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Phrase frequency does not modulate transposed-word effects
in the visual and auditory modalities

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Abstract: We provide a further examination of the influence of top-down sentence-level constraints on the transposed-word effect by manipulating a factor – phrase frequency – that directly implicates sentence-level representations. The focus was on ungrammatical transposed-word sequences, and under the assumption that top-down influences would play a role in driving transposed word effects, we predicted that ungrammatical decisions would be harder (longer RTs and higher error rates) when the ungrammatical transposed-word sequences were derived from high-frequency compared with low-frequency phrases. **Five** experiments were conducted in which participants performed a speeded grammatical decision task. The results are clear-cut. Although phrase-frequency did influence grammatical decisions to grammatically correct phrases, with shorter RTs and lower error rates for high-frequency phrases relative to low-frequency phrases (Experiment 4), ungrammatical decisions were not influenced by the frequency of the base sentences from which the transposed-word sequences were formed, neither in the auditory (Experiments 1 & 2) nor in the visual modality (Experiment 3). In Experiment 5 we show that a transposed-word effect is observed when comparing the transposed-word sequences of Experiment 3 with non-transposed control sequences. We conclude that frequency-sensitive sentence-level constraints, as measured as the frequency of occurrence of a sequence of words in corpora of spoken and written language, do not modulate transposed-word effects.

Key words: transposed-word effects; speeded grammatical decision task; top-down sentence-level constraints

Is a sequence of words such as “the white was cat big” more easily confused as being grammatically correct than a sequence like “the white was cat slowly”? A growing body of research (e.g., Huang & Staub, 2021; Huang & Staub, 2023; Liu et al., 2020; Liu et al., 2022; Mirault et al., 2018; Mirault et al., 2022; Snell & Grainger, 2019) indicates that this is indeed the case. In particular, these studies have shown that ungrammatical sequences created by transposing two words in a correct sentence are harder to reject as being grammatically correct than ungrammatical sequences that cannot be resolved into a correct sentence by transposing any two words. This finding suggests that flexibility in the processing of word order allows participants to access a mental representation of the grammatically correct base sentence, which then interferes (i.e., generates longer RTs and more errors) when making an “ungrammatical” decision (see Dufau et al., 2012, for a computational model that describes the possible mechanisms involved). This flexibility in the processing of word order echoes the flexibility found in processing letter positions in written words (e.g., Perea & Lupker, 2004; see Grainger, 2008, for a review) and more recently in processing phoneme positions in auditory words (e.g., Dufour et al., 2021), leading participants to misperceive the transposed-letter/phoneme nonword *caniso* /kasino/ as being the word *casino*.

Two mechanisms have been envisaged to account for the transposed-word effect (see e.g., Pegado & Grainger, 2020; Snell & Grainger, 2019). The first mechanism 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. It results that 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 proposal for the word-in-sentence is analog of the noisy letter position coding for letters in words proposed by Gomez

et al. (2008). The second mechanism involves sentence-level representations with syntactic and semantic constraints supervising the encoding of word-order information. These top-down constraints would rectify word order so that ungrammatical sequences respect syntactic rules and can be assigned to a plausible interpretation under the assumption that readers/listeners are trying their best to interpret the linguistic input (see Gibson et al., 2013, for a description of this “rational analysis” approach). It results that the reordering of words imposed by sentence-level constraints increases the likelihood that ungrammatical sequences formed by transposing words are misperceived as being grammatically correct.

In an attempt to disentangle the relative contribution of top-down sentence level influences and the influence of bottom-up positional noise on ungrammatical decisions, reading studies (Huang & Staub, 2023; Liu et al., 2022; Mirault et al., 2022) have examined the transposed-word effect when written words are presented simultaneously (i.e., parallel presentation) and when they are presented one after the other (i.e., serial presentation). The logic behind this manipulation is that a serial presentation would reduce word positional uncertainty in bottom-up processing, and if a transposed-word effect emerges under this type of presentation, it would mainly reflect the impact of top-down sentence-level constraints on word-order encoding. The global picture that has emerged from these studies is that transposed-word effects can be found with both parallel and serial word presentation conditions, but the effect is more robust under parallel presentation. In particular, under parallel presentation, the transposed word effect is systematically observed on both reaction times (RTs) and error rates, while in the majority of studies using serial presentation the effect is only observed in error rates (but see Millege et al. (2023) and Hossain and White (2023) for exceptions).

To sum-up, the above-mentioned studies suggest that when uncertainty in word order is minimized, the transposed-word effect is reduced such that it is mainly visible in RTs.¹ It is therefore tempting to conclude from these studies that bottom-up positional noise is the main source of the transposed-word effect. However, the only study (Dufour et al., 2022), to the best of our knowledge, that has examined the transposed-word effect with spoken sentences in which words are naturally and not “artificially” presented sequentially one after the other has reported a robust transposed word effect on both error rates and RTs. On the basis of these results, the authors suggested that the smaller effect observed with a serial presentation of written words is due to the atypical format (i.e., written words presented sequentially rather than in parallel), and that top-down sentence-level constraints constitute one main factor in driving transposed-word effects, and this independently of how words are presented.

The present study provides a further test of top-down sentence-level constraints on transposed-word effects by manipulating a factor that directly implicates sentence-level processing. To do so, we manipulated the frequency of four-word phrases from which the transposed-word sequences were formed. Much prior research on the effects of phrase frequency in language comprehension (Armando et al., 2023; Arnon & Snider, 2010; Siyanova-Chanturia et al., 2011) involved written language. More recently, Dufour et al. (2024) investigated phrase-frequency effects in spoken language comprehension using the auditory version of the speeded grammatical decision task. In all these studies phrase-frequency was found to facilitate language comprehension (see Dufour et al., 2004, for a summary of prior research in the visual modality).

¹ We are currently performing a meta-analysis of all published studies investigating transposed-word effects under serial presentation of words in order to provide a proper evaluation of the effects observed in these conditions (Wen & Grainger, in preparation).

In the present study we build on these two phenomena – transposed-word effects and phrase-frequency effects. We reasoned that word-order should be more easily corrected when transposed-word sequences are derived from sentences that are frequently encountered in a language. The focus here is thus on ungrammatical transposed-word sequences, and our prediction is as follows: If sentence-level representations play a dominant role in driving the transposed-word effect (i.e., a top-down effect), we predicted that ungrammatical decisions would be harder (longer RTs and higher error rates) when the ungrammatical transposed-word sequences are derived from high-frequency compared with low-frequency sentences. Five experiments were conducted in which participants performed a speeded grammatical decision task. Experiments 1, 2 & 4 were conducted in the auditory modality and Experiments 3 & 5 in the visual modality.

Experiment 1

In Experiment 1 we examined the influence of phrase-frequency on deciding that a sequence of spoken words was ungrammatical. High- and low-frequency phrases of four words were used as grammatically correct base-sequences, and the third and fourth words were transposed to form the critical ungrammatical sequences.

Method

Participants: 60 participants were recruited on-line for the experiment. **The number of participants was chosen to respect the number tested in the on-line study of Dufour et al. (2024) in which a phrase-frequency effect on grammatical decisions was observed.** They

reported to be native speakers of French and their reported age was between 20 and 68 years. 23 reported to being female, 36 male, and 1 preferred not to respond. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: We selected 80 phrases made up of four words from the French corpus of film subtitles of 316 million words (New et al., 2007). Half of them were low-frequency phrases and the other half were high-frequency phrases. High- and low-frequency phrases were matched on grammatical structure. For example, the high-frequency phrase *le lieu de travail* “the work place” and the low-frequency phrase *le champs de maïs* “the maize field” are both composed of a definite article, a noun, a preposition and a noun. The phrases with their grammatical structure are given in the Appendix. The high- and low-frequency phrases were also matched on word frequency. The main characteristics of the phrases are given in Table 1. The ungrammatical transposed-word sequences were created by simply transposing the two last words of these 80 phrases (e.g., *le lieu travail de* for the high-frequency phrase *le lieu de travail*; *le champ maïs de* for the low-frequency phrase *le champ de maïs*). For the purpose of the grammatical decision task, 80 other grammatically correct phrases were selected. The 80 ungrammatical transposed-word sequences and the 80 grammatical sequences were recorded using “text-to-speech” software (<https://ttsfree.com/>) for French using the female voice referred to as “Denise” and digitized at a sampling rate of 44100 Hz.

Procedure: 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 phrase. 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, feed-back was provided for a duration of 500 ms in the form of a green circle for a correct response and a red cross for an incorrect response was presented. The order of presentation of sequences was randomized for each participant. The experiment began with 6 practice trials.

Results and Discussion

Six participants were removed from the analyses. Five participants had an error rate greater than 40 % averaged across all conditions, the other had an average RT greater than 2000 ms. Two sentences, one in the high-frequency condition and the other in the low-frequency condition, that gave rise to an error rate of more than 40% were also removed. RTs to the ungrammatical sequences (available at <https://osf.io/59x6p/>; 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 336 (7.98%) data points out of 4212. RTs greater than 4,500 ms (0.46%) 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 3858 data points. We tested a model with the factor Phrase-frequency (low, high) entered as fixed effect. The reference was the high-frequency condition. The model failed to converge when random

slopes were included (see Barr et al., 2013). Therefore, the final model only included random intercepts for participants and items.

The effect of phrase-frequency was not significant ($b = 0.0088$, $SE = 0.0213$, $t = 0.41$, $p > .20$; RTs (high-frequency) = 1405 ms; RTs (low-frequency) = 1413 ms). A Bayes factor analysis (see Wagenmakers et al., 2018) using the `lmBF` function from the `BayesFactor` package indicated strong evidence in favor of H_0 ($BF_{01} = 11$).

Response accuracy on ungrammatical sequences was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of phrase-frequency was again not significant ($b = -0.0363$, $SE = 0.2646$, $z = -0.14$, $p > .20$; Correct responses (High-frequency) = 92%; Correct responses (Low-frequency) = 92%). Accuracy of responses to the grammatical sequences was 97%.

To sum-up, ungrammatical decisions were not influenced by the phrase frequency of the base sequences used to create the critical transposed-word sequences by transposing the last two words. One possible cause for the null effect of phrase frequency is that in Experiment 1 the transposition involved the final word of the phrases, but studies conducted in the visual modality have revealed stronger transposed-word effects when the transpositions involve internal words rather than final words (e.g., Snell & Grainger, 2019). In Experiment 2 we thus reexamined the influence of phrase-frequency on ungrammatical decisions with transposed-word sequences created by transposing the internal words of four-word phrases.

Experiment 2

The same set of four-word phrases as in Experiment 1 was used in Experiment 2 but this time the transposition involved the second and third words. The transposed-word sequences were again presented auditorily.

Method

Participants: 61 participants were recruited on-line for the experiment. They reported to be native speakers of French and their reported age was between 18 and 66 years. 30 reported to being female, 30 male and 1 preferred not to respond. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: Among the 80 test phrases of Experiment 1, 66 were re-used. 14 were removed because they the first two words were connected with an apostrophe (e.g., *c'est la vérité* “it is the truth”), making it impossible to transpose the second word with the third word. 66 phrases, 33 of high-frequency and 33 of low-frequency, were thus tested in Experiment 2. The main characteristics of the phrases are given in Table 2. The transposed-word ungrammatical sequences were created by transposing the second and third words of these 66 phrases (e.g., *le de lieu travail* for the high-frequency phrase *le lieu de travail*; *le de champ maïs* for the low-frequency phrase *le champ de maïs*). For the purpose of the grammatical decision task, 66 other grammatically correct phrases were used and were taken from the grammatical filler sentences of Experiment 1. Recording of these stimuli was the same as for Experiment 1.

Procedure: This was the same as in Experiment 1

Results and Discussion

Eight participants were removed from the analyses. Five participants had an error rate greater than 40 %, and the three others had RTs greater than 2000 ms. Two sentences in the high-frequency condition that gave rise to an error rate of more than 40% were also removed. RTs to the ungrammatical sequences (available at <https://osf.io/59x6p/>; Open Science Framework; Foster & Deardorff, 2017) were analyzed using linear mixed effects models following the same procedure as in Experiment 1. The RT analysis was performed on correct responses, thus removing 263 (7.75%) data points out of 3392. RTs greater than 4,500 ms (0.61%) 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 3110 data points. We tested a model with the factor Phrase-frequency (low, high) entered as fixed effect. The reference was the high-frequency condition. The model failed to converge when random slopes were included (see Barr et al., 2013). Therefore, the final model only included random intercepts for participants and items.

The effect of phrase-frequency was again not significant ($b = 0.0039$, $SE = 0.0166$, $t = 0.24$, $p > .20$; RTs (high-frequency) = 1306 ms; RTs (low-frequency) = 1313 ms). A Bayes factor analysis (Wagenmakers et al., 2018) indicated strong evidence in favor of H0 (BF01 = 22).

Response accuracy for the ungrammatical sequences was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of phrase-frequency was again not significant ($b = 0.2290$, $SE = 0.2407$, $z = 0.95$, $p > .20$; Correct responses (High-frequency) = 91%; Correct responses (Low-frequency) = 93%). Accuracy of responses to the grammatical sequences was 97%.

To sum-up, we again failed to observe an influence of phrase-frequency on decisions to ungrammatical transposed-word sequences in the grammatical decision task. This null effect of phrase-frequency was observed when the transposition concerned both final (Experiment 1) and internal words (Experiment 2). Thus, we can be confident that this failure to observe an influence of phrase-frequency is not due to the position of the transposed words in the auditory sequences. It remains to be seen, however, whether this absence of an influence of phrase-frequency was due to our testing sequences of spoken words. Indeed, the auditory modality, with words occurring sequentially one after the other, might not provide optimal conditions for observing an impact of phrase frequency on transposed-word effects, under the assumption that such effects are augmented by parallel word processing (e.g., Mirault et al., 2022). The influence of phrase-frequency on ungrammatical decisions was thus re-examined in Experiment 3 but this time in a reading context where all the words in the phrases were presented simultaneously.

Experiment 3

Experiment 3 consisted in a replication of Experiment 2 in the visual modality. Internal transpositions were tested in this third experiment, because as indicated above transposed-word effects are generally stronger in the visual modality when the word transposition is internal to the phrase than when it involves words at the beginning or the end of the phrase.

Method

Participants: 60 participants were recruited on-line for the experiment. They reported to be native speakers of French and their reported age was between 18 and 66 years. 25 reported to be female, 32 male, and 3 preferred not to respond. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: Exactly the same materials as in Experiment 2 were used

Procedure: The procedure was the same as in Experiment 2 except that phrases were presented visually, with all words presented simultaneously and aligned horizontally as with regular text in French.

Results and Discussion

Six participants were removed from the analyses. Five participants had an error rate greater than 40 %, the other had RTs greater than 3000 ms². RTs to the ungrammatical sequences (available at <https://osf.io/59x6p/>; 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) following the same procedure as in Experiments 1 & 2. The RT analysis was performed on correct responses, thus removing 295 (8.28%) data points out of 3564. RTs greater than 6,000 ms (0.80%) 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 3243 data points. We tested a model with the factor Phrase-frequency (low, high) entered as fixed effect. As in Experiments 1 & 2, the model included random intercepts for participants and items. The reference was the high-frequency condition.

The effect of phrase-frequency was again not significant ($b = 0.0119$, $SE = 0.0299$, $t = 0.39$, $p > .20$; RTs (high-frequency) = 1418 ms; RTs (low-frequency) = 1441 ms). A Bayes factor analysis (see Wagenmakers et al., 2018) indicated strong evidence in favor of H0 (BF01 = 19).

Response accuracy was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of phrase-frequency was again not

² Participants were overall slower in the visual than in the auditory modality, which necessarily induced a modification in the criteria used to exclude participants.

significant ($b = 0.3052$, $SE = 0.2262$, $z = 1.35$, $p = .18$; Correct responses (High-frequency) = 90%; Correct responses (Low-frequency) = 93%). Accuracy of responses to the grammatical sequences was 97%.

To sum-up, even under conditions that promote parallel word processing (i.e., simultaneous visual presentation of word sequences), there was no sign of an influence of phrase-frequency on grammatical decisions to ungrammatical transposed-word sequences.

Experiment 4

Although, as noted in the Introduction, phrase frequency effects have already been reported in the auditory grammatical decision task (Dufour et al., 2024), these effects were obtained with phrases/sentences that differed from the base-sentences used in the present study. Given the null effects reported so far, it was therefore important to demonstrate a phrase-frequency effect for the base-sentences used to generate the critical transposed-word sequences that were tested here. This was the aim of Experiment 4.

Method

Participants: 60 participants were recruited on-line for the experiment. They reported to be native speakers of French and their reported age was between 21 and 65 years. 25 reported to

being female and 35 male. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: The 80 phrases of Experiment 1, 40 of high frequency and 40 of low frequency, were used. For the purpose of the grammatical decision task we selected a different set of 80 grammatical phrases of four words and we replaced the last word by another word which rendered the sequence ungrammatical. For example, the last word *match* which is a noun in the phrase *la balle de match* “the match point” was replaced by the adverb *tranquillement* leading thus to “la balle de tranquillement” which is grammatically incorrect since in French the preposition *de* cannot be followed by an adverb. Note that the last word was changed to force participants to process the entire phrase prior to giving their response. Recording of these stimuli was the same as for Experiments 1 & 2. The mean duration of the phrases was 929 and 928 ms in the high- and low-frequency condition, respectively.

Procedure: This was the same as in Experiments 1 & 2

Results and Discussion

RTs to the grammatical sequences (available at <https://osf.io/59x6p/>; 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

145 (3.02%) data points out of 4800. RTs greater than 4,500 ms (0.54%) 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 4630 data points. We tested a model with the factor Phrase-frequency (low, high) entered as fixed effect. The model also included participants and items as random intercepts, plus random participant slopes. The reference was the high-frequency condition.

The effect of phrase-frequency was significant ($b = 0.0494$, $SE = 0.0216$, $t = 2.29$, $p < .05$). Participants responded 59 ms faster in the high-frequency (Mean = 1263 ms) than in the low-frequency (Mean = 1322 ms) condition. A Bayes factor analysis (Wagenmakers et al., 2018) indicated extreme evidence in favor of H1 ($BF_{10} > 100$).

Response accuracy was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of phrase-frequency was significant ($b = -0.7013$, $SE = 0.2610$, $z = -2.69$, $p < .01$). Participants made fewer errors to high-frequency (Mean correct responses = 98%) than to low-frequency phrases (Mean correct responses = 96%).

To sum-up, we observed a robust effect of phrase-frequency on grammatical decisions to the base-sentences used to generate the transposed-word sequences tested in Experiments 1 to 3. This effect contrasts with the null effects of phrase-frequency found in Experiments 1 to 3 for decisions made to ungrammatical transposed-word versions of the same base-sentences

(see Figure 1 for a summary of the results observed in Experiments 1 to 4). However, in order to rule-out the possibility that this absence of a phrase-frequency effect on transposed-word effects was simply due to an overall absence of transposed-word effects we ran Experiment 5 where we directly examined transposed-word effects by comparing the transposed-word sequences tested in Experiment 3 with control ungrammatical sequences.

Experiment 5

Methods

Participants: 100 participants were recruited on-line for the experiment. **The sample size was larger than the four previous experiments because two experimental lists were tested with two groups of participants due to the counterbalancing procedure we applied.** Participants reported to be native speakers of French and their reported age was between 18 and 59 years. 47 reported to being female, 51 male, and 2 preferred not to respond. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: The same transposed word sequences as in Experiments 2 & 3 were used except for two sequences, one in the high-frequency condition and the other in the low-frequency condition. These two sequences were removed in order to have an even number of sequences within each frequency condition (i.e. 32). Within each frequency condition, ungrammatical control sequences were created from the same set of pairs of correct sentences by first making them ungrammatical by switching the final words in each sentence by another word of the set

of sentences (e.g., je peux tout téléphone; un numéro de expliquer). Then, the same words as in the transposed-word sequences were transposed (e.g., je tout peux téléphone; un de numéro expliquer) but contrary to the transposed-word sequences, transposing any two words in the control sequences could not generate a correct sentence. This further meant that across the whole set of stimuli the transposed-word 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. 64 grammatically correct sentences taken from Experiments 2 & 3 were also used for the purpose of the grammatical decision task. Because the 64 ungrammatical transposed-word sequences (i.e., 32 for the low-frequency condition and 32 for the high-frequency condition) and the 64 ungrammatical control sequences were created from the same 64 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 (transposed-word, control). Each list thus contained 32 transposed-word sequences (i.e., 16 in each frequency condition) and 32 control sequences, and 64 grammatically correct sentences.

Procedure: The procedure was the same as in Experiment 3.

Results and Discussion

Fourteen participants were removed from the analyses. Seven participants had an average error rate greater than 40 %, the seven others had average RTs greater than 2000 ms.

Two sentences, one in the high-frequency condition and the other in the low-frequency, that gave rise to an error rate of more than 40%, were also removed. RTs to the ungrammatical sequences (available at <https://osf.io/59x6p/>; 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 330 (6.19%) data points out of 5332. RTs greater than 5,000 ms (0.08%) 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 4998 data points. We tested a model with the factor Phrase-frequency (low, high), Transposition (transposed-word, control) and their interaction entered as fixed effect. 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 model also included participants and items as random intercepts, plus random participant slopes. The mean RT and percentage of correct responses in each condition are shown in Table 3.

Crucially, the effect of Transposition was significant ($b = -0.0302$, $SE = 0.0070$, $t = -4.30$, $p < .001$). Participants were 37 ms slower at classifying transposed-word sequences as being ungrammatical in comparison to control sequences. The effect of Phrase-frequency was not significant ($b = 0.0009$, $SE = 0.0275$, $t = 0.03$, $p > .20$), and the interaction between Phrase-frequency and Transposition was also not significant ($b = -0.0029$, $SE = 0.0141$, $t = -0.21$, $p > .20$).

Response accuracy was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of Transposition was again significant ($b = 1.4670$, $SE = 0.1442$, $z = 10.17$, $p < .001$). Participants made 7% more errors in the transposed-word condition than in the control condition. The effect of Phrase-frequency was not significant ($b = 0.2756$, $SE = 0.3191$, $t = 0.863$, $p > .20$), and the interaction between Phrase-frequency and Transposition was again not significant ($b = 0.0322$, $SE = 0.2880$, $t = 0.11$, $p > .20$).

Experiment 5 was designed to rule-out the possibility that the absence of an influence of phrase-frequency on transposed-word effects seen in the previous experiments was simply due to an overall absence of transposed-word effects. In Experiment 5 we directly examined transposed-word effects by comparing the transposed-word sequences tested in Experiment 3 (visual modality) with control ungrammatical sequences, and we found a reliable transposed-word effect.

General Discussion

In the present study, we provided a further examination of the influence of top-down sentence-level constraints on the transposed-word effect by manipulating a factor that directly implicates sentence-level representations. In particular, under the assumption that top-down influences would play a major role in driving transposed word effects, we predicted that word-order should be more easily corrected when transposed-word sequences are derived

from phrases / sentences that are frequently encountered in a language, thus causing a stronger interference on ungrammatical decisions when transposed-word sequences are derived from high- than from low-frequency phrases. The results are clear-cut. Although phrase-frequency did influence grammatical decisions to grammatically correct phrases, with shorter RTs and lower error rates for high-frequency phrases relative to low-frequency phrases (Experiment 4), ungrammatical decisions were not influenced by the frequency of the base sentences from which the transposed-word sequences were formed. This null effect of phrase-frequency on transposed-word effects was observed in the auditory modality (Experiments 1 & 2), but one could argue that transposed-word effects are diminished in this modality due to the strictly sequential presentation of stimuli. However, the same null effect of base-sentence frequency was also found in the visual modality (i.e., parallel presentation; Experiment 3) under which stronger transposed-word effects are generally observed (e.g., Mirault et al., 2022). Crucially, Experiment 4 showed that the grammatically correct base-sequences used to generate the critical ungrammatical stimuli tested in Experiments 1-3 did show an effect of phrase frequency. Moreover, Experiment 5 showed that the same transposed-word sequences as tested in Experiment 3 did show a robust transposed-word effect when contrasted with matched ungrammatical control sequences, and again this transposed-word effect was not influenced by the frequency of the base-sequences.

With respect to the two accounts of the transposed-word effect discussed in the Introduction, our results plead in favor of a rather limited role of top-down sentence-level constraints on the transposed word-effect. This is all the more remarkable that Experiments 1 and 2 were conducted in the auditory modality with words presented one after the other. That is, under conditions that should reduce bottom-up word position uncertainty, and that in turn should encourage a greater role for top-down constraints on the processing of word order

information. Although we will not argue here that top-down constraints play no role at all, we must acknowledge that the null effect of phrase frequency on ungrammatical decisions to transposed-word sequences (Experiments 1-3) accompanied by a clear effect of phrase frequency on grammatical decisions to the same sentences from which the transposed-word sequences were derived (Experiment 4) points to a major role for bottom-up positional noise in driving transposed-word effects.

Nevertheless, there are multiple means by which sentence-level constraints might affect transposed-word effects as well as other potential top-down influences (from sentence to word) during language comprehension. In the present study we manipulated phrase-frequency, which is the frequency of occurrence of a sequence of word-forms (either phonological or orthographic) in a given corpus of spoken or written language. Another measure of interest would be the frequency of a given syntactic structure, independently of the word forms that compose that structure. In its simplest formulation, syntactic frequency can be calculated as the frequency of occurrence of a sequence of parts-of-speech. This is clearly an important avenue for future research where more general sentence-level constraints are distinguished from purely syntactic constraints (see e.g., Keshev & Meltzer-Asscher, 2021, who showed that readers prefer incorrect sentences with a high-frequency structure over correct sentences with a low-frequency structure).

Our main conclusion is in line with studies conducted in the visual modality where transposed-word effects were observed in conditions that arguably minimize the impact of top-down sentence-level constraints. For example, Pegado and Grainger (2020) reported transposed-word effects in a same-different matching task that does not require the computation of syntactic structures, in contrast to the grammatical decision task. More

crucially, a transposed-word effect was found in this study when the reference was ungrammatical (e.g., green wants these he apples), and thus under conditions that prevent sentence-level constraints to operate. In particular, the authors observed that different responses were harder to make when the difference was generated by transposing two words (e.g., green these wants he apples) compared with replacing two words with different words (e.g., green talks their he apples). On the basis of this result, the authors concluded that bottom-up positional noise is one key mechanism underlying transposed-word effects. Also, using the same-different matching task implying two ungrammatical word sequences, Wen et al. (2024) reported a transposed-word effect which was independent of the relative length of the transposed words, a result that the authors interpreted as reflecting length-independent noisy word position coding.

The conception that word position coding is noisy is easily conceivable in the visual modality when written words are presented simultaneously and under the assumption that they are at least partly processed in parallel (see Snell & Grainger, 2019). But how can bottom-up uncertainty about word positions occur when words are presented one after the other, as is the case in the auditory modality with spoken sentences? The fact that our group (Dufour et al., 2022) previously reported a robust transposed-word effect with spoken sentences on both RTs and error rates pleads in favor of the existence of a short-term memory buffer in which spoken words are temporarily maintained before they are integrated into a sentence level representation (see also Huang & Staub, 2023; Snell & Melo, 2024; and Snell, 2024). It would be at this intermediary level of processing, between the lexical and sentence levels, that flexibility in the encoding of word order would occur, thus causing confusion

about word order³. On the basis of the present study and our previous study (Dufour et al., 2022), we argue that this confusion would occur before words are integrated into a sentence-level representation, and before top-down sentence-level constraints intervene. Future research could specifically target this intermediate level of processing, especially in the auditory modality where words that made-up spoken sequences are naturally presented one after the other. In particular, the links with working memory span could be examined and, for example, one key question for future research is whether transposed-word effects found in the auditory modality are modulated by the number of words that compose the auditory sequences (note that Dufour et al., 2022, tested short spoken sentences of five words in length).

To conclude, the results of the present study suggest that sentence-level constraints play a relatively minor role in driving transposed-word effects. These findings are in line with effects obtained with ungrammatical sequences in the same-different matching task (Pegado & Grainger, 2020), and with recent studies manipulating the relative length of the transposed words (Wen et al., 2024). Overall, it would appear that bottom-up positional noise is one major factor driving transposed-word effects in both the visual and auditory modalities.

³ The fact that the error rate in the auditory modality (Experiments 1 & 2) was similar to that in the visual modality (Experiment 3) also pleads in favor of the role played by a short-term memory buffer when accounting for transposed-word effects observed with sequences of spoken words.

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Table 1: Characteristics of the phrases used in Experiment 1 (mean values with frequency ranges in parentheses).

	Phrase- frequency	Word 1 frequency	Word 2 frequency	Word 3 frequency	Word 4 frequency	Phrase duration
High-frequency condition	3.39 (2.68-4.22)	4.20 (2.33-4.92)	3.40 (1.46-4.86)	4.35 (2.54-4.90)	2.66 (1.00-3.94)	905
Low-frequency condition	2.11 (2.06-2.22)	4.20 (2.33-4.92)	3.48 (1.02-4.86)	4.32 (2.65-4.90)	2.66 (1.06-4.00)	906

Note: Zipf values for frequency; in ms for duration

Table 2: Characteristics of the phrases used in Experiments 2 & 3 (mean values with frequency ranges in parentheses).

	Phrase- frequency	Word 1 frequency	Word 2 frequency	Word 3 frequency	Word 4 frequency	Phrase duration
High-frequency condition	3.26 (2.68-4.05)	4.56 (3.13-4.92)	3.12 (1.46-4.86)	4.38 (2.54-4.90)	2.62 (1.00-3.94)	973
Low-frequency condition	2.11 (2.06-2.22)	4.56 (2.98-4.92)	3.25 (1.02-4.58)	4.39 (2.65-4.90)	2.71 (1.06-4.00)	953

Note: Zipf values for frequency; in ms for duration

Table 3: Mean Reaction Times (in ms) and percentages of correct responses for the control and transposed-word sequences in each frequency condition in Experiment 5.

	Control	Transposed	Transposed-word effect
High-frequency			
RT	1101	1136	-35
Error rates	97	89	8
Low-frequency			
RT	1105	1144	-39
Error rates	98	92	6

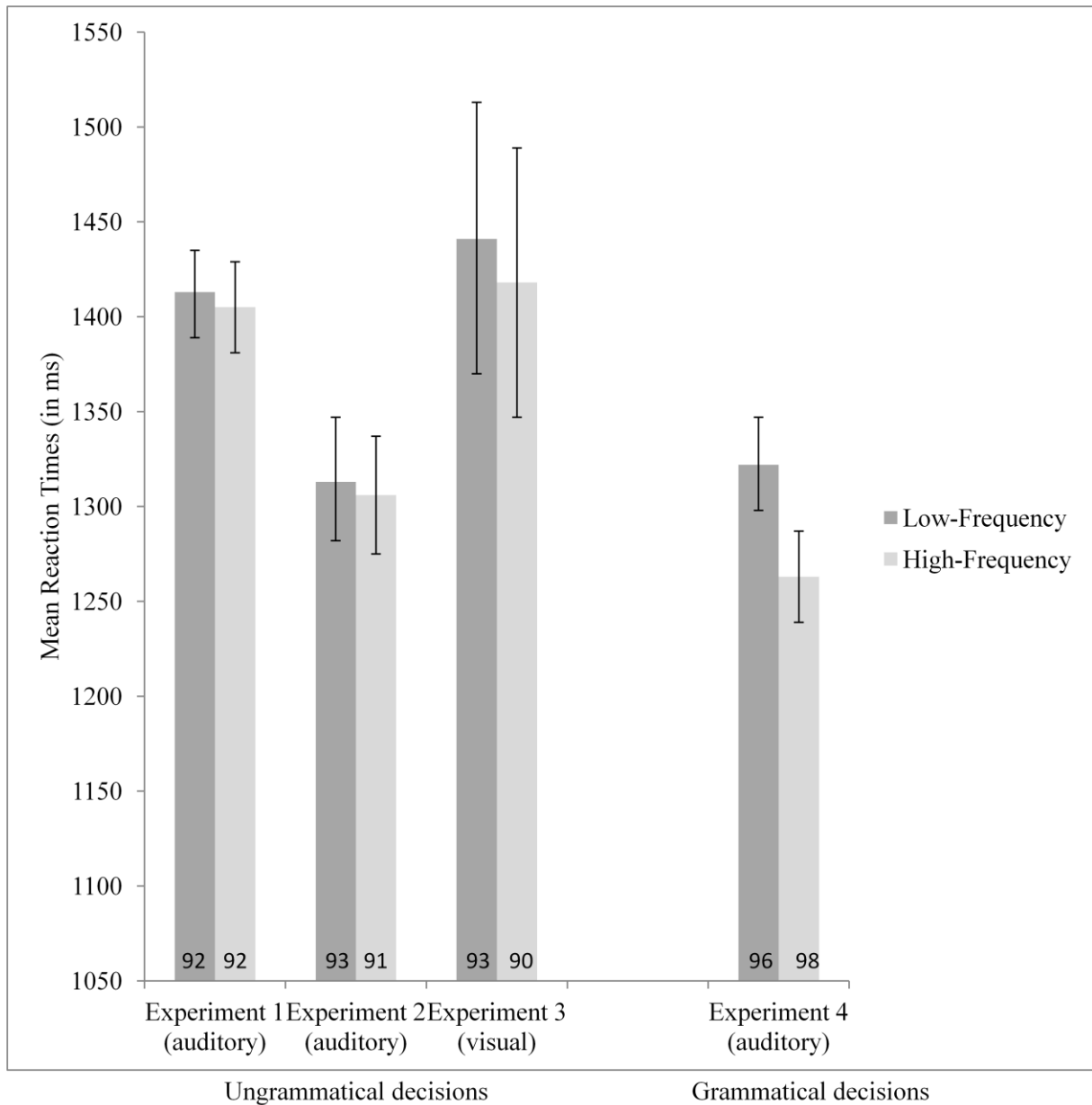


Figure 1: Summary of the mean RTs for the low- and high-frequency sequences in Experiments 1 to 4. Percentages of correct responses in each condition are shown at the bottom of the graph. Error bars are standard errors.

Appendix 1: Four-word phrases used in Experiments 1 to 4 (*not used in Experiments 2 & 3)

High-Frequency condition	Grammatical structure	Low-Frequency condition	Grammatical structure
le moment est venu	art:def nom aux ver	le type est mort	art:def nom aux ver
le dîner est servi	art:def nom aux ver	le plein est fait	art:def nom aux ver
la salle de bain	art:def nom pre nom	le bureau de police	art:def nom pre nom
la scène de crime	art:def nom pre nom	la fête de demain	art:def nom pre nom
une partie de plaisir	art:ind nom pre nom	le champ de maïs	art:def nom pre nom
un mot de passe	art:ind nom pre nom	le gala de charité	art:def nom pre nom
la voie est libre	art:def nom ver adj	le monde est dangereux	art:def nom ver adj
le lieu de travail	art:def nom pre nom	un film de guerre	art:ind nom pre nom
une lampe de poche	art:ind nom pre nom	une boule de poils	art:ind nom pre nom
une femme de chambre	art:ind nom pre nom	un enfant de dieu	art:ind nom pre nom
un morceau de viande	art:ind nom pre nom	un bol de riz	art:ind nom pre nom
une botte de foin	art:ind nom pre nom	un problème de voiture	art:ind nom pre nom
un conte de fées	art:ind nom pre nom	une fin de semaine	art:ind nom pre nom
un numéro de téléphone	art:ind nom pre nom	une poupée de chiffon	art:ind nom pre nom
la veille de Noël	art:def nom pre nom	une école de droit	art:ind nom pre nom
c'est bon signe*	pro:dem ver adj nom	c'est juste impossible*	pro:dem ver adj nom
c'est ma faute*	pro:dem ver adj:pos nom	c'est mon pantalon*	pro:dem ver adj:pos nom
c'est mon père*	pro:dem ver adj:pos nom	c'est mon médecin*	pro:dem ver adj:pos nom
c'est la vérité*	pro:dem ver art:def nom	c'est leur vie*	pro:dem ver adj:pos nom
c'est une blague*	pro:dem ver art:ind nom	c'est le papa*	pro:dem ver art:def nom
je suis si fatigué	pro:per aux adv adj	je suis déjà pris	pro:per aux adv adj
elle est venue ici	pro:per aux ver adv	j'ai tout risqué*	pro:per aux adv ver
il a été tué	pro:per aux ver ver	vous avez laissé faire	pro:per aux ver ver
j'en ai assez*	pro:per pro:per ver adv	il en fait trop	pro:per pro:per ver adv
vous avez cinq minutes	pro:per ver adj:num nom	on a deux options	pro:per ver adj:num nom
vous avez ma parole	pro:per ver adj:pos nom	je veux ton bonheur	pro:per ver adj:pos nom
je fais mon travail	pro:per ver adj:pos nom	vous êtes ma mère	pro:per ver adj:pos nom
vous perdez votre temps	pro:per ver adj:pos nom	je suis votre roi	pro:per ver adj:pos nom
je suis si contente	pro:per ver adv adj	je suis toujours prête	pro:per ver adv adj
je peux tout expliquer	pro:per ver adv ver	je sais tout faire	pro:per ver adv ver
je suis au courant	pro:per ver art:def nom	j'appelle les urgences*	pro:per ver art:def nom
vous avez le droit	pro:per ver art:def nom	nous sommes les parents	pro:per ver art:def nom
il était une fois	pro:per ver art:ind nom	tu as un petit	pro:per ver art:ind nom
on a du boulot	pro:per ver art:def nom	je veux une famille	pro:per ver art:ind nom
j'ai une question*	pro:per ver art:ind nom	nous avons des projets	pro:per ver art:ind nom
je commence à comprendre	pro:per ver pre ver	tu veux à manger	pro:per ver pre ver
on peut le faire	pro:per ver pro:per ver	tu vas les tuer	pro:per ver pro:per ver
tu devrais avoir honte	pro:per ver ver nom	il doit avoir faim	pro:per ver ver nom
Donne-moi ta main	ver pro:per adj:pos nom	crois en mon expérience	ver pro:per adj:pos nom
allons boire un verre	ver ver art:ind nom	venez faire un tour	ver ver art:ind nom

Note: pro:per = personal pronoun; pro:dem = demonstrative pronoun; art:def = definite article; art:ind = indefinite article; ver = verb; adv = adverb; aux = auxiliary; adj:pos = possessive adjective; adj:num = numeral adjective; nom = noun; pre = preposition.