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ABSTRACT

Can several words be read in parallel, and if so, how is information about word order encoded under such circumstances? Here we focused on the bottom-up mechanisms involved in word-order encoding under the hypothesis of parallel word processing. We recorded EEG while participants performed a visual same-different matching task with sequences of five words (reference sequence followed by a target sequence each presented for 400 ms). The reference sequence could be grammatically correct or an ungrammatical scrambling of the same words (e.g., he wants these green apples/green wants these he apples). Target sequences for 'different' responses were created by either transposing two words in the reference (e.g., he these wants green apples/green these wants he apples), or by changing two words (e.g., he talks their green apples/green talks their he apples). Different responses were harder to make in the transposition condition, and this transposed-word effect started to emerge around 250 ms post-target onset. The transposed-word effect was first seen on an early onsetting N400 component, with reduced amplitudes (i.e., less negative ERPs) in the transposed condition relative to a two-word replacement condition. A later transposed-word effect was seen on a more temporally widespread positive-going component. Converging behavioral and EEG results showed no effects of reference grammaticality on 'different' responses nor an interaction with transposed-word effects. Our results point to the noisy, bottom-up association of word identities to spatiotopic locations as one means of encoding word order information, and one key source of transposed-word effects.

Recent behavioral findings have challenged the prevalent view that skilled readers typically apply a serial word-by-word reading strategy such as implemented in the EZ-Reader model (Reichle et al., 1998). A serial reading strategy has the advantage of providing a simple mechanism for encoding information about word order (Reichle et al., 2009) that is crucial for computing the syntactic structures necessary for text comprehension. The prevalent view is supported mainly by studies recording eye-movements during text reading, where indeed it is noted that readers' eyes typically move from one word to the next, with the occasional regressive eye-movement and a limited amount of word skipping (see Rayner, 1998, for a review). However, eye movements are not necessarily a transparent reflection of the cognitive processes involved in reading, and research using different measures (e.g., electrophysiology) and different paradigms (e.g., grammatical decision task, flankers task) points to the possibility that more than one word can be read at a time (see Snell and Grainger, 2019a, for a summary of the arguments). This raises the key question as to how word-order information would be encoded under conditions of parallel word processing.

In the present study we investigate word-order encoding in arguably the simplest of paradigms that requires processing of word identities and their positions. The use of artificial reading paradigms is important since these can provide insights into the limits of the reading process (Snell and Grainger, 2019a). Here we adopt this general strategy by using a low-level task (same-different matching) in order to investigate the most elementary processes involved in reading multiple words.[1] We focus on one of the key phenomena thought to reflect parallel word processing – transposed-word effects – and we use these as an index of how well word-order information is encoded. We record EEG in order to provide crucial information about the timing of the processes driving such effects, and therefore about the timing of the association of word identities to word positions when processing multiple words.

Transposed-word effects were first reported by Mirault et al. (2018) using the grammatical decision task. Mirault et al. presented

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[1] In the same way that understanding letter-position encoding has been crucial for understanding visual word recognition (e.g., Grainger, 2008), we expect that understanding the basic mechanisms involved in word-order encoding will be a crucial ingredient of understanding the bigger picture of sentence and text comprehension.

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Table 1
Examples of the reference and target sequences for the 'different' response trials.Grammatical reference.

	Examples from the experiment	Examples to illustrate the design
Grammatical reference		
Reference	il veut ces pommes vertes	he wants these green apples
Transposed Word Target	IL CES VEUT POMMES VERTES	HE THESE WANTS GREEN APPLES
Replaced Word Target	IL DIRA MES POMMES VERTES	HE TALKS THEIR GREEN APPLES
Ungrammatical reference		
Reference	vertes veut ces il pommes	green wants these he apples
Transposed Word Target	VERTES CES VEUT IL POMMES	GREEN THESE WANTS HE APPLES
Replaced Word Target	VERTES DIRA MES IL POMMES	GREEN TALKS THEIR HE APPLES

participants with a mixture of grammatically correct 5-word sequences (e.g., *The car was light blue*) and ungrammatical sequences, and asked them to respond as rapidly and accurately as possible if the sequence they read was grammatically correct or not. The key manipulation in the Mirault et al. (2018) study concerned the nature of the ungrammatical sequences, which could be formed by transposing two words in a grammatical sequence (e.g., *The white was cat big*), and control sequences (e.g., *The white was cat slowly*) for which a grammatically correct sequence of words could not be formed by any transposition. Mirault et al. found that the transposed-word sequences were harder to classify as being ungrammatical compared with the control sequences – a transposed-word effect. In a follow-up study, Snell and Grainger (2019b) showed that transposed-word effects were greater when the transposition involved two adjacent internal words compared with external word transpositions. Snell and Grainger argued that this was evidence for the noisy bottom-up assignment of word identities to their positions in a line of text as one key source of transposed-word effects.

In order to investigate the time-course of transposed-word effects, Wen et al. (2020) recorded EEG while participants made grammatical decisions to 4-word sequences. Moreover, the sequences were presented for only 200 ms (Rapid Parallel Visual Presentation – RPVP) and followed by a backward mask. This rapid parallel presentation procedure enabled collection of EEG uncontaminated by eye-movement artefacts, while maintaining the simultaneous presentation of words that is typical of normal reading (as opposed to the more standard sequential RSVP procedure). The key findings were obtained in Experiment 2 of that study where EEG responses were compared across transposed-word ungrammatical sequences and control ungrammatical sequences as in the Mirault et al. (2018) study. In line with the results of Mirault et al. participants in the Wen et al. study found it harder to categorize transposed-word sequences as being ungrammatical compared with the control sequences. ERP analyses revealed that the transposed-word effect started to emerge around 300 ms post-sequence onset and took the form of a reduction in amplitude of an N400-like component.[2] Transposed-word sequences generated a less negative-going N400 compared with the control sequences. Thus, the transposed-word sequences were being processed more like true sentences than the control sequences, and this resulted in a reduced N400 accompanied by an increased difficultly in judging them to be ungrammatical.

It is important to note that the timing and spatial distribution of the transposed-word ERP effect reported in Wen et al. (2020) resembles the effect reported by Wen et al. (2019) in an ERP investigation of the sentence superiority effect. Using RPVP methodology, with 4-word sequences presented for 200 ms, participants had to identify one of the four words at a post-cued location. Identification accuracy was greater when the sequence of words was a grammatically correct sequence compared with an ungrammatical scrambled sequence of the same words (see also Declerck et al., 2020; Snell and Grainger, 2017), and ERPs were less negative-going in the grammatically correct condition starting around 300 ms post-sequence onset. These findings were interpreted as reflecting the rapid computation of some form of primitive syntactic representation, when available, followed by top-down feedback to on-going word identification processes. The resemblance with the transposed-word ERP effect therefore points to top-down processes as another likely source of transposed-word effects. Sentence-level constraints would impose an interpretation of the transposed-word sequences as the syntactically correct sequences from which they were derived.

In the present study we use a different parallel presentation paradigm and a different set of stimuli designed to isolate the distinct contributions of bottom-up processes relative to top-down processes on transposed-word effects. The paradigm is the same-different matching task used in prior behavioral studies (Pegado & Grainger, 2019, 2020a, 2020b). In this task, a first sequence of words, the reference sequence, is presented for a brief duration (400 ms in our prior work), and immediately followed by the target sequence of words. Participants are required to respond as rapidly and as accurately as possible if the two sequences are same or different while taking into consideration both word identities and word order. Reference and target sequences are both centered on the computer screen and are presented in different case and separated by one line in order to avoid physical overlap. In the Pegado and Grainger (2020a) study, the reference sequence could either be a grammatically correct sequence of words or an ungrammatical scrambled sequence of the same words (see Table 1 for examples). In the critical trials involving a 'different' response the difference could be generated by transposing two adjacent internal words in the reference sequence or by replacing the same two words with different words. Participants found it harder to classify the transposed-word condition as being different compared with the replaced-word condition. In Experiment 1 of that study, reference grammaticality did not interact with the transposed-word effect. However, in Experiment 2, where the replaced-word condition involved only one word, transposed-word effects were found to be greater with grammatical references. Pegado and Grainger concluded that one main factor driving transposed-word effects is the noisy bottom-up association of word identities to spatiotopic locations along a line of text, and that top-down influences are only detectable in same-different matching when the 'different' responses are made harder.

Given the present focus on fast-acting, bottom-up mechanisms driving transposed-word effects, we used the design and stimuli of Pegado and Grainger's (2020a) Experiment 1. We investigated the time-course of these effects using EEG. Timing information is critical with respect to distinguishing between serial and parallel accounts of transposed-word effects. According to serial models of reading (e.g., E-Z Reader: Reichle et al., 1998), word order information is provided by the sequential identification of words as readers move their eyes along a line of text (Reichle et al., 2009; Snell and Grainger, 2019). Transposed-word effects could arise either by readers fixating the two words out-of-order, or by adding noise to the order information provided by the rapid sequential identification of the two words. Mirault and Grainger (2020a)

[2] In order to be consistent with our prior publications we will use N400 to refer to this component in the present work, or the term 'N400-like' in order to acknowledge that it might not be a classic 'semantic' N400 given its distinctly earlier peak (around 300 ms). We return to this point in the Discussion.

recorded readers eye-movements and rejected the "reading out-of--order" account. Here we put the "rapid serial identification" account to test by measuring the timing of transposed-word effects. With word identification during reading proceeding at roughly 250 ms per word (Rayner, 1998), the fastest possible onset of transposed-word effects is in the order of 500 ms according to this account.[3]

1. Methods

1.1. Participants

Thirty-one[4] participants (19 females) were recruited at Aix-Marseille University (Marseille, France). All participants were native speakers of French. They received monetary compensation (10 €/hour) or course credit. All reported normal or corrected-to-normal vision, ranged in age from 18 to 38 years (M = 23.6 years, SD = 4.29), and signed informed-consent forms prior to participation. Ethics approval was obtained from the "Comité de Protection des Personnes SUD-EST IV" (No. 17/051).

1.2. Design and stimuli

The forty grammatical word sequences and corresponding ungrammatical sequences tested by Pegado and Grainger (2020a, Experiment 1) were used here. Each of these sequences was composed of five words. These forty sentences and forty ungrammatical sequences formed the set of sequences that were presented as the first of two sequences on each trial, called the reference. In the same manner as Pegado and Grainger (2020a), for every reference we generated three types of target sequence (the second sequence on each trial), for a total of 240 trials. The three types of target were: 1) repetition – the same sequence as the reference; 2) transposition – the words at positions 2 and 3 or positions 3 and 4 in the reference were flipped; 3) replacement – the words at positions 2 and 3 or positions 3 and 4 in the reference were replaced with different words. The replacement words had the same length, syntactic function and word frequency (on average) as the words they replaced. The average length of these critical words was 4.54 letters (range 1–6 letters) and the average frequency based on values obtained from Lexique2 (New et al., 2004) was 6.50 on the Zipf scale (van Heuven, 2014), range 2.85–7.51. The design focused on the 'different' response trials for which the analysis involved a 2 (Reference Grammaticality) X 2 (Type of Change) factorial design. Table 1 provides examples of reference and target sequences used in the 'different' response conditions in the Experiment (French), and also in English for expository purposes. The 'same' response analysis contrasted grammatical and ungrammatical references (Reference Grammaticality factor). For each participant, every reference was repeated three times associated with one of its three target sequences (1 same response, 2 types of different response).[5]

1.3. Apparatus

Stimuli were presented using OpenSesame (Version 3.0.7; Mathôt et al., 2012) and displayed on a CRT monitor (18″, 1024 × 768 pixels, 75 Hz). Participants were seated about 70 cm from the monitor, such that every four characters (monospaced font in black on a gray background) equaled approximately 1° of visual angle, and the complete word sequence spanned approximately 6°. Responses were recorded via a gamepad.

1.4. Procedure

The experiment took place in a quiet room. The instructions were given both by the experimenter and on screen. On every trial, participants had to decide if the two sequences presented one after the other on the computer screen were the same or different, where 'same' was defined as being composed of the same words in the same order (see Fig. 1). Note that participants were not requested to "read" the sequences of words, but simply to detect changes that occurred across the target sequence and the reference sequence. A training phase was performed before the experiment to ensure good comprehension and familiarization with the task. The first sequence, the reference, was always presented in lower case, and the second sequence, the target, was always shown in uppercase, in order to avoid purely visual matching. In order to compensate for the difference in the size of lowercase and uppercase letters, the font size of the reference was greater than that of the target (24 pixels and 22 pixels respectively) such that one character corresponded to approximately 0.3 cm in both cases. All stimuli were presented in droid monospaced font, the default font in OpenSesame. The words in each sequence were presented simultaneously for a duration of 400 ms. Targets immediately followed the reference. The position of the reference was slightly higher than the central fixation cross and the position of the target sequence was slightly lower, such that the two sequences were separated by approximately one line of text. Participants were requested to respond as fast and as accurately as possible. Each trial started with a fixation cross for 300 ms followed by the reference for 400 ms, followed by the target for 400 ms, followed by a question mark "?" presented until the participants' answer (or for a maximum of 5 s). Then a neutral gray screen was displayed for 200 ms and a new trial started.

Note. Not shown here is the condition where targets were the same word sequence as the reference but printed in uppercase (i.e., 'same' response trials). The transpositions and replacements operate on the 2nd and 3rd words in these examples and could equally be on the 3rd and 4th words in the experiment.

1.5. EEG recording and preprocessing

EEG data were recorded at 1024 Hz using the Active-Two BioSemi system with 64 active electrodes in reference to CMS and DRL (Metting van Rijn, Peper and Grimbergen, 1990; Schutter, 2006). Two external electrodes were placed at left and right mastoids for off-line re-referencing. Four external electrodes were placed below and at the outer canthus of each eye to monitor eye movements. Before data acquisition electrode offset were checked and kept below 30 mV.

EEG data analysis was conducted using EEGlab (Delorme and Makeig, 2004) and ERPlab (Lopez-Calderon and Luck, 2014). The average of left and right mastoids was used as the off-line reference. Independent component analysis (ICA) was first conducted with the data high-pass filtered at 2 Hz, an optimized procedure (Dimigen, 2018; Dowding et al., 2015). Then, ICA weights were applied to the data high-pass filtered at 0.1 Hz. Next, ICA components associated with typical artefacts such as those generated by eye-blinks, eye-movements, muscular activity, and heartbeat (Winkler et al., 2014) were removed using MARA, an open-source EEGlab plug-in (Goh, 2017). The data was then segmented in epochs of 900 ms starting 100 ms before the onset of the target sequence. The epochs were baseline-corrected and low-pass filtered at 30 Hz. As a security procedure to detect possible remaining artefacts, we used a peak-to-peak moving window (200 ms large) by

[3] However, this is assuming that participants perform the task by only identifying two words, whereas the change could involve any two of the three central words in the sequence. This therefore pushes the timing estimate up to 750 ms. We provide a fuller analysis of this point in the Discussion.

[4] Based on our prior behavioral study (Pegado and Grainger, 2020a, Experiment 1, 28 participants) and EEG work (Wen et al., 2020, Experiment 2, 26 participants) we reckoned we had ample power to detect word transposition effects in the present experiment.

[5] Note that 80 different reference sequences were presented to guarantee sufficient variability across trials. Note also that the focus here is on responses when reference and target differed, and not the responses to the references per se. Importantly, even in the eventuality of a reduction of ERPs for previously-seen stimuli (i.e., an effect of reference repetition), this potential effect would be distributed across all conditions.

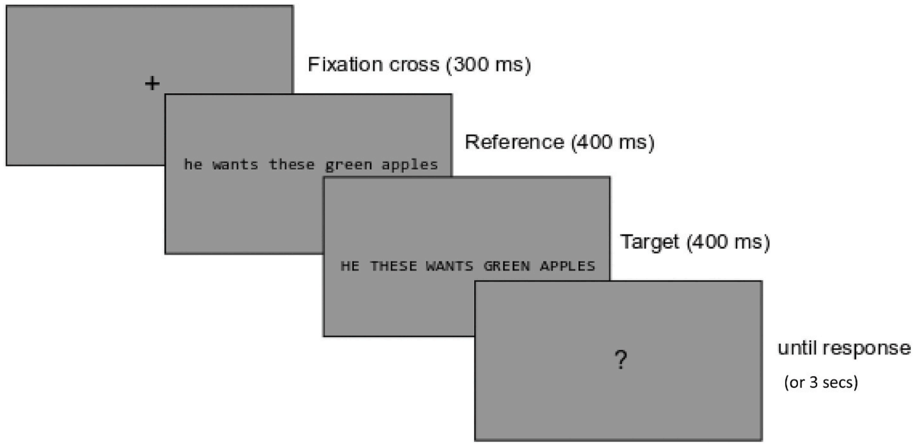

Fig. 1. The same-different matching paradigm applied to sequences of words. Participants had to decide as rapidly and as accurately as possible if the two sequences of words were the 'same' or 'different' by pressing appropriate response keys. In this example, the target sequence differed from the reference sequence by the transposition of the 2nd and 3rd words.

steps of 50 ms, using a threshold of 100 μV: epochs still containing ocular artefacts were automatically rejected (only 0.54% of the data). This demonstrates the efficiency of the present ICA state-of-the-art artefact removal procedure, preserving epochs. For comparison, when not using this ICA procedure, on average, 13.8% of epochs presented artefacts and seven participants would need to be excluded when using a traditional rejection threshold of 25% contaminated epochs for a given participant. One participant presenting inappropriate behavior, reporting significant sleep deprivation and presenting high levels of artefacts (more than 40% of the epochs) was excluded from the analysis.

1.6. Statistical analysis

Behavioral data were analyzed with Linear Mixed Effects (LME) models for response times (RTs - log 10 transformed) and Generalized (logistic) Linear Mixed Effects (GLME) models for errors, with random effects for participants and items, using the lme4 library (version 3.5.1) in R software (Bates et al., 2015). These analyses tried to maximize randomness by including whenever possible random slopes in addition to random intercepts (Barr et al., 2013). We report *b*-values, standard errors (SEs) and *t*-values (for RTs) and *z*-values (for Error Rates), with *t*- and *z*-values beyond |1.96| deemed significant (Baayen, 2008). A complementary Bayes factor analysis (Wagenmakers, 2007) was performed using the BayesFactor library in R (Rouder, 2012; Morey and Rouder, 2011). Type of Change (transposition vs. replacement) and Reference Grammaticality were declared as fixed-effect factors.

The EEG data were analyzed with a cluster-based random permutation test implemented by Mass univariate ERP toolbox (https://openwetware.org/wiki/Mass_Univariate_ERP_Toolbox), from 0 ms to 800 ms post-target on all 64 electrodes, using an alpha level of 0.05 and applying 2500 permutations.

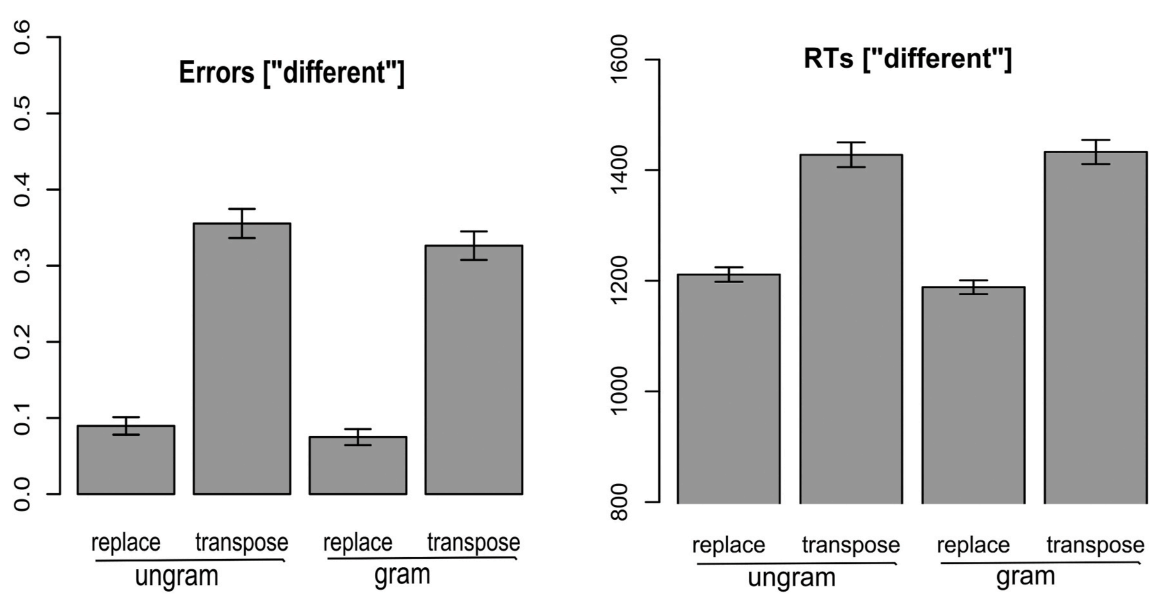

Fig. 2. Behavioral results. Error rates in probabilities and response times (RTs) in milliseconds for 'different' response trials as a function of reference grammaticality (ungrammatical vs. grammatical) and type of change (replace vs. transpose). Error bars represent 95% confidence intervals.

2. Results

Here we present the analyses pertaining to the critical trials of the experiment, that is trials that required a 'different' response. For completeness, the analyses of 'same' response trials are provided in the Appendix.

2.1. Behavioral results

Participants presented an overall error rate of 21.1% and a median RT from target onset restricted to correct responses of 1220 ms. Condition means are shown in Fig. 2.

In the analysis of errors, the model had random intercepts for all factors and random slopes only by-participant for Type of Change, again because more complex models did not converge. We found a small but significant main effect of Reference Grammaticality ($b = 0.22$, SE $=$ 0.11, $z = 1.99$), and Type of Change ($b = 2.02$, SE $= 0.17$, $z = 11.6$). Participants made more errors with ungrammatical references (22.3%) than grammatically correct references (20.1%). They made four-fold more errors when the change involved a transposition (34.1%) compared with a replacement (8.23%). The interaction between these two factors was not significant ($b = 0.07$, SE $= 0.13$, $z = 0.51$). To confirm this null interaction, we performed a Bayes factor analysis using Bayesian Information Criteria (Wagenmakers, 2007), which compares the fit of the data under the null hypothesis relative to the alternative hypothesis. Results revealed that the data were 21.5 times more likely to occur under the null than the alternative hypothesis for the interaction term, providing positive evidence for the lack of interaction.

The analysis of RTs only included random intercepts because more complex models did not converge. There were main effects of Type of Change ($b = 0.07$, SE $= 0.003$, $t = 23.6$), and Reference Grammaticality ($b = 0.007$, SE $= 0.003$, $t = 2.69$), and no interaction ($b = 0.007$, SE $=$ 0.004, $t = 1.72$). Participants took longer to respond correctly on transposed-word trials (1430 ms) than replace trials (1200 ms). They also took longer to respond with ungrammatical references (1301 ms) than grammatical references (1291 ms). We again performed a Bayes factor analysis of the absence of an interaction effect. This analysis revealed that the data were 5.3 times more likely to occur under the null than the alternative hypothesis for the interaction term.

2.2. ERP results

Comparing the transposed and replacement conditions for 'different' response trials, we could observe widespread transposed-word effects across the scalp, with two separate components presenting opposite-going waveforms: an early component between ~250 and 400 ms post-target and a later component starting around 450 ms until the end of the epoch (800 ms) (see Fig. 3). The effect of Reference Grammaticality was not significant, neither was the interaction between Reference Grammaticality and Type of Change. Here we present the results concerning the main effect of Type of Change. The results of the cluster-based random permutation test for this factor are shown in Fig. 4.

The ERP analyses highlight two distinct phases in the transposed-word effect. The earliest phase onsets just before 250 ms post-target and continues on to just over 400 ms. In this time-window the transposed-word condition generated less negative-going ERPs than the replaced-word condition. The scalp maps show that this early effect becomes more widespread, covering central and posterior sites, after about 300 ms post-target onset. Following this early pattern, we observed a transposed-word effect starting just after 400 ms and exhibiting a less positive-going waveform than the replaced-word condition, and this continued to the end of the 800 ms recording limit. The scalp maps show that this later effect is even more widespread, covering anterior as well as central and posterior sites.

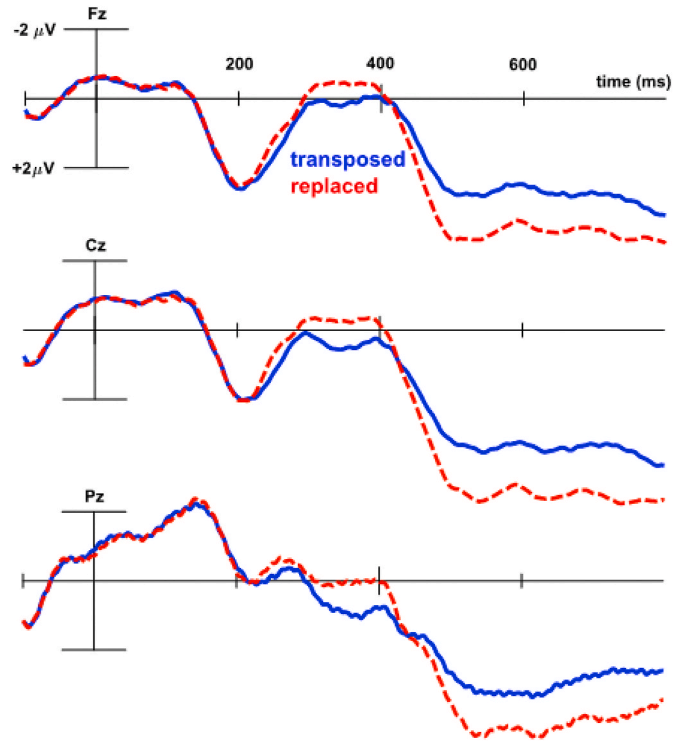

Fig. 3. Grand average waveforms at three representative electrode sites for the transposed (full blue) and replaced (dashed red) conditions for 'different' responses averaged across grammatical and ungrammatical references. ERPs are time-locked to the onset of the target sequence.

3. Discussion

The present study used the same-different matching task with sequences of five words in order to investigate the bottom-up processing involved in associating word identities with word positions when reading multiple words. One advantage of the same-different matching task compared with the grammatical decision task (e.g., Wen et al., 2020) is that effects of sequence grammaticality can be examined in conditions involving an identical behavioral response (i.e., 'different' response). The focus of the present work was on the 'different' responses made to two types of difference between reference and target sequences. One difference involved transposing two words in the reference sequence, and the other difference involved replacing the same two words with different words. Replicating our prior behavioral work (Pegado & Grainger, 2020a, 2020b) we found that 'different' responses were harder to make in the transposed-word condition compared with the replaced-word condition – a transposed-word effect. Crucially, reference grammaticality did not influence this transposed-word effect, suggesting that we had successfully isolated purely bottom-up contributions to this effect.

The novelty of the present work lies in the use of EEG to estimate the timing of the bottom-up processing driving transposed-word effects. The cluster-based permutation test revealed that our transposed-word effect was first robust around 250 ms post-target onset. The grand average

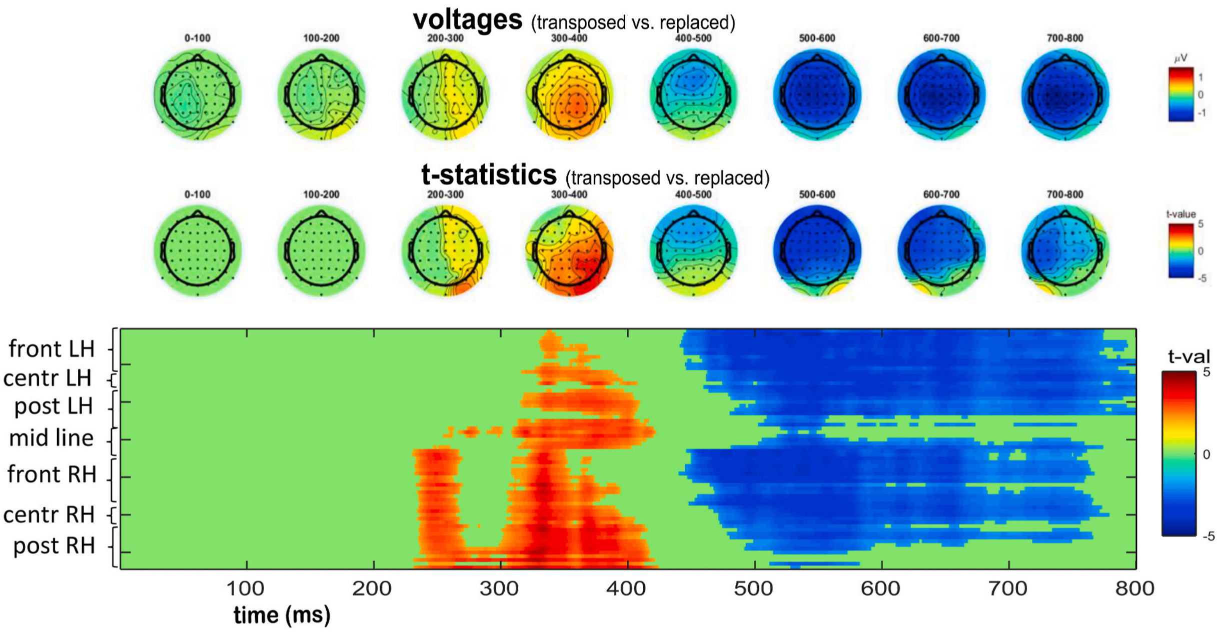

Fig. 4. Top: scalp maps of transposed-word effects (difference between the transposed and replaced conditions) averaged across successive 100 ms time slices. The upper panel shows voltage differences and the lower panel shows the corresponding t-statistics. Bottom: Permutation test results for the contrast between the transposed and replaced conditions. Scalp regions: LH = left hemisphere; RH = right hemisphere; front = frontal; centr = central; post = posterior. Electrode Cz is located in the space between front RH and centr RH.

waveforms further revealed that the effect took the form of less negative-going waveforms in an early N400-like component, with the bulk of this early effect occurring between 300 and 400 ms post-target onset. The scalp maps further revealed that this early effect had a centro-posterior distribution that is typical of the N400. Following this early component, there was a later more sustained positive-going component that revealed less-positive waveforms in the transposed-word condition.

The timing of the early ERP transposed-word effect is in line with current knowledge concerning the bottom-up activation of whole-word orthographic representations during reading (e.g., Grainger and Holcomb, 2009). Work using the masked-priming technique combined with EEG recordings has revealed that the bulk of location-invariant sub-lexical and lexical orthographic processing is seen in two successive ERP components, the N250 and the N400. Identification of whole-word orthographic representations is thought to be reflected in processing at the intersection of these two components, which roughly corresponds to the 300–400 ms timing of the first manifestation of transposed-word effects seen in the present study. This provides further support for our interpretation of transposed-word effects as reflecting the association of word identities (whole-word orthographic representations) with different locations along a line of text. It is the association of word identities to spatiotopic locations that is thought to enable the computation of word order information for syntactic processing and text comprehension (Grainger, 2018; Snell et al., 2017, 2018).

It is interesting to note that the pattern of ERP transposed-word effects found in the present work resembles the pattern of transposed-letter effects reported by Duñabeitia et al. (2012) for strings of four consonants in a same-different matching task. The timing of the effects is understandably faster for letter strings than sequences of words, but letters showed the same initial reduced negativity in the transposition condition compared to a replacement condition, and a later reversal of this effect. The early transposed-letter effect was most pronounced in a time-window spanning 200–325 ms post-target. Given the general consensus that transposed-letter effects reflect parallel letter processing, the similarity of the ERP effects for letters and words can be taken as further evidence that transposed-word effects reflect parallel word processing.

It is also informative to compare the ERP findings of the present study with those reported by Wen et al. (2020) using a grammatical decision task and the RPVP procedure with 200 ms presentation durations for sequences of four words. In the Wen et al. study, the transposed-word effect onset slightly later, but its earliest manifestation was very similar to the early effect seen in the present work. Furthermore, very similar patterns were found when contrasting grammatically correct word sequences with ungrammatical word sequences (Wen et al., 2019, 2020), suggesting that the early N400-like component seen systematically in all these experiments might reflect the operations involved in the computation of a primitive syntactic structure from a sequence of words – an early 'syntactic' N400. However, the present findings clearly demonstrate that syntax is not a necessary condition for obtaining this ERP effect, and therefore support our proposal that parallel processing of word identities might be the common underlying mechanism, independently of how this information is subsequently used. Further evidence in support of this interpretation was provided in the flanker study of Snell et al. (2019) and the fixation-related potential (FRP) study of Mirault et al. (2020b). In both of these studies, related parafoveal words caused a reduced negativity in a negative-going component that peaked around 300 ms post-stimulus onset, in conditions where the combination of the target word and the related parafoveal word was ungrammatical.

The transposed-word effect seen on a later positive-going component was much more pronounced in the present work compared with the Wen et al. (2020) study. This might reflect the fact that the size of the behavioral transposed-word effect was much larger in the present study compared with Wen et al. (2020). This in turn would suggest that the later transposed-word effect seen in ERPs in the present work might reflect decision-related processing. On the other hand, these effects could be affecting another well-defined ERP component, the late positive component (LPC), that is known to be sensitive to repetitions of consciously processed stimuli (Misra and Holcomb, 2003). However, repeated stimuli generate more positive-going waveforms on the LPC, whereas our transposed-word effect went in the opposite direction. Moreover, a greater positivity on the LPC is generally associated with slower RTs (e.g., Guo, 2012; Wen et al., 2018), therefore it is unclear, under this interpretation, why the transposed-word condition generated a reduced positivity on this component in the present study. A better interpretation of this late effect might therefore reside in differences in the degree of perceived syntactic anomaly in our transposition and replacement conditions, a difference that is typically found on the P600 ERP component (Hagoort et al., 1993; Osterhout and Holcomb, 1992; see Kuperberg, 2007; Leckey and Federmeier, 2020; for reviews of the P600 and related components). On the other hand, the absence of an influence of reference grammaticality on our transposed-word effects pleads against such an interpretation. Alternatively, the later component could be interpreted as a P3b, which is thought to capture some level of context updating or cognitive closure, in that participants could be updating their context models as they recognize that items in the replaced condition do not convey the same information as the reference, leading to the increased positivity. Furthermore, there is evidence that the syntactic P600 is is in fact a later P3b (Leckey and Federmeier, 2020; Sassenhagen and Fiebach, 2019).

Once again in line with the results of Wen et al. (2020, Experiment 2), the apparent opposition in the direction of behavioral and ERP effects was also seen in the early transposed-word effect. That is, reduced negativity on the N400 component is generally associated with greater ease in responding, and not the greater difficulty in responding in the transposed-word condition seen in the present work and in Wen et al. (2020). This suggests that the ERPs generated by transposed-word sequences are not reflecting difficulty in preparing or executing a behavioral response, but rather that they reflect the ease with which word identities are associated with distinct locations along a line of text, independently of syntactic structure. Given that such associations provide the ingredients for syntactic computations, the transposed-word manipulation not only impacts on attempts to rapidly compute a primitive syntactic structure (see e.g., Declerck et al., 2020), but can also continue to influence continuing attempts to make sense out of a sequence of words.

Finally, we consider possible ways that a serial word reading model might be able to account for the present results, other than arguing that this has nothing to do with reading (see Snell and Grainger, 2019a, for a defense of the use of "artificial" paradigms to study reading). For example, it is possible that our participants applied a 2-word identification strategy in order to perform the task. That is, given a sequence of five words - W1 W2 W3 W4 W5 – participants could randomly choose to identify either W2 W3 or W3 W4, and base their decision on the matching of the two selected words. The problem with this account is that it predicts an average accuracy of 50% in the replaced-words condition, and just focusing on W2 and W3 or W3 and W4 makes the same prediction. Further note that just focusing on the central word (W3) would lead to 100% accuracy in 'different' responses, so it is clear that our participants were not using any of these minimalist strategies. It is also possible that, given the central fixation point, our participants were focusing on the three central words (W2, W3, W4) and ignoring the two outer words (W1, W5). This strategy would have produced the pattern of behavioral results we obtained with 'different' responses and would explain the absence of an influence of reference grammaticality on these responses. However, it cannot account for the effects of grammaticality we observed on 'same' responses in the behavioral data (see Appendix). Nevertheless, we acknowledge that a very fast serial word identification process might possibly be able to account for our findings.[6] Future research could include an equal number of changes at the first and last positions in the string in order to exclude such a strategy.

Summing-up, we used the same-different matching task with sequences of five words and we successfully replicated the transposed-word effect on an early N400-like component that had been observed in prior work using the grammatical decision task. The timing of the early effect is in line with current knowledge concerning the bottom-up activation of whole-word orthographic representations during reading. Crucially, this early modulation of ERP amplitude was not influenced by reference grammaticality, hence pointing to bottom-up processes as the source of the effect. We conclude that one important source of early ERP effects found with word sequences presented in parallel is the noisy association of word identities to locations along a line of text.

Credit author statement

Felipe Pegado: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. Yun Wen: Software & Validation, Formal analysis, Investigation. Jonathan Mirault: Software & Validation, Resources. Stéphane Dufau: Methodology, Software & Validation. Jonathan Grainger: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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APPENDIX. Analysis of 'same' response trials

Behavior

Here, we performed LME analyses by declaring Reference Grammaticality (grammatical vs. ungrammatical sequences) as a fixed-effect factor. The models were fully randomized for errors but due to convergence issues in RTs, random slopes for items or participants could not be included. We found a significant effect of Reference Grammaticality both for errors ($b = 0.56$, SE $= 0.13$, $z = 4.32$) and RTs ($b = 0.016$, SE $= 0.003$, $t = 5.60$), indicating that ungrammatical sequences were more difficult to judge as being the same compared with grammatically correct sequences (respectively 25.5% vs. 16.4% errors, and 1432 ms vs. 1383 ms).

[6] See Mirault and Grainger (2020) for an estimate of just how fast such a serial reading mechanism would have to be, given that accurate grammatical decisions to 5-word sequences are achieved with as little as 300 ms exposures.

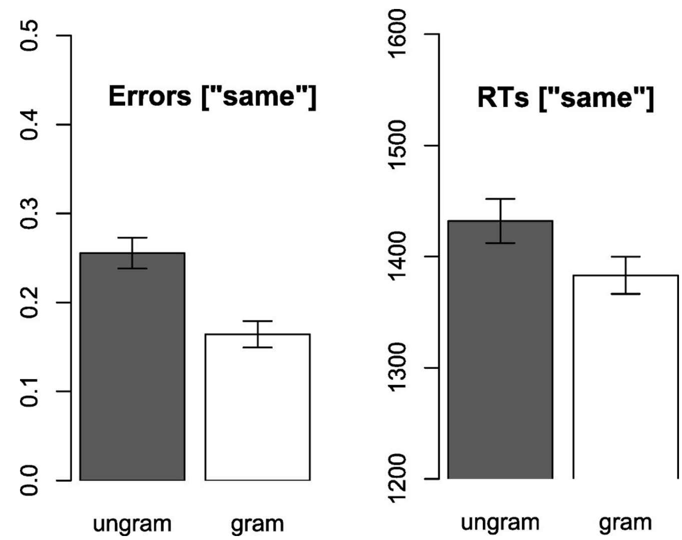

Fig. A1. Error rates in probabilities (left) and RTs in milliseconds (right) for 'same' response trials with ungrammatical sequences and grammatical sequences. Error bars represent 95% CI.

EEG

Contrary to the behavioral data there were no significant effects of Reference Grammaticality on 'same' response trials in the ERPs. The scalp distribution of effects of Reference Grammaticality are shown in Fig. A2 along with the results of the cluster-based permutation test.

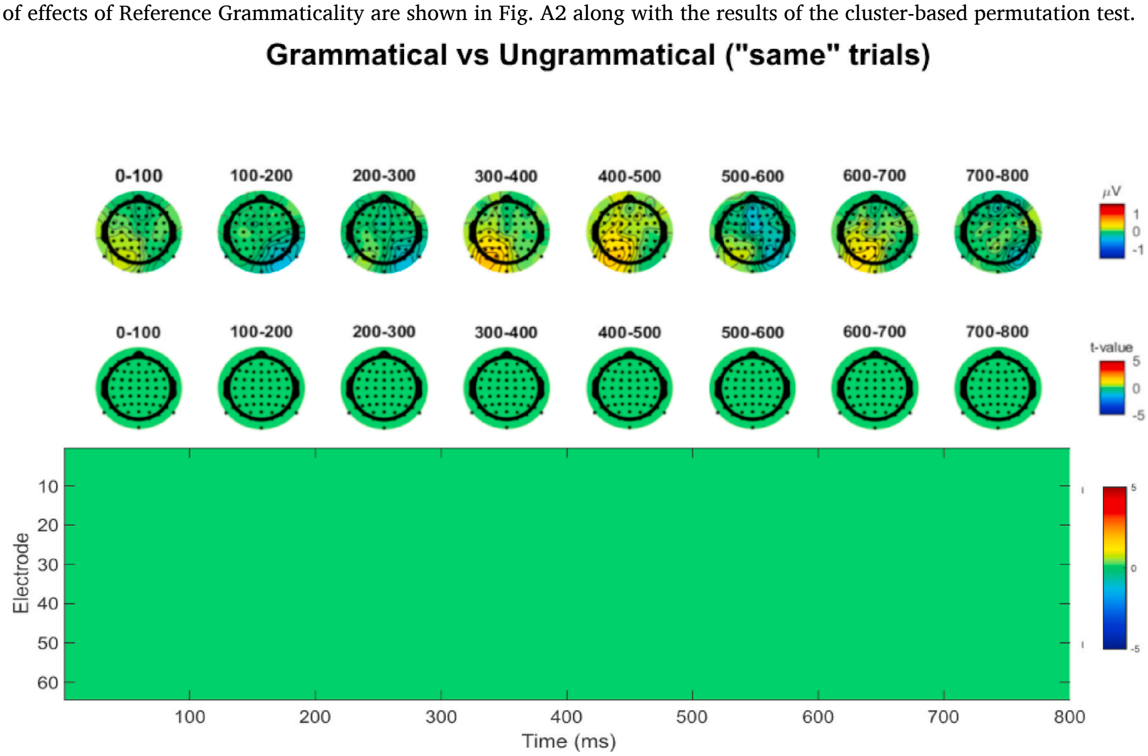

Fig. A2. Top: Scalp maps of grammaticality effects (difference between the grammatical and ungrammatical reference conditions) for 'same' response trials averaged across successive 100 ms time slices. The upper panel shows voltage differences and the lower panel shows the corresponding t-statistics. Bottom: Permutation test results for the contrast between the grammatical and ungrammatical reference conditions.

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