the sentence-final positions, e.g., *himself* is the critical word in *the girl helps himself* (e.g., Hagoort, 2003; Hagoort & Brown, 1999; Osterhout, 1997). The sentence-final N400 effect is generally interpreted as processing difficulty in generating semantic representations of syntactically ill-formed sentences (Hagoort et al., 1993; Osterhout, 1997; Osterhout & Holcomb, 1992).[3] In other words, the final-word N400 effect reflects a global processing of semantics and the critical-word P600 effect indicates a local difficulty in syntactic processing. Such incremental sentential processing in the RSVP paradigm stands in clear contrast to parallel proceeding in the RPVP paradigm. Furthermore, the cognitive mechanisms underlying the P600 effect of syntactic processing difficulty (e.g., syntactic violations or ambiguities) and our N400 effect (i.e., sentence superiority or transposed-word effects) are obviously distinct.

Admittedly, another possibility is that the P600 effect in response to syntactic difficulty is restricted to the RSVP studies. The fact that the semantic N400 component proceeds the syntactic P600 component is seemingly in contrast to the traditional syntax-first view of language processing (e.g., Friederici & Weissenborn, 2007) or the parallel view of semantic and syntactic processing (e.g., Jackendoff, 2007).[4] If relatively late syntactic P600 effect is due to the serial presentation techniques (RSVP), an early effect is expected when the parallel presentation is used. Future studies should examine this issue by presenting the syntactically ill-formed sentences in the RPVP paradigm. In short, the most parsimonious conclusion is that our observations of syntactically-driven N400 effects are not necessarily in contradiction with the classic P600 literature due to differences in the linguistic phenomena under investigation and presentation techniques.

The observed ERP evidence of the sentence superiority effect and transposed-word effect fits well with the idea that parallel processing of multiple words is possible during sentence reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Grainger, 2018; Snell & Grainger, in press; Snell, Meeter, & Grainger, 2017). This conclusion is fully compatible with the parafoveal-on-foveal effect obtained in the FRP and RSVP-with-flanker studies as discussed in the Introduction. Although growing evidence from electrophysiological investigations has suggested that the parallel word processing account is more plausible, the one-word-at-a-time incremental processing approach still dominates current theories of reading (for a review, see Reichle et al., 2009). It should be noted that these popular serial theories are mainly proposed on the basis of behavioural eye-tracking data rather than the ERP data. However, ERP data provide a direct real-time measurement of reading, and these electrophysiological studies are abundant and essential in empirical investigations. Accordingly, theories of reading will be more informative if they consider electrophysiological data as well. Therefore, we tentatively suggest that future theoretical models of reading should take neural data into accounts in order to capture the complete picture of cognitive mechanisms underlying reading (see Brouwer, Crocker, Venhuizen, & Hoeks, 2017, for a neurocomputational approach).

Overall, the present study demonstrates that the RPVP paradigm is a useful methodology in electrophysiological investigations of reading comprehension which complements the mainstream RSVP as well as other newly developed methods (e.g., co-registering eye-tracking and EEG, RSVP-with-flanker, see Payne & Federmeier, 2017, for the self-paced ERP paradigm). We would like to emphasise that the RPVP is not exactly the same as natural reading, but at least we demonstrate that words presented in parallel can be quickly processed by skilled readers in the RPVP paradigm. Using this neat though artificial paradigm, we can avoid some potential complexities or confounds (e.g., temporal overlaps issue in the FRP studies) and better focus on a fundamental nature of reading behaviour. However, one might question whether the parallel presentation of RPVP forces participants to process the words in parallel, contrary to natural reading. Although this possibility cannot be ruled out with our own data, it is noteworthy that such parallel processing is observed in other studies using different paradigms (see the FRP and RSVP-with-flanker studies discussed in the Introduction). Based on the converging evidence from different paradigms, we believe that it is reasonable to suggest that parallel word processing also occur during natural reading.

Another speculative issue of the present study as well as Wen et al. (2019) is that word sequences only consist of four words. It is true that the length of word sequences is highly constrained, but various sentence structures were used in our studies so that it is unlikely that our conclusions are limited to specific types of sentences. Given that the beauty of language is its infinite nature, it is impossible to test all the sentence types in one single experiment, and this limitation is shared across all the studies on sentence reading. Nevertheless, future RPVP explorations could use word sequences with various length to further test the sentence superiority and transposed-word effects.

In conclusion, the present study introduces the RPVP as a new and useful approach in electrophysiological investigations of reading and addresses the central question of serial and parallel processing views in skilled reading. The observations of the sentence superiority and transposed-word effects in terms of the reduced N400 reflect the influence of the syntactic representations on word identification. Our findings suggest that words presented in parallel can be quickly processed by skilled readers, and we advocate the use of RPVP as a complementary approach in future studies to better understand the neural and cognitive underpinnings of reading comprehension.

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Footnotes

1. The sentence superiority effect has also been investigated in memory research (e.g., Bonhage, Meyer, Gruber, Friederici, & Mueller, 2017). See also Jackson and McClelland (1975) for an early application of the RPVP paradigm, and Asano and Yokosawa (2011) for an investigation of sentence superiority in Japanese Kanji using a similar paradigm.

2. We also conducted a conventional AVOVA analysis on ERP mean amplitudes, which revealed the same finding.

3. Another slightly different view of the final-word N400 effect is that it may reflect a sentence wrap-up effect (for a recent review, see Stowe, Kaan, Sabourin, & Taylor, 2018).

4. We note here that the left anterior negativity (LAN: Friederici, Hahne, & Mecklinger, 1996), another ERP component associated with syntactic processing, may appear earlier than the N400. However, the LAN effect is generally limited to morphosyntactic violations and the occurrence of LAN is not systematically consistent across studies (Caffarra, Mendoza, & Davidson, 2019; Kaan, 2009; Molinaro et al., 2011; Tanner, 2015; Tanner & Van Hell, 2014). In contrast, the P600 is sensitive to most syntactic manipulations, and consequently is considered as the neural index of syntactic processing in general.

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Tables

Table 1 Results of Logistic Mixed-Effects Modelling on Accuracy Data (Experiment 1)

Random effects		**Variance**		**SD**	
Item	Intercept	0.5380		0.7335	
	Scrambled vs. Normal	2.5252		1.5891	
Subject	Intercept	0.7935		0.8908	
	Scrambled vs. Normal	0.8940		0.9455	
Fixed effects		**Estimate**	**SE**	**z value**	***p***
Scrambled vs. Normal		0.8641	0.2438	3.545	< .001

Table 2 Results of Mixed-Effects Modelling on RT Data (Experiment 1)

Random effects		**Variance**		**SD**	
Item	Intercept	3848		62.03	
	Scrambled vs. Normal	12286		110.84	
Subject	Intercept	75664		275.07	
	Scrambled vs. Normal	11924		109.19	
Fixed effects		**Estimate**	**SE**	**t value**	***p***
Scrambled vs. Normal		-81.79	24.22	-3.376	< .01

Table 3 Results of Logistic Mixed-Effects Modelling on Accuracy Data (Experiment 2)

Random effects		**Variance**		**SD**	
Item	Intercept	0.4509		0.6715	
Subject	Intercept	0.5379		0.7334	
Fixed effects		**Estimate**	**SE**	**z value**	***p***
Transposed-word vs. Control		0.81364	0.09865	8.248	< .001

Note. The maximal model failed to converge, and a backward model selection procedure was used. The random slopes of items were first removed, and then the random slopes of subjects. The complex model was compared to the simpler model using a Chi-squared test. We proceeded with the simpler model because the Chi-squared test was not significant.

Table 4 Results of Mixed-Effects Modelling on RT Data (Experiment 2)

Random effects		**Variance**		**SD**	
Item	Intercept	5038		70.98	
Subject	Intercept	102127		319.57	
	Transposed-word vs. Control	1750		41.83	
Fixed effects		**Estimate**	**SE**	**t value**	**p**
Transposed-word vs. Control		-50.56	14.53	-3.481	< .01

Note. The maximal model failed to converge, and a backward model selection procedure was used. The random slopes of items were first removed, and then the random slopes of subjects. The complex model was compared to the simpler model using an ANOVA test. The more complex model was chosen because the ANOVA test was significant.

Figures

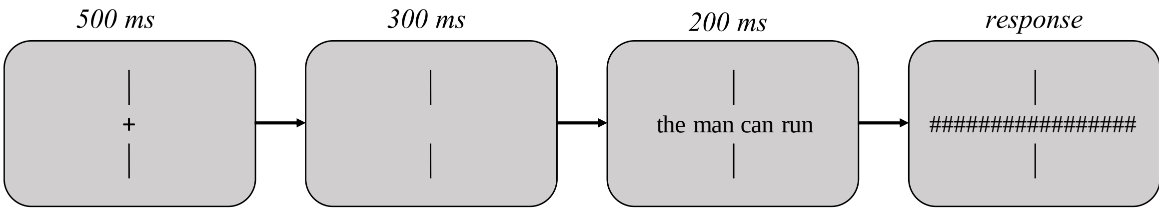

Figure 1 Illustration of the sequence of events in the Rapid Parallel Visual Presentation (RPVP) procedure used in Experiment 1

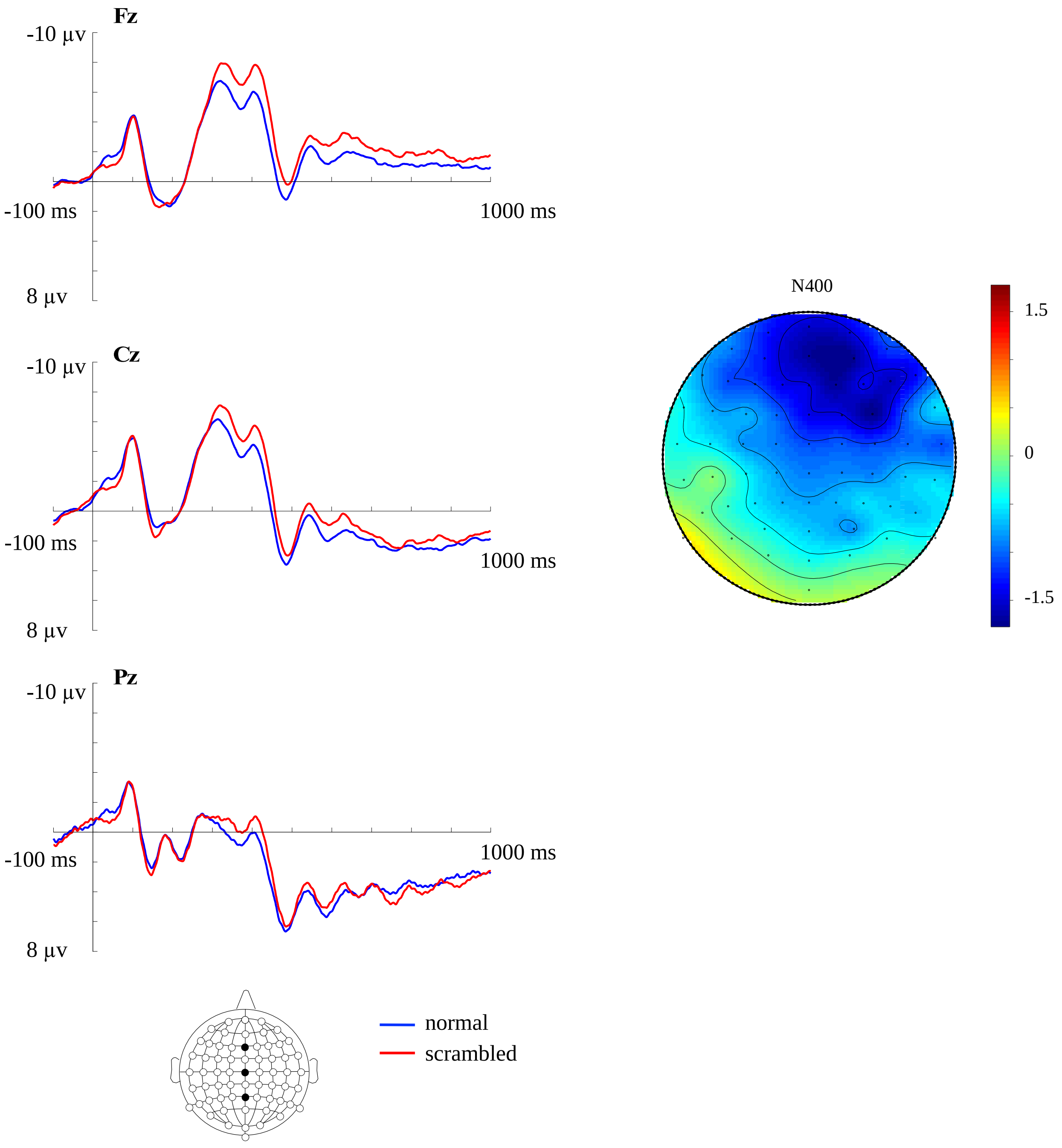

Figure 2 Results of ERP analyses of Experiment 1. Left: ERPs time-locked to the onset of word sequences (Fz, Cz, Pz); Right: Topography of voltage differences (normal minus scrambled) between 289 and 499 ms

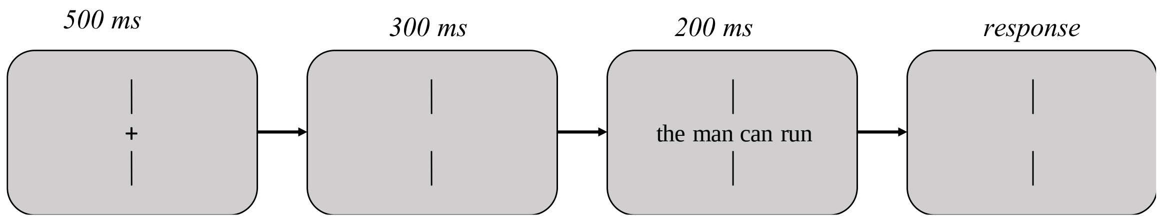

Figure 3 Illustration of the sequence of events in the Rapid Parallel Visual Presentation (RPVP) procedure used in Experiment 2

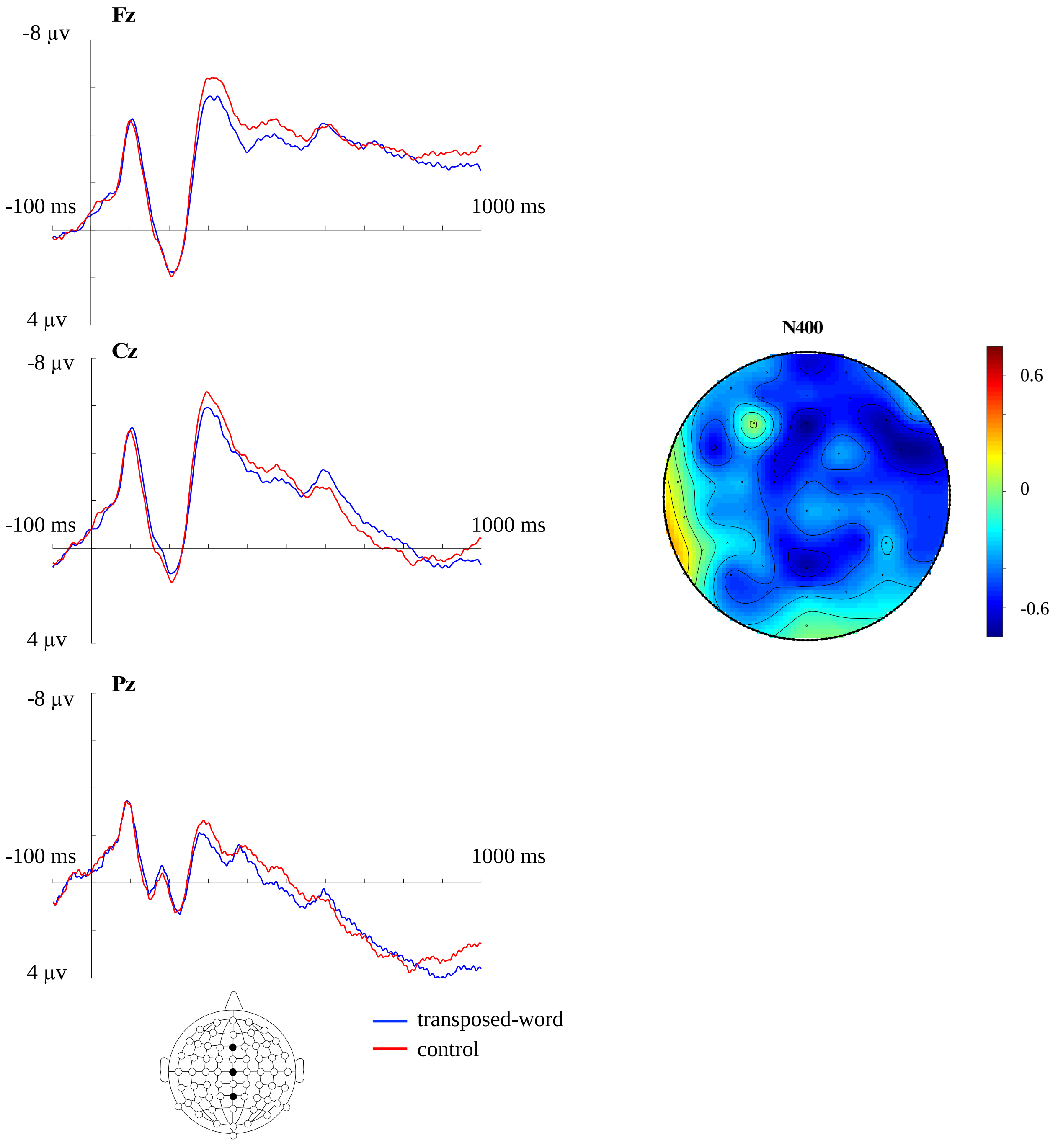

Figure 4 Results of ERP analyses of Experiment 2. Left: ERPs time-locked to the onset of word sequences (Fz, Cz, Pz); Right: Topography of voltage differences (transposed-word minus scontrol) between 290 and 500 ms