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Dissociating lexical and sublexical contributions to transposed-word effects

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ABSTRACT

When two sequences of words are presented successively for 400 ms each, it is harder to decide that the two sequences differ when the difference is generated by transposing two words compared with a condition where the same two words are replaced by different words. Interestingly, this transposed-word effect is obtained even when the first sequence is ungrammatical. One account of the effect seen with ungrammatical sequences is that participants detect mismatching letters rather than words. Under this account, the migration of letter identities across adjacent words would make it harder to judge the transposed-word condition as being different. The present experiment put this account to test by comparing transposition effects to sequences of words vs. pseudowords. We hypothesized that if same-different judgments are made on the basis of sublexical orthographic information only, then we should observe similar effects for words and pseudowords. Although transposition effects were found with pseudoword stimuli, the effects were significantly reduced compared to word sequences. This suggests that the noisy bottom-up allocation of word identities to locations along a line of text is one key mechanism driving transposed-word effects.

1. Introduction

Recent research has highlighted a new phenomenon in reading research that has potentially important consequences with respect to adjudicating between alternative accounts of skilled reading behavior. This is the transposed-word effect found in a speeded grammatical decision task (Mirault, Snell, & Grainger, 2018; Snell & Grainger, 2019a). Mirault et al. (2018) compared the ease with which participants could judge ungrammatical word sequences as such in two different conditions: one where the ungrammaticality was generated by transposing two words in a grammatically correct sentence (e.g., "The white cat was big" became "The white was cat big"), and the other where the ungrammatical sequences that could not be transformed into a correct sentence by a word transposition (e.g., "The white was cat slowly"). Mirault et al. found that the transposed-word sequences were harder to judge as being ungrammatical. These findings suggest that the adjacent transposed-words provided evidence that these two words were in the grammatically correct order hence making an ungrammatical decision harder.

As argued by Snell and Grainger (2019b), these results are important because they fly in the face of strictly sequential "one-word-at-a-time" accounts of reading, such as the influential EZ-Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998). If words were identified sequentially, then their sequential identification should provide error-free information about word order, and no transposed-word effects should be observed (Reichle, Liversedge, Pollatsek, & Rayner, 2009). The very title of the Reichle et al. (2009) paper – "Encoding multiple words simultaneously in reading is implausible" – nicely summarizes this position (see Snell & Grainger, 2019b, and Schotter & Payne, 2019; White, Boynton, & Yeatman, 2019, and Snell & Grainger, 2019c, for alternative views concerning this debate).

Important evidence against serial models of reading had already been reported in the seminal work of Kennedy and Pynte (2008) who investigated the other side of the coin with respect to transposed-word effects. That is, when readers read correctly ordered text out of order. Kennedy and Pynte reported a significant proportion of out-of-order fixations (i.e., skipping a word and then regressing back to that word) in a corpus analysis, and noted the problems that such numerous out-of-order fixations pose for strictly serial models of reading. They concluded in favor of parallel word processing during reading, a stance that was later adopted in our own theoretical work (Snell, Meeter, & Grainger, 2017; Snell, van Leipsig, Grainger, & Meeter, 2018).

However, another study had investigated transposed-word effects in an arguably more natural reading situation, and came to diametrically opposite conclusions (Rayner, Angele, Schotter, & Bicknell, 2013). Using the boundary technique (Rayner, 1975), Rayner et al. (2013) compared preview effects of two-word previews that could either be a transposition of the normal continuation of the sentence, two unrelated

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Table 1
Examples of the Reference and Target Sequences for the "Different" Response Trials.

Word sequences		
	Examples from the experiment	Examples to illustrate the design
Reference	loin le blanc court chat	far the white cat run
Transposed Word Target	LOIN LE COURT BLANC CHAT	FAR THE CAT WHITE RUN
Replaced Word Target	LOIN LE PASSE JURAI CHAT	FAR THE BLACK DOG RUN
Pseudoword sequences		
Reference	niol el bancl cotur acht	raf eth tehiw tac nur
Transposed Word Target	NIOL EL COTUR BANCL ACHT	RAF ETH TAC TEHIW NUR
Replaced Word Target	NIOL EL SAPSE RAIJU ACHT	RAF ETH CALBK OGD NUR

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

words, or an identical preview. Thus, for example, in the transposed-word preview condition the regular sentence "The neighbor painted the white walls black" would be first presented as "The neighbor painted the walls white black" up to the point where readers' eyes crossed the invisible boundary between "the" and "walls", at which point the regular continuation was restored. Rayner et al. (2013) found increased processing difficulty with transposed-word previews compared with identical previews. The authors concluded in favor of a serial processing account of reading, as exemplified in the EZ Reader model (Reichle et al., 1998), and against parallel processing. We would argue that the combination of a word transposition and a parafoveal preview manipulation in the Rayner et al. study left open the possibility that much of the interference observed in the transposed-word condition was driven by prelexical incompatibilities between the transposed words and their regular replacements.

More recent evidence in favor of a parallel word processing account of transposed-word effects has been obtained in a same-different judgment task in which a first sequence of five words (the reference sequence) is briefly presented and immediately followed by a second sequence of five words (the target sequence) that can either be the same as the reference or a different sequence (Pegado & Grainger, 2019). In that study, the reference could either be a grammatically correct sentence or an ungrammatical scrambled version of the same words. The second sequence could differ from the first either by a transposition of the 2nd and 3rd or 3rd and 4th words in the sequence, or by replacing the same two words with different words in Experiment 1 or replacing only one of the transposed words in Experiment 2. In both experiments "different" judgments were harder to make when the difference involved a word transposition compared with a word replacement.

One key finding of the Pegado and Grainger (2019) study is that transposed-word effects are robust when the reference is an ungrammatical sequence of words. This finding points to a role for a purely bottom-up mechanism in generating transposed-word effects. We hypothesized that such a mechanism involves the noisy association of word identities to spatiotiopic locations along a line of text. That is, evidence that a given word identity is at a given location can also be taken as evidence that the same word identity is at a neighboring location, albeit with a lower likelihood (see Gomez, Ratcliff, & Perea, 2008, for an analogous account of transposed-letter effects). An alternative interpretation, however, is that "different" judgments with ungrammatical references are based on mismatching letter information. The migration of letters in the transposed-word condition would then increase the similarity of the target and reference sequence (see Vandendaele, Snell, & Grainger, 2019, for evidence for letter migration effects in the flanker paradigm). In other words, the transposed-word effect seen in the ungrammatical reference condition would be a sublexical rather than a lexical effect. The present study was designed to test this alternative interpretation by comparing transposition effects with words and pseudowords in the same-different judgment task. If transposed-word effects are driven by sublexical orthographic overlap, then we should observe the same effects with word and pseudoword sequences. On the other hand, greater effects with word sequences compared with pseudoword sequences would be evidence in favor of word-level influences.

2. Methods

2.1. Participants

Twenty-eight participants (22 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 32 years (M = 21.5 years, SD = 2.85), 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).

2.2. Design and stimuli

We used the forty ungrammatical word sequences previously used in the Pegado and Grainger (2019) study. Each of these word sequences was composed of five French words. We also constructed forty new pseudoword sequences. The pseudowords were made by changing the letter order within the original words (see examples in Table 1). Note that the order of pseudoword sequences was the same as used in the word sequences. Each of these word and pseudoword sequences was composed of five word or pseudoword stimuli. These forty word and forty pseudoword sequences formed the set of sequences that were displayed as the first of two sequences on each trial, henceforth called the reference. 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 stimuli at positions 2 and 3 or positions 3 and 4 in the reference were flipped; 3) replacement – the stimuli at positions 2 and 3 or positions 3 and 4 in the reference were replaced with different words. The replacement word had the same length, syntactic function and word frequency (on average) as the words they replaced. The replacement pseudowords was created by scrambling the letter order of the equivalent replacement words. 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, Pallier, Brysbaert, & Ferrand, 2004) was 6.50 on the Zipf scale of van Heuven, Mandera, Keuleers, and Brysbaert (2014)), (range 2.85–7.51 Zipf). The design involved distinct analyses for the "same" response trials and the "different" response trials. The "same" response analysis contrasted word and pseudoword references (Reference Lexical factor). The "different" response analysis involved a 2 (Reference Lexicality) X 2 (Type of Change) design. Table 1 provides examples of the reference and target sequences used in the "different" response conditions in the Experiment (French), and also in English for expository purposes. 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). With 80 trials per condition and 28 participants the number of data points per condition exceeded that recommended by Brysbaert and Stevens (2018).

2.3. Apparatus

Stimuli were presented using OpenSesame (Version 3.0.7; Mathôt, Schreij, & Theeuwes, 2012) and displayed on a 47.5 x 27 cm LCD screen (1024 × 768 pixels resolution). 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. Responses were recorded via a computer keyboard (keys 'j' for the right- and 'f' for the left index fingers).

2.4. 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. 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, while 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 lower and upper case letters, the font size of the reference was slightly 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 for OpenSesame.

The words in each sequence were presented simultaneously for a duration of 400 ms. The target sequence was immediately followed by the reference sequence. 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.

3. Results

Participants presented an overall error rate of 20.7% and a median response time (RT) from target onset restricted to correct responses of 717 ms (trials with RTs +/- 2.5 SD from the mean were excluded prior to statistical analysis). Statistical analysis of error rates and log10 transformed RTs were performed using R software (version 3.5.1), separately for "same" and "different" responses. Linear Mixed Effects (LME) models were used declaring participants and items as crossed random factors. As recommended by Barr and colleagues (Barr, Levy, Scheepers, & Tily, 2013), we included the full complement of random slopes in our models, except in cases where the full model would not converge. Effects were deemed significant for t- and z-values beyond $|1.96|$ (Baayen, 2008). Condition means are shown in Fig. 1.

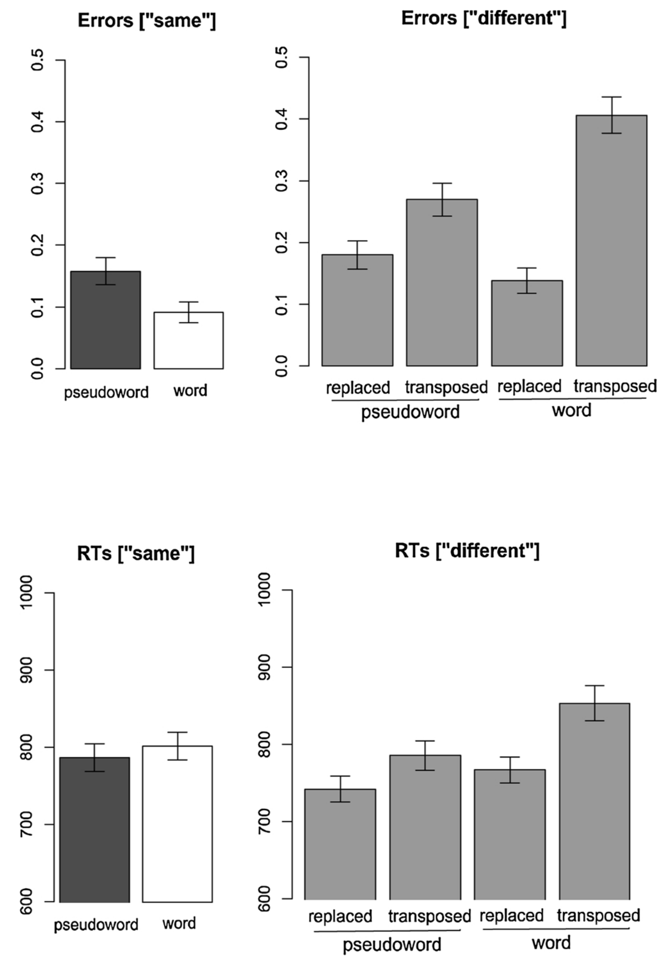

Fig. 1. Error rates in probabilities (upper panel) and response times (RTs) in milliseconds (lower panel), for "same" response trials (left) and "different" response trials (right) as a function of reference lexicality (pseudowords vs. words) and type of change (replaced vs. transposed). Error bars represent 95% confidence intervals.

3.1. "Same" response trials

For trials requiring a "same" response we performed a LME analysis by declaring Reference Lexicality (word vs. pseudoword sequences) as a fixed-effect factor. Fully randomized models were applied both for error rates and RTs, except for the by-items RT analysis which used random intercepts only). The analyses revealed a significant effect of Reference Lexicality ($b = 0.6$, SE = 0.21, $z = 2.89$) indicating that pseudoword sequences (15.8% errors) were more difficult to judge than word sequences (9.1% errors). On the other hand, RTs did not differ significantly across these two conditions (786 ms vs 801 ms; $b = 0.005$, SE = 0.005, $t = 0.86$).

3.2. "Different" response trials

For trials requiring a "different" response a LME analysis was performed by declaring Type of Change (transposition vs. replacement) and Reference Lexicality as fixed-effect factors. Both for error rates and RTs, the models included random intercepts for both factors and random slopes for the by-participant analysis of Reference Lexicality in RTs and for the by-participant analysis of Type of Change in error rates. Error rates revealed no main effect of Reference Lexicality (27.1% for words vs. 22.5% for pseudowords; $b = 0.24$, SE = 0.15, $z = 1.66$), but a significant effect of Type of Change ($b = 0.69$, SE = 0.18, $z = 3.84$). Participants made two-fold more errors when the change involved a transposition (33.8%) compared with a replacement (15.9%). Crucially there was a significant Reference Lexicality x Type of Change interaction ($b = 0.96$, SE = 0.16, $z = 5.95$). Transposition effects (i.e., transposed minus replaced) were much greater for words (26.8%) than pseudowords (9.0%).

The analysis of log-transformed RTs revealed main effects of Type of Change ($b = 0.03$, SE = 0.006, $t = 4.31$), and Reference Lexicality ($b = 0.01$, SE = 0.005, $t = 2.30$) that were qualified by a significant interaction between these factors ($b = 0.03$, SE = 0.008, $t = 3.51$). Participants took longer to respond correctly on transposed trials (816 ms) than replacement trials (755 ms). They also took more time to answer trials with word sequences (802 ms) than pseudoword sequences (762 ms). Importantly, as with error rates, the transposition effect was again stronger for words (86 ms) than pseudowords (44 ms).

4. Discussion

The present study used the same-different matching task to further investigate the nature of bottom-up contributions to transposed-word effects seen in prior work using this paradigm (Pegado & Grainger, 2019) and the grammatical decision task (Mirault et al., 2018; Snell & Grainger, 2019a). Notably, Pegado and Grainger (2019) found transposed-word effects in conditions that arguably minimized the role of top-down syntactic constraints. They did so by not only using the same-different judgment task but also by including a condition with ungrammatical reference sequences. The use of ungrammatical sequences should greatly impede the construction of any kind of syntactic representation, hence minimizing any top-down influence from the sentence-level. The transposed-word effects found with ungrammatical references were taken as clear support for one specific mechanism thought to be driving transposed-word effects in general: the noisy bottom-up association of word identities to spatiotopic locations along a line of text (Snell & Grainger, 2019a; Mirault et al., 2018). However, the effects reported in the Pegado and Grainger (2019) study could have been driven by sublexical rather lexical mismatches impacting on "different" responses. That is, it could have been the greater letter-level overlap at nearby positions between the reference and the transposed-word targets that made "different" decisions harder in that condition.

The present study put that alternative explanation to test by further examining transposed-word effects in a same-different judgment task with ungrammatical references. The ungrammatical word sequences were used to generate an equivalent number of pseudoword sequences formed of the same letters. We reasoned that if transposed-word effects were driven by sublexical orthographic overlap, then we should observe the same effects with word and pseudoword sequences. On the other hand, greater effects with word sequences compared with pseudoword sequences would be evidence in favor of word-level influences. The results were clear-cut. We found greater transposed-word effects with word sequences, in both RTs and error rates (see Fig. 1).

Under the assumption that the same-different judgment task combined with ungrammatical word sequences minimizes any contribution of top-down syntactic constraints, the main conclusion of the present work is that bottom-up word identification processes are one key component of transposed-word effects. More precisely, the parallel identification of the two transposed words and the noisy association of these word identities to specific locations in the word sequence would lead participants to perceive the two transposed words in the opposite locations, hence matching the reference sequence. Our prior research also pinpointed a contribution of top-down sentence-level constraints by showing that, in certain conditions, transposed-word effects are greater with grammatically correct references compared with ungrammatical word sequences (Pegado & Grainger, 2019). This overall pattern therefore fits with the general framework of parallel processing accounts of reading, such as the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005) and OB1-reader (Snell et al., 2018). Our results are also in line with the conclusions drawn on the basis of the transposed-word effects seen in the grammatical decision task (Mirault et al., 2018; Snell & Grainger, 2019a).

Serial models such as EZ-Reader (Reichle et al., 1998) could nevertheless account for the transposed-word effects reported by Mirault et al. (2018) by assuming that the two words were in fact read out of order on some occasions. That is, participants would actually be skipping the first word so as to fixate the word on the right before regressing back to the word on the left, and therefore be reading the transposed words in their grammatically correct order. This alternative interpretation was tested and rejected in the recent work of Mirault, Guerre-Genton, Dufau, and Grainger (2019). Using the same stimuli and task as Mirault et al. (2018) and recording eye-movements, Mirault et al. indeed found that the transposed-words were sometimes read out of order, but this occurred to the same extent in the control condition, and crucially, transposed-word effects were highly robust when the out-of-order trials were removed prior to analysis. Could right-to-left eye movements account for the transposition effects found in the present study? Given the timing of events in the present work, plus the central fixation point, it is possible that two fixations were made on target sequences, and these could have been from right-to-left. However, this should have been equally likely for the word and the pseudoword sequences, and therefore cannot explain the greater transposition effects seen with words, the key finding of the present work.

In sum, using the same-different judgment task and ungrammatical word sequences as reference, we have provided further evidence for the role of noisy bottom-up association of word identities to locations in a line of text as one factor contributing to transposed-word effects in sentence reading. The key finding was that transposition effects were greater for word sequences compared with pseudoword sequences composed of the same letters. This suggests that words, and not just letters, can be processed in parallel and tentatively assigned to spatiotopic locations. It is this fast parallel processing of word identities that is thought to enable the rapid computation of syntactic structures as revealed in related work from our group.

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Open practice statement

The data and materials of the experiment are available at https://osf.io/b6ejq/?view_only=b46ff24d8a9242e7b98cc42f1ba5fce6

Declaration of Competing Interest

None.

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