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You That Read Wrong Again! A Transposed-Word Effect in Grammaticality Judgments

Jonathan Mirault, Joshua Snell, and Jonathan Grainger
Laboratoire de Psychologie Cognitive, Centre National de la Recherche Scientifique,
Aix-Marseille University

Abstract

We report a novel transposed-word effect in speeded grammaticality judgments made about five-word sequences. The critical ungrammatical test sequences were formed by transposing two adjacent words from either a grammatical base sequence (e.g., "The white cat was big" became "The white was cat big") or an ungrammatical base sequence (e.g., "The white cat was slowly" became "The white was cat slowly"). These were intermixed with an equal number of correct sentences for the purpose of the grammaticality judgment task. In a laboratory experiment (N = 57) and an online experiment (N = 94), we found that ungrammatical decisions were harder to make when the ungrammatical sequence originated from a grammatically correct base sequence. This provides the first demonstration that the encoding of word order retains a certain amount of uncertainty. We further argue that the novel transposed-word effect reflects parallel processing of words during written sentence comprehension combined with top-down constraints from sentence-level structures.

Keywords

transposed words, grammaticality judgments, sentence comprehension, parallel word processing, reading, open data, open materials

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It is a well-established finding that lexical decisions about pseudowords formed by transposing two letters in real words (e.g., "gadren" from *garden*) are harder to make than decisions about pseudowords formed by replacing two letters in the same word (e.g., "gatsen"; Andrews, 1996; Chambers, 1979; Frankish & Turner, 2007; O'Connor & Forster, 1981). This transposed-letter effect was one of the driving forces behind recent theoretical advances concerning the mechanisms used by skilled readers to encode for letter-position information. The main conclusion from this research is that the encoding of letter-position information is endowed with a certain degree of positional uncertainty (e.g., Gomez, Ratcliff, & Perea, 2008) and flexibility (e.g., Davis, 2010; Grainger & van Heuven, 2003; Whitney, 2001).

Here, we investigated whether a similar positional uncertainty or flexibility might characterize the manner in which the order of words in a sentence is encoded. In the same way that letter-order information is essential for identifying words, in most languages, word-order information is essential for constructing an accurate sentence-level representation via assignment of the appropriate roles to the different words in the sentence. How might word-order information be encoded by skilled readers? According to standard accounts of written sentence processing (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998), word identities are processed one at a time, sequentially, from the beginning to the end of the sentence. Information about word order is therefore provided by the relative timing of word identification, just like in spoken-language comprehension. This strictly sequential retrieval of word identities and the accompanying syntactic and semantic information fit well with

Corresponding Author:
Jonathan Mirault, Laboratoire de Psychologie Cognitive, Aix-Marseille University, 3 Place Victor Hugo, 13331, Marseille, France
E-mail: jonathan.mirault@etu.univ-amu.fr

the classic incremental-parsing theories of syntactic analysis during sentence processing (Frazier & Fodor, 1978; Frazier & Rayner, 1982; for a review of early studies, see Frazier, 1987) and account for one of the principle phenomena of the field: garden path effects (e.g., Mitchell & Holmes, 1985; Osterhout, Holcomb, & Swinney, 1994).

The classic approach to syntactic analysis during written-sentence comprehension builds on the underlying principle that the input to syntactic parsing mechanisms is an error-free sequence of words (Gibson, Bergen, & Piantadosi, 2013). However, this general approach has been contested by several authors by pointing to the evidence for underspecified syntactic representations (Sanford & Sturt, 2002) or noisy input to the syntactic parser (Bergen, Levy, & Gibson, 2012; Gibson et al., 2013; Levy, 2008), both of which provide support for what has been referred to as "good-enough" representations for language comprehension (Ferreira, Bailey, & Ferraro, 2002; Ferreira & Lowder, 2016).[1] Prior research has notably reported evidence that readers maintain uncertainty about the identities of previously read words during sentence comprehension (Levy, Bicknell, Slattery, & Rayner, 2009). The present study specifically seeks evidence for noisy encoding of word order during written-sentence processing and, thus, provides a test of Levy et al.'s (2009) prediction that uncertainty should operate not only with respect to word identities but also with respect to word positions.

Our own recent work has led us to question the viability of a strictly sequential one-word-at-a-time approach to word identification during reading. In the general vein of processing gradient models of eye movements and reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Reilly & Radach, 2006), we have suggested that several word identities might be processed in parallel. Such parallel processing of word identities during sentence reading then raises the question as to how readers keep track of word order. In recent work (Grainger, 2018; Snell, Declerck, & Grainger, 2018; Snell & Grainger, 2017; Snell, Meeter, & Grainger, 2017), we have proposed that readers keep track of the positions of words by associating word identities with spatiotopic coordinates in short-term memory. Spatiotopic coordinates provide a reference frame for representing the location of an object in a visual scene independently of where the viewer's eyes are looking at the scene. During reading, the spatiotopic coordinates for written words represent a word's location in a line of text, independently of the position of the reader's gaze on that line of text. It is these spatiotopic word representations that provide information about word identity and word order to higher-level sentence-comprehension processes. They provide a short-term memory representation of the spatiotopic location of several word identities that is updated as new words join this short-term store and old words drop out.

The hypothesized parallel processing of word identities during sentence reading opens up the possibility that word identities might not be as strongly tied to a strictly sequential word order as previously thought. Considering that the parallel processing of letter identities is associated with noisy and/or flexible letter-position encoding, we hypothesized that the parallel processing of word identities is associated with a certain degree of positional uncertainty or noise such that evidence that a given word is at one spatiotopic location is also taken as evidence that the same word is at a neighboring location.

To provide an appropriate test of this hypothesis, we aimed to provide as close an analogy as possible, at the sentence level, to the transposed-letter effect seen with pseudoword targets in the lexical decision task. We opted for a grammaticality judgment task because grammaticality judgments for word sequences are somewhat analogous to lexical decisions for letter strings. Both tasks arguably reflect judgments of well formedness or acceptability. Given that the illegal word sequences in the current experiments all contained syntactic violations, we refer to this as a *grammaticality judgment*.

The critical comparison in the present study is between two types of ungrammatical test sequence: one formed by transposing two words in a grammatical base sequence (i.e., a well-formed sentence) and the other formed by transposing two words in an ungrammatical base sequence. For the latter type of ungrammatical test sequence, we made sure that transposing any two words in the sequence would not generate a correct sentence. A key feature of the design of the present experiment is that across all trials, the same set of words appeared in both types of ungrammatical test sequence. In this way, any observed difference between these conditions could be assigned to sentence-level processing and not to the characteristics of individual words or local differences in grammaticality (i.e., some words or word combinations appearing more grammatical than others). If we were to find that grammaticality judgments are harder to make when the ungrammatical test sequence is formed by transposing two words of a grammatically correct sentence (we refer to this as the *transposed-word* condition), this would imply that the incorrect order of the transposed words has gone unnoticed, hence providing evidence that a grammatically correct sentence is present. We tested the same set of stimuli in a laboratory experiment and an online experiment.

Laboratory Experiment

Method

Participants. Fifty-eight participants (14 men) were recruited at Aix-Marseille University (Marseille, France). All participants were native French speakers and received monetary compensation (€10/hr) or course credit. They reported having normal or corrected-to-normal vision, ranged in age from 18 to 30 years (M = 22.2 years, SD = 2.9), 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), and this research was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

Design and stimuli. We selected pairs of grammatically correct sentences[2] that were then used to generate the corresponding ungrammatical word sequences formed of the same words. First, we constructed pairs of five-word sentences that contained two words (e.g., "was big," "ran slowly"), such that recombining the two words while respecting word order led to ungrammatical sequences (e.g., "was slowly," "ran big"). This led to a set of four base sequences (i.e., a sequence of five words), two of which were grammatical and two ungrammatical (see Table 1). Using these four base sequences, we then created transposed-word versions of each sequence by transposing the words at Positions 3 and 4. The transpositions involved words from different grammatical categories, and 21% (17 of 80) of the transpositions involved a function word. We then constructed four different ungrammatical test sequences, two of which were derived from a grammatical base sequence and two from an ungrammatical base sequence. This structure of quadruplets of base sequences and the corresponding test sequences allowed us to test the same words in the grammatical and ungrammatical base-sequence conditions. For simplicity, we refer to the grammatical base-sequence condition as the transposed-word condition, and the ungrammatical base-sequence condition as the control condition, which represent the two levels of base-sequence grammaticality. This experimental design notably allowed us to control for the position in which the sequence becomes ungrammatical, as well as the nature of the grammatical violation in the transposed-word and control conditions.

Following the above constraints, we constructed 160 ungrammatical test sequences, each containing five words. These ungrammatical test sequences were constructed from 80 grammatically correct base sequences (i.e., syntactically correct sentences in French) and 80 ungrammatical base sequences (see Table 1). The words in all of these sequences were 1 to 11 letters long with an average length of 4.95 letters and an average frequency of 3,575 occurrences per million (New, Pallier, Brysbaert, & Ferrand, 2004), which is equivalent to 6.55 Zipf (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). Grammaticality of the base sequence was the only manipulation, giving rise to the two types of ungrammatical test sequence: transposed word (derived from a grammatically correct base sequence) and control (derived from an ungrammatical base sequence). For the purposes of the grammaticality judgment task, the experiment included an equal number of grammatically correct sentences. These were constructed to have the same grammatical structures as the grammatically correct base sequences. To avoid repetition of sequences containing the same words (e.g., "Ton petit avait chat faim," "Ton

Table 1. Construction of the Critical Ungrammatical Test Sequences Using French Examples Taken From the Experiments and Providing English Examples for Convenience

Sequence	Example from the experiments (French)	Example used to illustrate the design (English)
Base		
Grammatical	Ton petit chat avait faim.	The white cat was big.
	Cette grande tasse est cassée.	The black dog ran slowly.
Ungrammatical	Ton petit chat avait cassée.	The white cat was slowly.
	Cette grande tasse est faim.	The black dog ran big.
Test		
Transposed word	Ton petit avait <u>chat</u> faim.	The white was cat big.
	Cette grande est <u>tasse</u> cassée.	The black ran dog slowly.
Control	Ton petit avait <u>chat</u> cassée.	The white was cat slowly.
	Cette grande est <u>tasse</u> faim.	The black ran dog big.

Note: Examples illustrating how the critical ungrammatical test sequences used in the experiments (French) were constructed from quadruplets of base sequences of five words that could form a correct sentence (grammatical) or not (ungrammatical). The point at which the sequence becomes ungrammatical is indicated by an underscore (not present in the experiments). This was either the third or the fourth word in the sequence and was the same in the transposed-word and control conditions. The English examples used in the main text are provided for convenience. They are not translations of the French examples.

petit avait chat cassée"), a Latin-square design was used in which each participant saw only one half of each type of test sequence: 40 in the transposed-word condition and 40 in the control condition.[3] Each participant also saw 80 grammatically correct sentences that were not related in any way to the base sequences used to generate the ungrammatical test sequences. These were randomly intermixed with the ungrammatical test sequences, and the 160 experimental trials were presented in a different random order for each participant and preceded by 10 practice trials that mimicked the structure of the experimental trials.

Apparatus. Stimuli were presented using OpenSesame (Version 3.1.2; Mathôt, Schreij, & Theeuwes, 2012) and displayed on a 24-in. LCD screen. Sentences were presented in 30-point monospaced font (droid sans mono) in white (72.3 cd/m^2) on a gray background (63.6 cd/m^2). Participants were seated about 60 cm from the monitor, such that every 2.5 characters (1 cm) equaled approximately 1° of visual angle. Responses were recorded via a game pad connected to the computer. Participants responded using their index fingers with two buttons on the game pad: one on the right for grammatical decisions and one on the left for ungrammatical decisions.

Procedure. Placed in a quiet testing room, participants received instructions both from the experimenter and on screen. Participants were instructed to decide as rapidly and as accurately as possible whether the sequence of words was grammatically correct. On each trial, a fixation cross was displayed on the center of the screen during a random time ranging between 500 and 700 ms, followed by the stimulus (a five-word sequence) centered on the screen. The distance between the central fixation cross and the first letter of the sequence varied between 8° and 18° of visual angle as a function of the length of the five-word sequence. The word sequence remained on screen until response. After this, a feedback dot was presented for 700 ms, in green if the response was correct or in red if the response was incorrect.

Results

We analyzed response time (RT; the time between onset of stimulus presentation and participant's response) for correct responses and response accuracy. Statistical analyses were performed only on the data concerning the ungrammatical sequences. We excluded 1 participant because of overall low accuracy (47.5%). All the other participants performed with average accuracy greater than 76% (M = 90.21%, SD = 5.83). RTs beyond 2.5 standard deviations from the grand mean were removed before analysis (2.35%), leaving a total of 3,970 data points. The mean RT and error rate for each condition are shown in Figure 1.

We used a linear mixed-effects (LME) model to analyze RTs and a generalized (logistic) linear mixed-effects (GLME) model to analyze response accuracy, with participants and items as crossed random effects (Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013). The models were fitted with lmer (for LME) and glmer (for GLME) functions from the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015) in the R statistical computing environment (Version 3.3.1; R Core Team, 2016). We report unstandardized regression coefficients, standard errors (SEs), and t values (for LMEs) or z values (for GLMEs). Fixed effects were deemed reliable if $|t|$ or $|z|$ was greater than 1.96 (Baayen, 2008). We used the control condition as the reference. RTs were inverse-transformed (−1,000/RT) prior to analysis to normalize the distribution. We used the maximal random structure model that converged (Barr et al., 2013), and this included by-participant and by-item random intercepts in all analyses that we report.

Perfectly in line with our hypothesis, results showed that participants were slower at classifying transposed-word sequences as being ungrammatical compared with the control sequences, b = 0.02, SE = 0.00, t = 5.60, and they also made more errors in the transposed-word condition than in the control condition, b = 1.86, SE = 0.13, z = 14.11.[4]

Online Experiment

Method

Participants. Ninety-four participants (62 women) between the ages of 18 and 75 years (M = 38.27 years, SD = 17.12) volunteered for the online experiment by responding to an announcement relayed by the French Information Network for Cognitive Sciences. The experiment was made available for 1 week, and all participants who completed the experiment in that week were retained for analysis. They all reported being native speakers of French and were asked to read and accept the conditions of the experiment before starting. The LME and GLME analyses performed with age as a continuous covariable revealed a significant effect of this factor for RTs, b = 0.00, SE = 0.00, t = 3.54, but not for error rates, b = 0.00, SE = 0.00, z = 1.17. More important, these analyses revealed no significant interactions with transposition effects—RT: b = 0.00, SE = 0.00, t = 0.75; ER: b = 0.00, SE = 0.00, z = 0.32. We therefore decided to retain all participants for analysis.

Design, stimuli, and procedure. These were the same as for the laboratory experiment except for the following

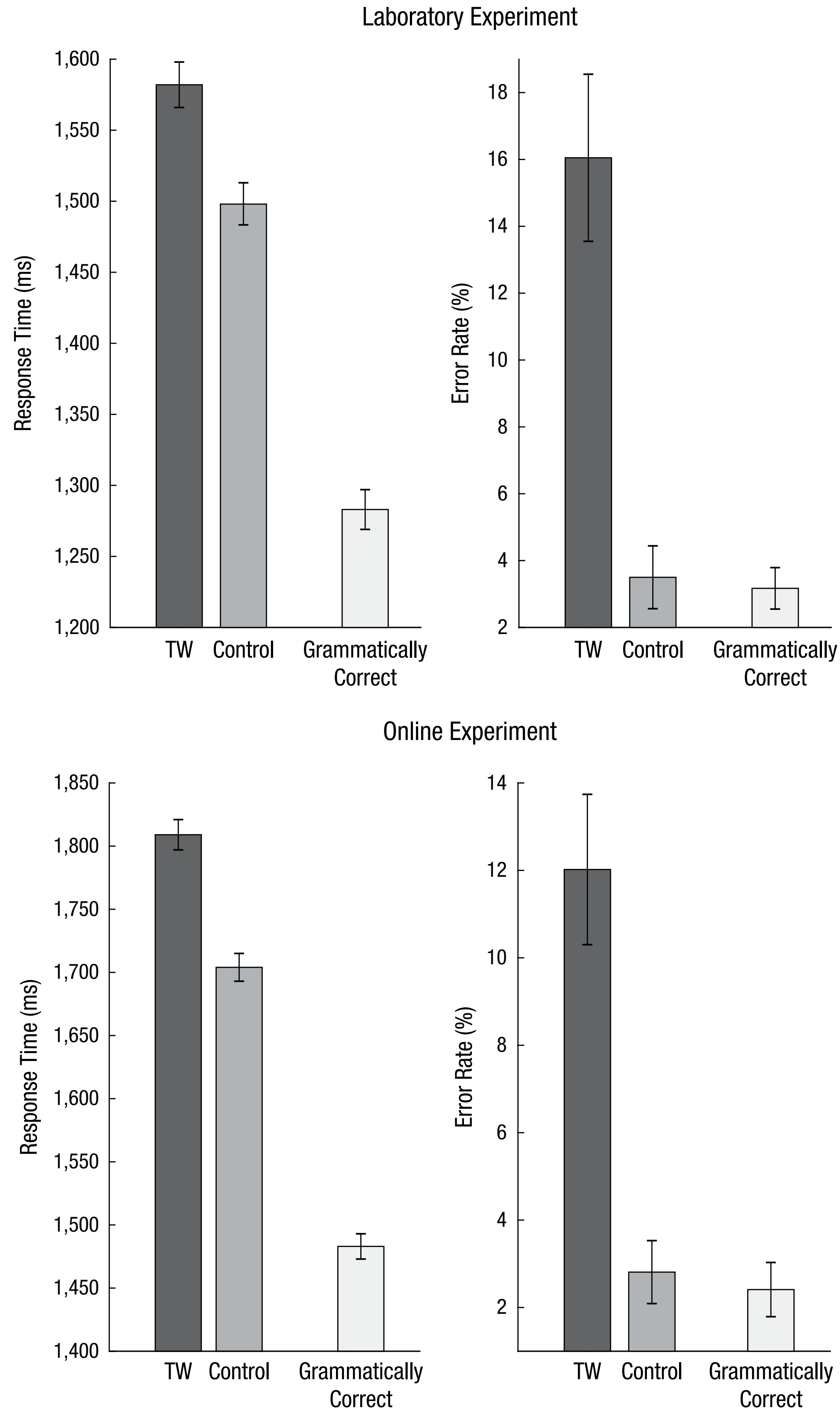

Fig. 1. Mean response time (left) and error rate (right) for the transposed-word (TW) and control ungrammatical sequences in the laboratory experiment (top) and the online experiment (bottom). Means for the grammatically correct sentences are given for comparison. Error bars show within-participants 95% confidence intervals.

procedural differences. Stimuli were presented online using Java protocol on the personal computer of the participant. Sentences were presented in 30-point monospaced font (droid sans mono) in black on a white background. Participants were asked to sit about 60 cm from the monitor, such that 1 cm equaled approximately 1° of visual angle. Participants responded using their index fingers with two arrows on the computer keyboard: right for grammatical decisions and left for ungrammatical decisions.

Results

Data were analyzed in the same way as for the laboratory experiment. Mean RT and error rate per condition are shown in Figure 1. Participants were significantly slower at classifying transposed-word sequences as being ungrammatical compared with the control sequences, $b = 0.03$, $SE = 0.00$, $t = 8.57$, and they made significantly more errors in the transposed-word condition than in the control condition, $b = 1.77$, $SE = 0.11$, $z = 15.30$.

General Discussion

In the present study, participants had to decide as rapidly and as accurately as possible whether a sequence of five words, presented simultaneously and centered on fixation, formed a grammatically correct sentence. The key results concerned the ungrammatical sequences, which could be formed by transposing two words in either a grammatically correct sentence (the transposed-word condition) or an ungrammatical sequence (the control condition). We found that it was more difficult for participants to classify the transposed-word sequences as being ungrammatical.

To our knowledge, this is the first demonstration of a transposed-word effect in grammaticality judgments, mimicking the well-established transposed-letter effect in lexical decisions. Crucially, this effect was established while controlling for potential local differences in perceived grammaticality (see Table 1). We interpret this novel transposed-word effect as reflecting parallel processing of word identities. Parallel processing of word identities enables the rapid construction of a tentative syntactic frame for the sentence under construction (Greenberg, Healy, Koriat, & Kreiner, 2004; Koriat & Greenberg, 1994; Snell & Grainger, 2017; Snell et al., 2017; Snell, van Leipsig, Grainger, & Meeter, 2018). The syntactic frame then constrains the range of possible word identities at each position in the frame. We argue that it is the combination of such top-down constraints and the noisy bottom-up processing of word identities and word order that pushes the sentence-level processor to interpret a sequence such as "You that read wrong again" as "You read that wrong again."

The present findings converge nicely with the recent report of a sentence-superiority effect (Snell & Grainger, 2017). In that study, sequences of four words were briefly presented simultaneously, centered on fixation, and followed by a backward mask and postcue to indicate which of the words was to be reported (postcued partial report). The sequence of words could form either a correct sentence (e.g., "the man was tall") or an ungrammatical scrambled version of the same set of words (e.g., "was man the tall"), and the same word at the same position (e.g., *man* at Position 2) was cued for identification. Partial report accuracy was found to be greater in the correct-sentence condition than in the ungrammatical condition, and this sentence-superiority effect was found at all four positions. Snell and Grainger (2017) interpreted their findings as evidence in favor of the rapid processing of several word identities in parallel, with cascaded transmission of information from the word to the sentence level, enabling construction of sentence-level structures that in turn facilitate ongoing word identification via feedback (for further evidence of parallel word processing using a flanker paradigm, see Snell et al., 2017, and Snell, Declerck, & Grainger, 2018).

Crucially, the present study provides evidence for parallel processing of word identities in conditions in which participants had to read whole sentences rather than respond to single-word targets. The present findings therefore strongly suggest that parallel word processing is a key component of everyday reading. This principle has already been integrated in two prominent accounts of eye movements and reading (Engbert et al., 2005; Reilly & Radach, 2006; for a recent computational model of parallel orthographic processing and eye movement control, see Snell, van Leipsig, Grainger, & Meeter, 2018) and has been extended to include parallel processing of word identities and the subsequent retrieval of syntactic and semantic information in recent accounts of word recognition and sentence reading (Grainger, 2018; Snell et al., 2017).

Future research could more fully explore the factors that might modulate transposed-word effects. Post hoc analyses of the present results (see Note 4) revealed an influence of one potentially interesting variable: word class (open-class/content words vs. closed-class/function words). We found that transposition effects were greater when the transposition involved at least one function word. However, given the post hoc nature of these analyses and the unbalanced distribution of the two classes of word in this study, this pattern requires confirmation. Nevertheless, it is in line with theories of text comprehension, according to which the role of function words is to rapidly generate a syntactic frame. In Koriat and Greenberg's (1994) structural account of reading, this syntactic frame is then used to correctly position content words as sentence-comprehension processes unfold, while the function words themselves recede into the background. This account correctly predicts less accurate memory for position for function words compared with content words. Finally, languages differ with respect to how word order determines syntax, and we predict that the size of transposed-word effects in grammaticality judgments should depend on this.

In conclusion, the novel transposed-word effect reported in the present work points to a noisy encoding of word-order information during sentence reading. Further investigations of this phenomenon should help elucidate the mechanisms used to represent word order during written-sentence comprehension and provide a further test of recent accounts of sentence reading, according to which multiple word identities can be associated with different spatiotopic locations in parallel under the constraints imposed by sentence-level structures.

Action Editor

Rebecca Treiman served as action editor for this article.

Author Contributions

J. Mirault prepared the experiments, analyzed the data, and participated in the design of the experiments and writing of the manuscript. J. Snell participated in the design of the experiments and the writing of the manuscript. J. Grainger participated in the design of the experiments and wrote the first draft of the manuscript. All the authors approved the final manuscript for submission.

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Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Supplemental Material

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Open Practices

All data and materials have been made publicly available via the Open Science Framework and can be accessed at osf.io/mvz3r/. The design and analysis plans were not preregistered. The complete Open Practices Disclosure for this article can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797618806296. This article has received the badges for Open Data and Open Materials. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

Notes

1. It is interesting to note the parallel between the concept of good-enough representation of word-in-sentence order and Grainger and Ziegler's (2011) coarse-grained representation of letter-in-word order.
2. Some of the grammatically correct sequences were noun phrases and not complete sentences, but we refer to these stimuli as sentences for simplicity.
3. We thus ended up collecting 2,320 measurements per ungrammatical condition, meeting the criterion of Brysbaert and Stevens (2018) stating that 1,600 measurements per condition are necessary for sufficient statistical power. We estimated that 2 weeks would be enough to collect this amount of data, and we retained for analysis all the participants who were tested in that period.
4. In response to a reviewer's request, we examined whether the transposition effects were influenced by word class (closed vs. open) or word length (number of letters). In these post hoc analyses (for details, see Table S1 in the Supplemental Material available online), word class was determined as closed if at least one of the two critical words was closed class, and word length was the average length of the two words involved in the transposition. Transposition effects were found to be greater, in both RTs and error rates, for the closed-class words and the short words. Crucially, however, the transposition effects remained significant for open-class words and for long words. The same pattern was found in the laboratory and online experiments.

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