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Transposed-word effects in the auditory modality also occur with a slow speech rate

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## **Abstract**

In the present study, we investigated transposed-word (TW) effects in the grammatical decision task with auditory stimuli presented at a slow speech rate. We hypothesized that slowing the rate of presentation of speech stimuli should diminish TW effects under the assumption that the encoding of word-order information should be more precise in these conditions. Evidence that this might indeed be the case had already been seen in the visual modality with the serial presentation of word sequences yielding less pronounced TW effects. In these visual studies the effects were mainly significant in error rates and not in response times (RTs) possibly because serial presentation enhances the precision of word-order encoding. Here, we observed significant TW effects in both RTs and error rates. The present results therefore demonstrate that a slower speech rate does not eliminate TW effects in RTs. These results therefore contradict the hypothesis that a slower speech rate might enhance word-order encoding and further suggest that it is not the serial presentation of stimuli per se that is the only reason for why TW effects are typically not found in RTs in studies that have used serial presentation procedures in the visual modality.

**Key words:** Transposed-word effects; Auditory grammatical decision; Slow speech rate

## **Introduction**

A growing body of studies in reading research conducted in various languages (e.g., Huang & Staub, 2021; Liu et al., 2020; 2022; Milledge et al., 2023; Mirault et al., 2018; Snell and Melo, 2024) has shown that ungrammatical sequences created by transposing two words in a correct sentence (e.g., “the white was cat big” from “the white cat was big”) are harder to reject as being ungrammatical sequences compared with control ungrammatical sequences that cannot be resolved into a correct sentence by transposing any two words (e.g., the white was cat slowly). This so-called transposed-word (TW) effect argues in favor of some flexibility in the coding of word-order during sentence processing leading participants to infer that the TW sequence is in fact grammatically correct, which then results in slower and less accurate ungrammatical decisions for the TW sequences compared to their controls.

Two main accounts of such TW effects have been proposed (see Huang & Staub, 2021; Liu et al., 2020; Snell & Grainger, 2019a; Snell & Grainger, 2019b; Snell & Melo, 2024). The first incorporates the notion of noise in the processing of word-order information such that a given word in a sentence would not be strictly associated to a single position, but would also be associated, with a lower likelihood, to neighboring positions (see Gomez et al., 2008, for a similar account of transposed-letter effects). That is, evidence for a word at a given position can be taken as evidence for that word at neighboring positions, thus explaining the difficulty that participants have in noticing word transpositions. This bottom-up account of TW effects implies that there is a certain amount of parallel word processing, just like the parallel letter processing required for noisy position coding accounts of transposed-letter effects. The second account involves sentence-level representations, with syntactic and semantic constraints supervising the encoding of word-order information. These

sentence-level constraints would rectify word order during the processing of ungrammatical sequences hence encouraging readers to interpret such sequences as being grammatically correct. Such constraints could either operate via top-down feedback from the sentence-level to on-going word identification (e.g., Snell & Grainger, 2019a) or via post-lexical integration/inference processes (e.g., Hossain & White, 2023; Huang & Staub, 2021; Gibson et al., 2013). According to this second account of TW effects, it is the reordering of words imposed by sentence-level constraints that increases the likelihood that ungrammatical sequences formed by transposing words are misperceived as being grammatically correct. Of course, both accounts (mechanisms) could contribute to TW effects. The critical issue is therefore the relative weight assigned to these two mechanisms during regular sentence reading (see e.g., Snell & Grainger, 2019b).

To better understand the relative contribution of bottom-up and top-down mechanisms to TW effects, several studies conducted in the visual modality (Hossain & White, 2023; Huang & Staub, 2023; Liu et al., 2022; Milledge et al., 2023; Mirault et al., 2022; Snell & Melo, 2024; Spinelli et al., 2024) presented words serially, one after the other (the Rapid Serial Visual Presentation procedure – RSVP). The logic behind using this serial presentation is that when written words are presented one after the other, this should reduce bottom-up uncertainty about word order, and if a TW effect emerges under this mode of presentation, it would mainly reflect the impact of sentence-level constraints on word-order encoding. However, no clear answer has emerged from these studies. Some studies have reported a robust TW effect in RTs and error rates (Hossain & White, 2023; Milledge et al., 2023; Spinelli et al., 2024), while others have found an effect only in error rates (Huang & Staub, 2023; Liu et al., 2022; Mirault et al., 2022), and one study failed to find an effect in RTs and error rates (Snell & Melo, 2024; see Wen & Grainger, 2025, for a summary of these studies

and a meta-analysis). What is clear however from the recent meta-analysis of Wen and Grainger (2025) is that TW effects are smaller and less robust when words are presented serially than when they are presented simultaneously and aligned as in regular text. In particular, the effects systematically emerged in both RTs and error rates under parallel presentation, but generally only in error rates under serial presentation.

To sum-up, TW effects in reading appear to be less robust when uncertainty about word order is reduced. This finding could be used to argue in favor of a predominant role of bottom-up mechanisms in driving TW effects. However, results from the auditory modality challenge this conclusion. Dufour et al. (2022) tested spoken sentences in which words are presented naturally the one after the other, and they reported a robust TW effect on both RTs and error rates. Such a result suggests, in contrast to reading studies, that top-down sentence-level constraints alone may be sufficient to generate robust TW effects in the auditory modality. The present study aims to clarify the respective contributions of bottom-up and top-down mechanisms in auditory sentence processing. This is an important endeavor since it remains possible that subtle forms of bottom-up word-order uncertainty are at work even in the auditory modality and have contributed to the TW effect observed in Dufour et al. (2022). If so, slowing down speech — and thereby providing even clearer information about word-order — should reduce or eliminate the TW effect. We thus asked whether the TW effect found in the auditory modality would also be observed with a slow speech rate, and thus in conditions where bottom-up positional uncertainty is reduced compared with typical speech rates. Note that in Dufour et al. (2022), the sentences were recorded at a speech rate of 4.98 syllables per second which corresponds to a normal/classic speech rate (typically between 4.2 to 6.1 syllables per second: see Radeau et al., 2000; Gaskell & Dumay, 2003). In the present

study, the sentences were recorded at a speech rate of 2.53 syllables per second, which corresponds to a speech rate two times slower than in the Dufour et al.'s (2022) study<sup>1</sup>.

Our reasoning was as follows. If TW effects remain robust at a slower speech rate, this would provide strong evidence that the effect in the auditory modality is mainly driven by sentence-level constraints. In contrast, If TW effects decrease with a slower speech rate, this would indicate that bottom-up word-order uncertainty also contributes to TW effects observed in the auditory modality.

## **Methods**

Participants: 100 participants were recruited on-line for the experiment. The number of participants corresponded to the number tested in the on-line study of Dufour et al. (2022) in which a clear TW effect on both RTs and error rates was found in the auditory modality. They reported to be native speakers of French and their reported age was between 20 and 64 years. 47 reported female gender, and 53 male. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

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<sup>1</sup> Examining the impact of speaking rate on the Uniqueness Point (UP) effect during spoken word recognition, Radeau et al. (2000) reported a greater UP effect at a slow speech rate of 2.2 syllables per second than at a more classic speech rate of 3.6 syllables per second. Hence, the slow speech rate used in our study was roughly equivalent to that used in the study of Radeau et al. (2000: 2.5 vs. 2.2 syllables per second). It should also be noted that Radeau et al. found an impact of speech rate with a slowdown of 1.4 syllables per second, and that in our study the slowdown in respect to Dufour et al.'s (2022) study was 2.45 syllables per second. Thus, in comparison to Radeau et al.'s (2000) study, we aimed to maximize the possibility of finding an effect of speech rate on auditory TW effects.

Materials: The same sequence of words and the same experimental lists as in Dufour et al. (2022) were used. In particular, the materials consisted in 40 pairs of grammatically correct sentences composed of five words (e.g., ton petit chat avait faim (your little cat was hungry); cette grande tasse est belle (this big cup is beautiful) from which the critical ungrammatical TW and control sequences were derived. The TWs sequences were created by simply transposing the third and fourth words in the correct sentences (e.g., ton petit **avait chat** faim; cette grande **est tasse** belle). Matched ungrammatical control sequences were created from the same set of pairs of correct sentences by first making them ungrammatical by switching the final words of each original sentence composing a pair (e.g., ton petit chat avait belle; cette grande tasse est faim). Then, the same words as in the TW sequences were transposed (e.g., ton petit **avait chat** belle; cette grande **est tasse** faim) but contrary to the TW sequences, transposing any two words in the control sequences could not generate a correct sentence. This meant that across the whole set of stimuli the TW sentences and control sentences contained exactly the same words in the same position and that both types of sequence became ungrammatical at exactly the same position. For the purpose of the grammatical decision task, 80 different grammatically correct sentences were constructed. The sequences were recorded using “text-to-speech” (<https://ttsfree.com/>) for French and with the female voice called “Denise”. In order to have an atypical speech rate, the function “adjust voice speed” was used with a speed adjusted to -100%, which leads to a speech rate two times slower than normal. The mean number of syllables was 6.83 for both the control and TW ungrammatical sentences. The mean duration of the critical ungrammatical sequences was 2,697 ms for both the TW and the control sequences, which thus corresponds to a speech rate of around two words per second, and to a speech rate of 2.53 syllables per second. For comparison the mean duration of ungrammatical sequences was 1,372 ms in Dufour et al. (2022), which thus corresponds to a speech rate of around one word per second, and to a

speech rate of 4.98 syllables per second. Because the 80 ungrammatical TW sequences and the 80 ungrammatical control sequences were created from the same 80 base sentences, two counterbalanced lists of stimuli were constructed to avoid repetition of the same words within a list and across the two types of ungrammatical sequence (TW, control). Each list thus contained 40 TW sequences and 40 control sequences, and 80 grammatically correct sentences.

Procedure: This was exactly the same as in Dufour et al. (2022) and is again explained here for convenience. The experiment was programmed using Labvanced software (Finger et al., 2017). Participants were instructed to put on their headphones and adjust the volume to a comfortable sound level. A trial began with a centrally aligned fixation cross for a duration of 500 ms, followed by the auditory sentence. For each word sequence, participants were asked to make a grammatical decision as quickly and accurately as possible by pressing the “right arrow” for grammatically correct sentences and the “left arrow” for ungrammatical sequences. After each response, a feedback consisting in a green circle in case of a correct response and in a red circle in case of an incorrect response was presented for a duration of 500 ms. The order of presentation of word sequences was randomized for each participant. Participants were tested on only one experimental list and began the experiment with 8 practice trials.

## **Results**

Six participants were removed prior to statistical analysis. Three participants had an error rate greater than 40 % averaged across all conditions, the three others had an average RT greater than 5000 ms. RTs to the ungrammatical sequences (available <https://osf.io/39bdz/?view>; Open Science Framework; Foster & Deardorff, 2017) were

analyzed using linear mixed effects models with participants and items as crossed random factors, using R software and the lme4 package (Baayen et al., 2008). The RT analysis was performed on correct responses, thus removing 409 (5.44%) data points out of 7520. Six extremely long RTs, greater than 8,000 ms, were considered as outliers and were also excluded from the analysis. For the model to meet the assumptions of normally-distributed residuals and homogeneity of variance, a log transformation was applied to the RTs (Baayen & Milin, 2010) prior to running the model. The model was run on 7105 data points. We tested a model with the factor Transposition (TW, control) entered as fixed effect. The model also included participants and items as random intercepts, plus random participant and item slopes (see Barr et al., 2013). We applied orthogonal contrast coding for the factor Transposition, namely 0.5 for one condition and -0.5 for the other condition, which allows an estimation of main effects.

The effect of Transposition was significant ( $b = 0.0171$ ,  $SE = 0.0062$ ,  $t = 2.76$ ,  $p < .01$ ). Participants were 41 ms slower at classifying TW sequences (RT = 2888 ms) as being ungrammatical in comparison to control sequences (RT = 2847 ms).

Response accuracy was analyzed using a mixed-effects logit model (Jaeger, 2008) with the same structure as for RTs. The effect of Transposition was again significant ( $b = -0.7081$ ,  $SE = 0.2166$ ,  $z = -3.27$ ,  $p < .01$ ). Participants gave more correct responses in the control condition (96 %) than in the TW condition (93 %).

### **Combined analysis of normal and slow speech rates**

To sum-up, we observed a clear and robust TW effect on both RTs and Error rates with a speech rate two times slower than in Dufour et al.'s (2022) study, and thus under conditions in which bottom-up positional uncertainty is even more reduced. Given that in the Dufour et al. (2022) study, the size of the TW effect was slightly smaller, around 29 ms, than in the present study, we performed a combined analysis of the “normal” speech rate data of Dufour et al. (2022) and the present slow speech rate data to confirm that a change in speech rate did not significantly impact on TW effects. Thus, an analysis of the data from the present experiment and the data from Dufour et al. (2022) was conducted with the factors Transposition (TW, control) and Speech Rate (slow, normal) on both RTs and error rates. The model also included participants and items as random intercepts, and random participant and item slopes for the factor transposition. We applied orthogonal contrast coding for the independent variables, namely 0.5 for one condition and -0.5 for the other condition, which allows an estimation of main effects. The results of the two studies are summarized in Figure 1.

RTs: The main effect of Transposition was significant with RTs slower on TW sequences in comparison to control sequences ( $b = 0.0148$ ,  $SE = 0.0042$ ,  $t = 3.53$ ,  $p < .001$ ). Not surprisingly there was also a main effect of Speech Rate with RTs slower at a slow speech rate than at the normal rate ( $b = 0.4616$ ,  $SE = 0.0191$ ,  $t = 24.19$ ,  $p < .001$ ). Crucially, the interaction between Transposition and Speech Rate was not significant ( $b = 0.0005$ ,  $SE = 0.0064$ ,  $t = 0.07$ ,  $p > .20$ ).<sup>2</sup> Note that a Bayes factor analysis (see Wagenmakers et al., 2018) using the `lmBF` function from the `BayesFactor` package revealed strong evidence in favor of

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<sup>2</sup> The relative size of the effect was 1.62% [(mean TW (1821 ms) – mean control (1792 ms))/ mean control (1792 ms)] in the Dufour et al. (2022) study and 1.44% [(mean TW (2888 ms) – mean control (2847 ms))/ mean control (2847 ms)] in the present study. Hence, despite longer RTs in the present study, the relative size of the effect is comparable in the two studies.

H0 ( $BF_{01} > 100$ ) for the critical Transposition  $\times$  Speech Rate interaction. Moreover, a power analysis indicated that a sample size of more than 1000 participants in each speech rate condition is required in order to observe a significant Transposition  $\times$  Speech Rate interaction with a power of .80. Of course, this sample size is massive and exceeds the sample sizes typically used in cognitive psychology experiments.

Accuracy: The effect of Transposition was again significant ( $b = -0.7070$ ,  $SE = 0.1453$ ,  $z = -4.87$ ,  $p < .001$ ) with more correct responses in the control condition than in the TW condition. The main effect of Speech Rate was not significant ( $b = -0.0618$ ,  $SE = 0.1598$ ,  $z = -0.39$ ,  $p > .20$ ). Again, the interaction between Transposition and Speech Rate was not significant ( $b = -0.1981$ ,  $SE = 0.1643$ ,  $z = -1.21$ ,  $p > .20$ ).

### Additional analyses

Given that the sentences used in present study became ungrammatical on the third word in the sequence of five words participants sometimes responded before the end of the sequence. We thus performed an additional analysis to examine whether the TW effect found in the present study with a slow speech rate differed as a function of whether or not participants waited to the end of the sequences to give their response. Among the 7105 data points included in the RT analysis, 2722 corresponded to a response “before” the end of the sequence, and 4383 corresponded to a response “after” the end of the sequence. The TW effect significantly interacted with the moment at which the response was made ( $b = 0.0213$ ,  $SE = 0.0066$ ,  $t = 3.25$ ,  $p < .01$ )<sup>3</sup>. A significant transposition effect of 80 ms was observed for responses

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<sup>3</sup> In Dufour et al.’s (2022) study, participants responded at the end of the sequence 91% of the time. Given the small number of responses occurring before the end of the sequence, this

occurring after the end of the sequence (RT (TW) = 3220 ms; RT (control) = 3140 ms; ( $b = 0.02146$ ,  $SE = 0.0102$ ,  $t = 2.10$ ,  $p < .05$ ). In contrast, no effect of transposition was observed for responses occurring before the end of the sequence (RT (TW) = 2369 ms; RT (control) = 2364 ms; ( $b = -0.0038$ ,  $SE = 0.0071$ ,  $t = -0.54$ ,  $p > .20$ ).

The interaction between Transposition (TW; control) and the moment of the response was marginally significant in the Error Rates ( $b = -0.7130$ ,  $SE = 0.3806$ ,  $t = -1.87$ ,  $p = .06$ ). Participants gave more correct responses in the control condition (95%) than in the TW condition (89) for responses occurring after the end of the sequence ( $b = -0.9189$ ,  $SE = 0.2627$ ,  $t = -3.50$ ,  $p < .001$ ). The effect of transposition, although numerically weak, went in the opposite direction for responses occurring before the end of the sequence, with more correct responses in the TW condition (98.47%) than in the Control condition (98.41%;  $b = 1.0558$ ,  $SE = 0.4632$ ,  $t = 2.28$ ,  $p < .05$ ).

The previous analysis as a function of the moment of the response suggests that the TW effect is dependent on the speed of participants' responses, with a greater effect for the slowest responses. To document in more detail the time-course of the TW effect, we conducted a delta plot analysis on both the RT data of the present study at a slow speech rate and the RT data of Dufour et al. (2022) at a normal speech rate. To do so, RTs were divided into 9 equal-sized bins and the TW effect (TW condition minus control condition) was calculated for each bin. This allowed us to examine how the TW effect evolves as RTs increase. As shown in Figure 2, the TW effect at a slow speech rate is negligible in vincentiles 0.1 to 0.6. It becomes sizeable at vincentile 0.7 (around 30 ms) and then increases progressively to reach 220 ms at the 9<sup>th</sup> vincentile. Also, the TW effect at a normal speech

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additional analysis including the moment of the response was not possible with the normal speech rate.

rate in Dufour et al. (2022), becomes sizeable at vincentile 0.7 (i.e. greater than 20 ms) to reach 130 ms at the 9<sup>th</sup> vincentile. Hence, in the two studies, the TW effect is more pronounced in the slow responses.

## **Discussion**

In the present study we asked whether transposed-word (TW) effects found in the auditory modality with a “normal” speech rate (Dufour et al., 2022) still occur with a slow speech rate, that is, in conditions that should minimize the influence of bottom-up positional noise on TW effects. Crucially, we observed a robust transposed word effect, significant in both RTs and error rates, and of the same magnitude as in our previous study that used a “normal” speech rate. A combined analysis of the data from these two experiments indeed revealed no significant interaction between speech rate and TW effects in either RTs or error rates. TW effects under auditory presentation of word sequences therefore appear to be insensitive to speech rate. Our results therefore suggest that TW effects in the auditory modality are mainly driven by sentence-level constraints.

The present results and those of Dufour et al. (2022) are not in accordance with reading studies using the rapid serial visual presentation (RSVP), that have mainly reported a TW effect in error rates but not in RTs (see Wen et al., 2025). The difference in the robustness of the TW effect in the auditory and visual modalities under conditions that reduce uncertainty about word order (i.e., serial presentation) could also suggest that TW effects linked to top-down mechanisms are modality dependent, and mainly occur when words are presented in the order that they naturally occur (i.e., serially for the auditory modality and in

parallel for the visual modality). In other words, listeners of TW sequences might be less sensitive to bottom-up word-order information than readers of TW sequences under RSVP. This would allow TW effects to remain robust in both RTs and accuracy in the auditory modality contrary to the visual modality.

Therefore, an explanation of the reduced TW effect seen in RTs under serial presentation of written words could be due to the atypical and unnatural format of word presentation, and in particular to the fact that in normal reading words are presented in parallel, and not serially, one after the other as in RSVP. Mirault et al. (2023) reported findings in support of the hypothesis that it is indeed the atypical/unnatural format that causes a reduced TW effect with the RSVP procedure. In particular, Mirault et al. found TW effects in error rates but not in RTs when written words were presented simultaneously (in parallel) but unspaced (e.g., thecatwhitewasbig) and when participants were instructed to read from right-to-left (e.g., big was white cat the). In order to provide a further test of the “atypical” presentation hypothesis, we now need to determine a means of presenting speech in an atypical format. The slow speech rate used in the present study might not have been perceived as being atypical, given that speech rate does vary in normal speakers. Hence, future research in the auditory modality could aim to find a different way to present spoken sentences in an atypical format. One possibility would be to alter voice from word to word, and to compare that with a case change in the visual modality.

An alternative explanation, however, was provided by Wen and Grainger (submitted) who proposed that grammatical decisions can either be based on the local detection of ungrammaticality or a global evaluation of grammaticality based on the evidence for grammaticality that is accumulated during the processing of the entire sequence of words.

Fast local detection of ungrammaticality would reduce TW effects in RTs since this local detection would operate similarly for the TW and control sequences. This early local detection of ungrammaticality could even produce an effect in the opposite direction (i.e., easier detection of ungrammaticality for the control sequences), as was seen in the accuracy analysis for responses occurring before the end of the sequence. On the other hand, use of a more global (evidence accumulation) decision making mechanism would allow TW effects to emerge in both RTs and accuracy (see Wen & Grainger, submitted, for more details).

Another important finding reported here is that TW effects were stronger, both in RTs and accuracy, when participants responded after hearing the final word in the sequence. One possible interpretation is that sentence-level constraints require time to exert their influence, which is consistent with the observation that the TW effect is more pronounced in the slow responses. Fast responses, occurring before the end of the auditory sequences, may primarily rely on the detection of local ungrammaticalities (Wen & Grainger, submitted), thereby reducing the TW effect. In contrast, delaying the response until the end of the sequence provides more time for the use of a global evaluation of grammaticality (via evidence accumulation, for example), which can favor the reordering of words into a correct sentence, increasing thus the TW effect.

To conclude, we found a robust TW effect with sequences of spoken words presented at a slow speech rate. This finding suggests that increasing bottom-up cues for word-order does not impact on TW effects during spoken sentence processing, and points to a greater role for sentence-level constraints in the auditory modality. This provides support for the “global” strategy for grammatical decision making proposed by Wen and Grainger (submitted), that would be the main mechanism driving TW effects observed in the auditory modality, but with

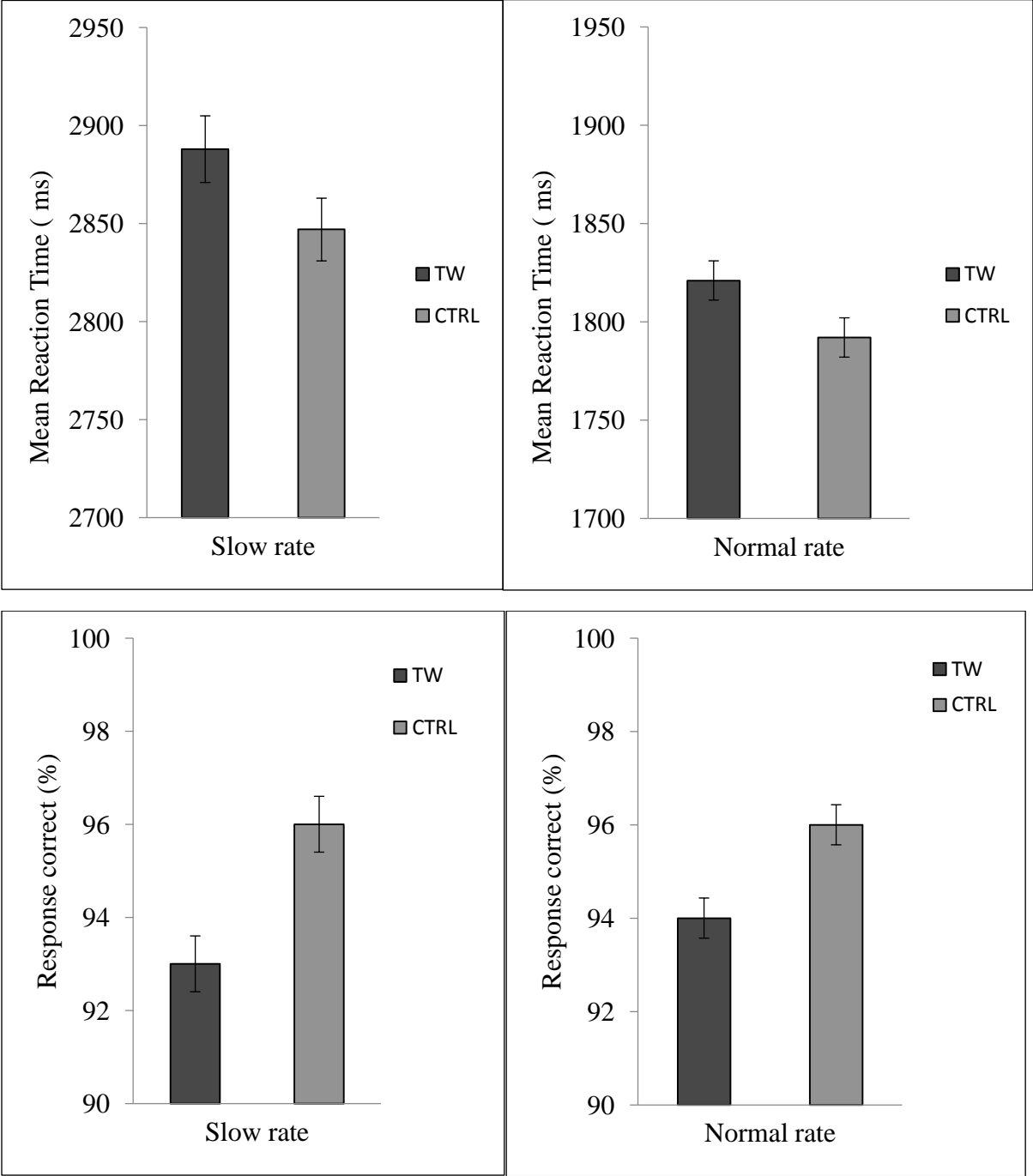
the local detection of ungrammaticality reducing the size of TW effects compared with those found in parallel visual presentation. Finally, our findings suggest that sentence-level constraints require time to exert their influence, with an impact on TW effects becoming stronger as more processing time is available. Again, this is compatible with Wen and Grainger's (submitted) account, whereby grammatical decisions in the auditory modality would rely more on global evidence accumulation than grammatical decisions made on serially presented written words. This explains the pattern seen in the delta plots (Figure 2) and why effects are greater when responses are made after the end of the sequence.

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**Figure 1.** Comparison of transposed-word effects (TW vs. CTRL) obtained in the present study with a slow speech rate and in the Dufour et al. (2022) study with a normal speech rate.



**Figure 2.** Delta plots of the TW effect in RTs (Delta = TW condition minus control condition) in milliseconds for the slow speech rate in the present study and the normal speech rate in the Dufour et al. (2022) study. The points represent the average TW effect observed at each of the 9 vincentiles. The dotted vertical line indicates the end of the word sequences in Dufour et al. (2022), and the solid vertical line indicates the end of the sequences in the present study.

