Fast structural priming of grammatical decisions during reading

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Abstract

In two grammatical decision experiments we used fast-priming as a novel method for uncovering the syntactic processes involved in written sentence comprehension while limiting the influence of strategic processes. Targets were sequences of four words that could be grammatically correct or not. Targets (e.g., *they see the moon*) were preceded by the brief (170 ms) presentation of four types of prime: 1) same syntactic structure / same verb (*you see a friend*); 2) same structure / different verb (*she writes a book*); 3) different structure / same verb (*he sees him now)*; or 4) different structure / different verb (*stay in our hotel*). Same structure primes facilitated decisions to grammatical targets in error rates, and this effect did not significantly interact with the facilitatory effect of a shared verb. These results provide evidence for structural priming of sentence reading in conditions that greatly limit any role for strategic processing.

(149 words)

Keywords: Fast-priming; Structural priming; Reading; Grammatical decision task

Introduction

For over 50 years researchers have used structural priming (sometimes referred to as syntactic priming) as a means to gain insights into the complex processes that are involved during sentence processing (e.g., Bock, 1986; Dell & Ferreira, 2016; Mehler & Carey, 1967). Structural priming is said to occur when recent exposure to a specific syntactic structure affects the subsequent processing of sentences having a similar or a different syntactic structure. Different accounts of structural priming effects have been proposed (these will be summarized below), but at present a consensus has yet to be reached in terms of the mechanisms underlying such effects. Moreover, while robust structural priming results have been observed in studies that focused on language production (for a review, see Pickering & Ferreira, 2008), the results are less robust in the domain of language comprehension (see Tooley, 2022; Tooley & Traxler, 2010, for reviews). The present study aims to further our understanding of the mechanisms driving structural priming effects in written language comprehension using a novel methodology with an aim to reduce the impact of strategic processes on such effects.

Evidence that structural priming can be found in spoken language comprehension was provided in an early investigation (Mehler & Carey, 1967) where participants had to report (by writing) auditorily presented sentences embedded in white noise. The test sentences were preceded by a set of 10 context sentences (without noise) that either shared the same syntactic structure as the test sentence or not. Test sentence reporting was more accurate following a syntactically homogenous context. More recent research has shown that structural priming effects in comprehension can also be observed with a single prime sentence as opposed to a context composed of several sentences (e.g., Arai et al., 2007; Branigan et al., 2005; Giavazzi et al., 2018; Pickering et al., 2013; Tooley et al., 2019; Ziegler & Snedeker, 2019). One such study used an ambiguous sentence (e.g., *the policeman prodding the doctor with the gun*) followed by two pictures (e.g., a picture of a policemen using a gun to prod a doctor, and a picture of a policeman using a stick to prod a doctor who does not have a gun), which the participants had to match with the sentence (Branigan et al., 2005). Thus, only one of the pictures matched the prime sentence (i.e., the picture of a policeman using a gun to prod a doctor in this example) and therefore disambiguated the prime sentence. The subsequent target sentence (e.g., *the waitress prodding the clown with the umbrella*) was also followed by two pictures, but now both pictures could match the sentence (i.e., a picture of a waitress using an umbrella to prod a clown, and a picture of a waitress using her finger to prod a clown that holds an umbrella). Branigan et al. found that participants preferred the picture that matched the version of the target sentence that had a similar syntactic structure as the previously disambiguated prime sentence (i.e., the picture of a waitress using an umbrella to prod a clown in this example). Further evidence regarding the influence of the previous sentence on structural priming was provided by Giavazzi et al. (2018). These authors also investigated structural priming with a sentence-picture matching task and varied the homogeneous vs. heterogeneous nature of the syntactic structure (active vs. passive) in a block of trials. Structural priming was observed in both block types. Moreover, it sufficed to have a single prior sentence with the same structure to obtain a structural priming effect.

While some comprehension studies have found evidence for structural priming, this is not the case for all studies (for a review, see Tooley & Traxler, 2010). Importantly, many of the studies that found evidence for structural priming during sentence comprehension only observed this effect when lexical items, typically the verb, were repeated between the prime and target sentence (e.g., Arai et al., 2007; Branigan et al., 2005; Carminati et al., 2008; Tooley et al., 2009; for a discussion, see Tooley, 2022). This so-called “lexical boost” effect could be taken as evidence that priming of syntactic information in the absence of lexical overlap is not sufficient to influence language comprehension. Nevertheless, some studies have shown that lexical overlap is not a necessary condition for obtaining structural priming in comprehension (e.g., Fine & Jaeger, 2016; Giavazzi et al., 2018; Kim et al., 2014; Mehler & Carey, 1967).

Based on the observations of structural priming effects and the evidence for the so-called lexical boost, Pickering and Branigan (1998) proposed an activation-based account of structural priming effects (see also e.g., Ferreira & Bock, 2006). More specifically, their account was founded on the concept of pre-activation, such that presentation of a given syntactic structure leads to the temporary activation of a representation of this structure in short-term memory (STM). When the same structure is used in a consecutive trial, pre-activation of that structure on the preceding trial will facilitate processing of the target sentence. When prime and target sentences also share a lexical representation (e.g., the same verb across prime and target sentence), this results in pre-activation of the connection between the shared lexical representation and the surrounding syntactic structure, which in turn was hypothesized to further facilitate processing of the target sentence.

Learning-based accounts of structural priming provide an alternative explanation of structural priming (e.g., Bock & Griffin, 2000; Fine & Jaeger, 2013; Tooley, 2022). Learning-based accounts are founded on the notion that presentation of a given syntactic structure leads to a relatively long-lasting modification of the strength with which that structure is represented in long-term memory (LTM). In turn, this should lead to facilitation when processing a sentence with the same structure as a previously encountered sentence. The key difference between the activation-based and learning-based accounts of structural priming can be interpreted within the general framework of connectionist models of language processing in terms of the distinction between the pre-activation of representations in STM vs. the updating of connection strengths in LTM (e.g., Grossberg, 1987).

However, there is another possible account of structural priming, namely expectation-based priming. We draw an important distinction here between expectation-based accounts of structural priming and learning-based accounts, both of which differ from fast-acting, automatic, activation-based accounts. This distinction is directly inspired by the seminal work of Neely (1977) on semantic priming of single words. The general idea is that when given enough time (for single primes) or enough context (i.e., repeated occurrences of the same structure with multiple primes), the observed priming effects could well be driven by participants' expectations. Such expectation-driven priming is thought to be generated by controlled strategic processes to be distinguished from more automatic activation-based processes. Evidence for controlled processes affecting priming during comprehension was first established by Neely (1977). Neely manipulated the semantic relatedness between single word primes and targets (e.g., bird-robin; bird-arm; with both priming effects being measured relative to a neutral "XXXX" prime) and varied the stimulus onset asynchrony (SOA) between prime and target stimuli (with primes presented at a fixed 150 ms duration). The key finding was that facilitatory priming effects (bird-robin) were not affected by SOA whereas inhibitory priming effects (bird-arm) diminished as the SOA decreased and disappeared at the shortest (250 ms) SOA. Neely suggested that the longer SOAs led to a greater involvement of controlled processes in driving priming effects (Posner & Snyder, 1975).

In the comprehension-based structural priming studies discussed so far, participants had to process (listen to or read) and typically respond to each prime sentence, which consisted of a minimum of four words. We suggest that such conditions leave plenty of room for priming effects to have been contaminated by controlled processes (i.e., explicit expectations), even in the single prime heterogenous block condition of the Giavazzi et al. (2018) study. In the current study, and following the logic of Neely (1977), we aimed to circumvent the possibility of controlled processes by using very short prime exposure durations. Any evidence for structural priming obtained with brief prime sentence exposures immediately prior to target sentence processing would constitute strong support for automatic activation-based accounts.

Prior research from our group has suggested that 4-word or 5-word written sentences presented as briefly as 170 – 200 ms can generate some form of sentence-level representation (e.g., Mirault et al., 2022; Mirault & Grainger, 2020; Snell & Grainger, 2017). The most relevant evidence with respect to the present study is that of Mirault et al. (2022). In that study, participants performed a grammatical decision task on 5-word sequences. These target sequences were preceded by a prime sequence of 5-words that was 1) either identical to the subsequent target sequence, 2) the same sequence but with two inner words transposed, 3) the same sequence with two inner words replaced by two other words, or 4) different words with a similar syntactic structure. These 5-word primes were presented for 200 ms followed by a 100 ms delay, after which the target sequence was presented. Participants made grammatical decisions to the target sequences. The results showed a repetition priming effect (i.e., better performance after identical primes than when the prime consisted of different words) and a transposed-word priming effect (i.e., better performance after a prime with a transposition of two inner words than after a prime with a replacement of two inner words). This led to the conclusion that fast-priming of grammatical decisions might be a useful tool for uncovering basic processes in sentence comprehension.

The present study builds on the Mirault et al. (2022) study in an investigation of structural priming of written sentence processing under conditions that allow us to minimize the influence of controlled, expectation-based processes. More specifically, participants performed a grammatical decision task in which they were shown a prime consisting of four words for 170 ms followed by a 100 ms delay after which the target sequence of four words was shown. Participants made grammatical decisions to the target sequences.

To investigate the effects of structural priming, we examined whether the same syntactic structure in the prime and its subsequent grammatically correct target sequence would facilitate grammatical decisions to the latter. A secondary goal was to investigate whether this structural priming effect is influenced by lexical overlap. To this end, primes and targets could either have the same or a different verb. Ungrammatical targets were included for the purpose of the grammatical decision task, and the priming conditions for these targets mimicked the primes for the grammatical targets as a further move to minimize strategic/controlled processing (i.e., preventing use of the strategy to respond “grammatical” when some degree of syntactic overlap is detected across prime and target sequences independently of the overall grammaticality of sequences).

Experiment 1

Methods

Participants

We first screened participants using the following criteria: 1) native speakers of French; 2) between 18 and 65 years old; and 3) no diagnosed reading impairment. One hundred native speakers of French (35 women, 61 men, and 4 participants who chose to not disclose gender information) participated with their personal computer in an online experiment for which they received £3 in compensation. The age of participants ranged from 19 to 60 years (M = 33.04 years; SD = 9.72). Prior to initiation of the experiment, participants were informed that data would be collected anonymously, and they then provided informed consent for participation, as well as information concerning age, native language, and gender.

Stimuli & Design

We first created 160 4-word grammatically correct French sentences between 16 and 25 letters in length (average = 19.48; SD =1.92). We performed part-of-speech (POS) tagging for each sequence with the spaCy library (Honnibal & Montani, 2017) and more precisely with the French transformer pipeline (camembert-base) named “fr_dep_news_trf”. Then, we combined the “NUMERICAL” and “ARTICLE” tags, and the “AUXILIARY” and “VERB” tags in order to reduce the number of tags and to simplify stimulus selection. For the grammatically correct target sequences, a total of 42 different syntactic structures (sequences of POS) were used to create these stimuli (see Figure 1 for the most commonly used syntactic structures and the number of times they were used in the experiment, and https://osf.io/45bwd/ for the full list of stimuli). We then generated 4 prime sequences for each target sequence according to 2 factors: POS structure (same vs. different) and verb (same vs different). There was no lexical overlap between primes and targets except in the same verb condition where the verb was the only lexical overlap (see Table 1). To ensure that the different prime sequences were matched in length in number of letters and given the non-normality of the distribution of lengths, a non-parametric test (Wilcoxon signed-rank test) was used to test for differences in length between the four types of prime. None of the pairwise comparisons were significant (all *p*s > 0.11). Together this resulted in the creation of 800 grammatical sequences of 4 words (160 target sequences, 160 prime sequences with the same POS structure & same verb, 160 prime sequences with same POS structure & different verb, 160 prime sequences with different POS structure & same verb and 160 prime sequences with different POS structure & different verb). For the purpose of the grammatical decision task, we then created a set of 160 ungrammatical French target sequences of 4 words and built their prime versions following the same criteria as for the grammatical sequences. The ungrammatical sequences were generated by first creating a new set of grammatical sequences (different from the target grammatical sequences) and then randomly re-ordering the words in these sequences to make them ungrammatical.

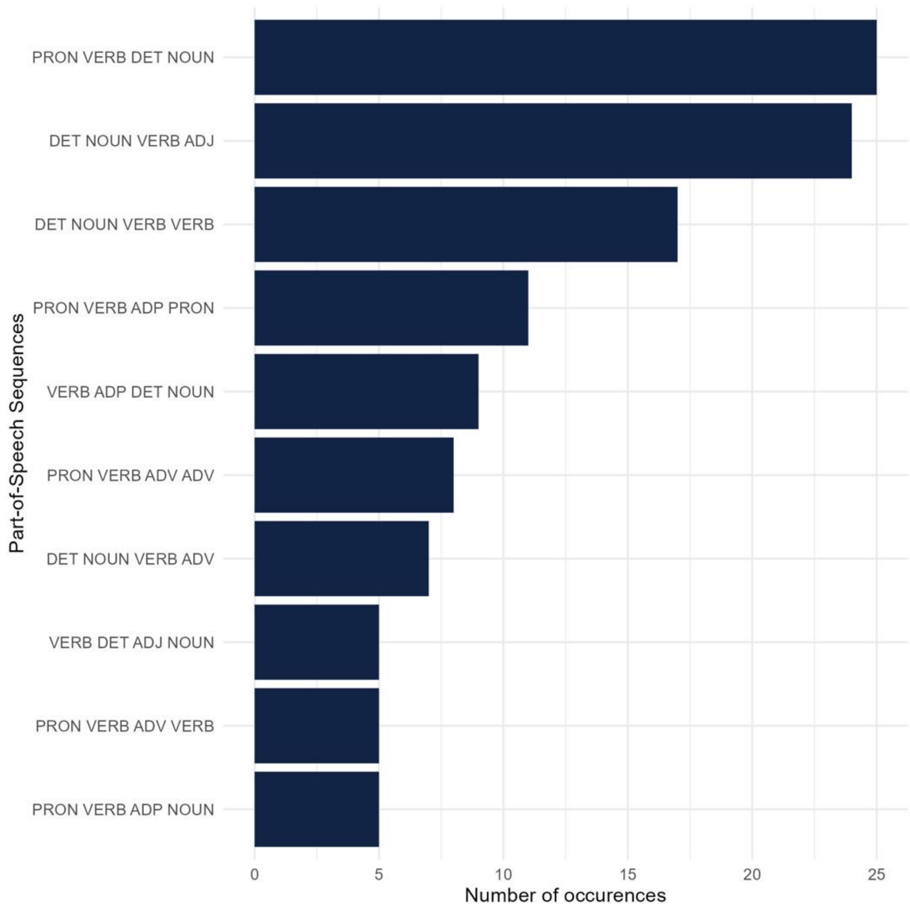

Figure 1. Most commonly used syntactic structures in the grammatical target sequences and number of occurrences per structure in the experiments (PRON = pronoun; DET = determiner; ADJ = adjective; ADP = adposition; ADV = adverb).

Each target sequence (grammatical and ungrammatical) was tested in all four prime conditions leading to a 2 (Structure) × 2 (Verb) factorial design. A Latin-square design was used such that each of the 4 types of prime sequence associated with a given target sequence were tested with different participants, and each participant was tested in all four priming conditions across different targets. Thus, four counterbalanced lists were created, and participants were randomly assigned to one of the lists. There were 40 trials per condition per participant, and therefore a total of 320 trials per participant.

Table 1. Examples of the 4 different types of prime word sequences for the grammatical target "**notre avion est plein**" and the ungrammatical target "**courir un repas avant**".

Grammatical	*Same structure*	**Same verb**	leur photo est nette
		Different verb	ton livre semble épais
	Different structure	**Same verb**	dormir trop est inutile
		Different verb	nous avons un chiot
Ungrammatical	*Same structure*	**Same verb**	courir le chemin sur
		Different verb	aller le métro dans
	Different structure	**Same verb**	courir plus vite bien
		Different verb	ses sont longs cheveux

Apparatus

The experiment was created with Labvanced (Finger et al., 2017) and we used the Prolific platform (Pallan & Schitter, 2018) to recruit participants. Only macOS, PC-Windows, and PC-Linux operating systems were allowed, and only Chrome, Firefox, Microsoft Edge, Safari and Opera browsers were accepted.

Procedure

Seated in front of their computer screen, participants were asked to click on the screen to launch the experiment. After that, they were shown the complete set of instructions for the experiment on a single page. Once they had read and understood the instructions, the participant could start the practice trials by pressing the space bar. The practice session was composed of 8 trials that were representative of the 8 conditions (4 prime conditions for grammatical and ungrammatical target sequences) tested in the main experiment but were not included in the main experiment. Once the practice session was complete, participants were prompted to press the space bar when they were ready to begin the main experiment.

Each trial started with a fixation cross for 250 ms indicating the center of the upcoming sequences. Then a blank screen was presented for 200ms before displaying the prime sequence for 170ms. Next, another blank screen was displayed for 100ms before the target sequence was presented. This target sequence was presented until participant's response. Participants were instructed to press the right arrow key on their computer keyboard if they thought that the target sequence was a grammatically correct sentence in French, or to press the left arrow if not. After their response, they received feedback in the form of a green circle (correct response) or a red cross (incorrect response) shown for 200 ms. Lastly, a final blank screen was displayed for 800ms before the next trial (for a visual depiction of the trial procedure, see Figure 2). A break was proposed after every 80 trials.

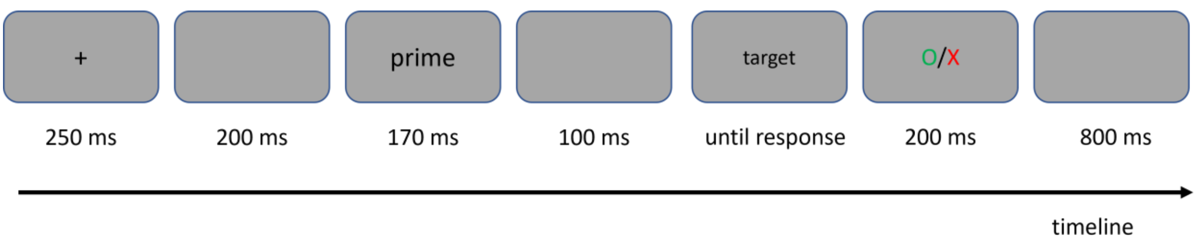

Figure 2. Procedure of one experimental trial in Experiment 1. Both prime and target sequences were presented in Courier New font. Target sequences were presented in size 16 and prime sequences were presented in size 20. In Experiment 2 targets were presented for a fixed duration (500 ms).

Analysis

We used Linear Mixed Effects Models (LME) to analyze response times (RTs) and Generalized (logistic) Linear Mixed Effects Models (GLME) to analyze error rates, with participants and items as crossed random effects (Baayen et al., 2008; Barr et al., 2013). The models were fitted with the lmer (for LME) and the glmer (for GLME) functions from the lme4 package (Bates et al., 2015) in the R statistical computing environment. We report regression coefficients (b), standard errors (SE) and t-values (for LME) or z-values (for GLME). The beta and standard error values obtained in the LME analyses were multiplied by 1000 to avoid zero values. Fixed effects were deemed reliable if |t| or |z| > 1.96 (Baayen, 2008). RTs were log transformed 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.

Results

We analyzed RTs of correct responses and error rates. All participants performed with accuracy above 75%. Prior to analysis, 26 items were removed due to their average accuracy being lower than 75%. Furthermore, we deleted 2.18% of trials with very short RTs (< 150ms) or very long (> 2,500ms) RTs. The remaining dataset was composed of 28,760 observations, with at least 3153 observations per condition (see below for the exact number of observations for each condition), which exceeds the recommendation of Brysbaert and Stevens (2018) for having sufficient power.

With respect to the RT analysis, we also excluded trials with incorrect responses (5.30%) and values lying beyond 2.5 standard deviations from the grand mean (2.99%). The remaining dataset was composed of 26,422 observations. The grammatical and ungrammatical trials were analyzed separately. Results are shown in Figures 3 (grammatical targets) and 4 (ungrammatical targets).

Grammatical targets

Response times

For the grammatical targets, the dataset was composed of 13,768 observations (3473 for *Same Structure/Same Verb*, 3404 for *Same Structure/Different Verb*, 3459 for *Different Structure/Same Verb,* 3452 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = 0.83, SE = 1.60, t = 0.52), and neither was the effect of Verb (b = 2.96, SE = 1.87, t = 1.59). The Structure × Verb interaction was not significant (b = -0.43, SE = 3.20, t = 0.13). Hence, no structural priming effects were observed in the response times.

Error rates

For grammatical targets, the dataset was composed of 14,697 observations (3677 for *Same Structure/Same Verb*, 3662 for *Same Structure/Different Verb*, 3683 for *Different Structure/Same Verb,* 3675 for *Different Structure/Different Verb*). The effect of Structure was significant (b = -0.24, SE = 0.11, z = **2.15**), with more errors made when the structure of the prime and target were different, indicating a structural priming effect. We also found a significant effect of Verb (b = -0.31, SE = 0.08, z = **3.72**), with participants making more errors in the different verb condition. The Structure × Verb interaction was not significant (b = 0.13, SE = 0.17, z = 0.81).

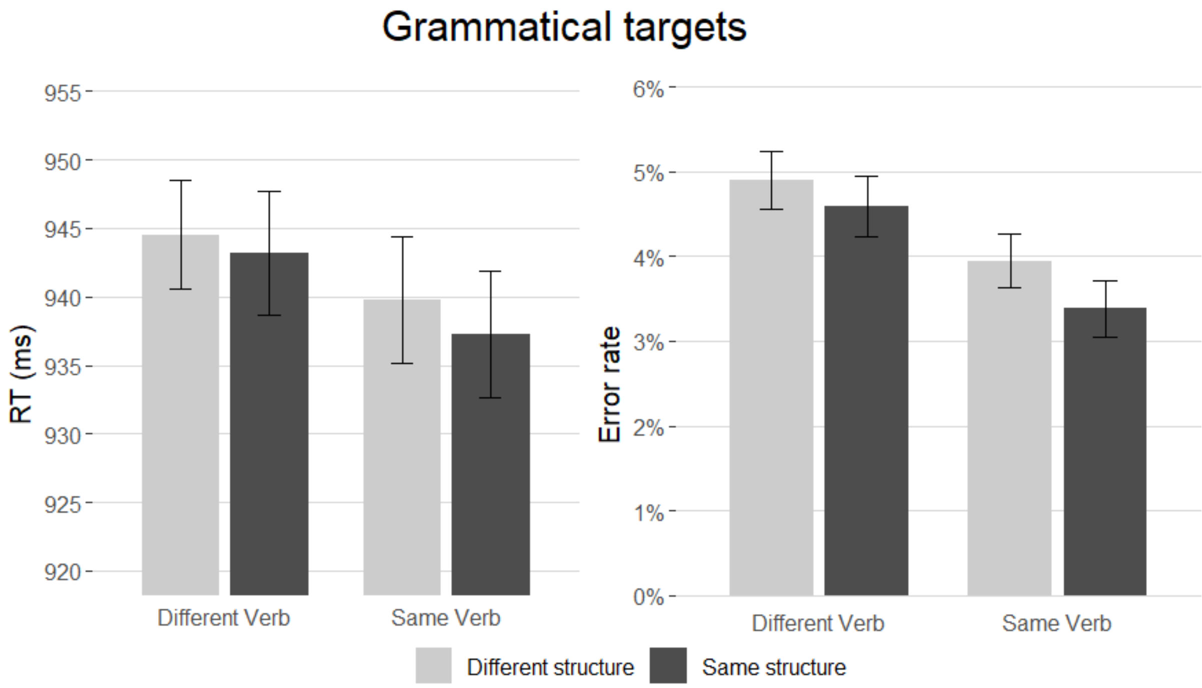

Figure 3. Mean RT (ms) and error rate (%) for the four priming conditions with the grammatical targets in Experiment 1. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005).

Ungrammatical targets

Response times

For ungrammatical targets, the dataset was composed of 12,654 observations (3173 for *Same Structure/Same Verb*, 3166 for *Same Structure/Different Verb*, 3162 for *Different Structure/Same Verb*, 3153 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = 1.16, SE = 1.95, t = 0.60), the effect of Verb was not significant (b = 1.54, SE = 1.83, t = 0.84), and neither was the interaction (b = -1.69, SE = 4.18, t = 0.40).

Error rates

For ungrammatical targets, the dataset was composed of 14,063 observations (3514 for *Same Structure/Same Verb*, 3512 for *Same Structure/Different Verb*, 3532 for *Different Structure/Same Verb,* 3505 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = -0.03, SE = 0.07, z = 0.43), and neither was the effect of Verb (b = 0.05, SE = 0.10, z = 0.50). The Structure × Verb interaction was not significant (b = -0.04, SE = 0.14, z = 0.31).

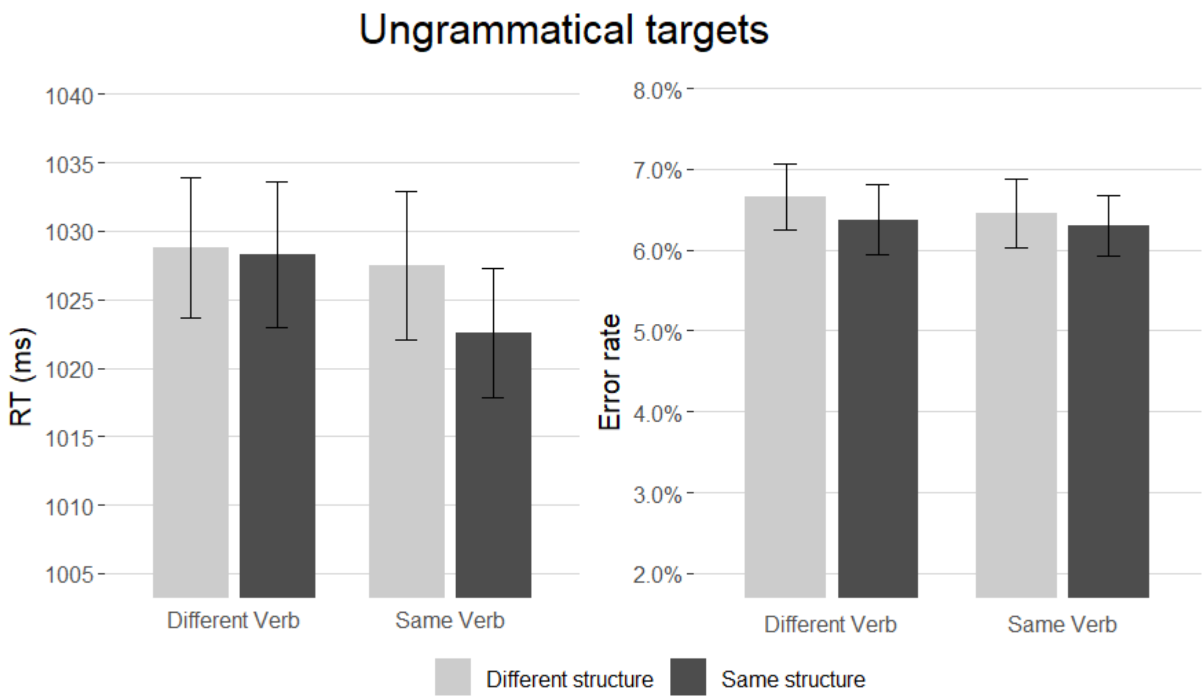

Figure 4. Mean RT (ms) and error rate (%) for the four priming conditions with the ungrammatical targets in Experiment 1. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005).

Discussion

In Experiment 1 we found a significant effect of structural priming, but only in error rates. We also found a significant effect of having the same verb in the prime and target sentences, but this did not impact the effect of structural priming. Given that the key result, a structural priming effect obtained with fast-priming, was only observed in error rates and was quite small in magnitude (0.44 %), we decided to perform a replication. However, rather than conducting a direct replication, we made one small modification to the procedure of Experiment 1. Targets were now presented for a fixed duration of 500 ms. This fixed target duration was implemented with the aim to increase error rates and therefore increase the sensitivity of our fast-priming paradigm combined with the grammatical decision task.

Experiment 2

Methods

Participants

The same screening criteria as for Experiment 1 were applied. One hundred native speakers of French (47 women, 50 male, and 3 participants who did not disclose gender information) participated with their personal computer in an online experiment for which they received £3 in compensation. The age of participants ranged from 19 to 65 years (M = 33.73 years; SD = 11.52). Prior to initiation of the experiment, participants were informed that data would be collected anonymously, and they then provided informed consent for participation, as well as information concerning age, native language, and gender.

Design, stimuli, and procedure

These were the same as in Experiment 1 except that target duration was now fixed at 500 ms.

Results

We used the same analysis as for Experiment 1. Prior to analysis, 10 participants and 46 items were removed due to their average accuracy being lower than 75%. Furthermore, we deleted 0.63% of trials with very short (< 150ms) or very long (> 2,500ms) RTs. The remaining dataset was composed of 24,505 observations, with at least 2543 observations per condition (see below for the exact number of observations for each condition), which exceeds the recommendation of Brysbaert and Stevens (2018) for having sufficient power.

With respect to the RT analysis, we also excluded trials with incorrect responses (6.69%) and values lying beyond 2.5 standard deviations from the grand mean (2.62%). The remaining dataset was composed of 22,266 observations. The grammatical and ungrammatical trials were analyzed separately. Results are shown in Figures 5 (grammatical targets) and 6 (ungrammatical targets).

Grammatical targets

Response times

For the grammatical targets, the dataset was composed of 12,021 observations (3054 for *Same Structure/Same Verb*, 3014 for *Same Structure/Different Verb*, 2991 for *Different Structure/Same Verb,* 2962 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = 3.07, SE = 1.71, t = 1.80), but there was a significant effect of Verb (b = 3.90, SE = 1.82, t = **2.14**) with slower responses in the different verb condition. The Structure × Verb interaction was not significant (b = -3.84, SE = 3.20, t = 1.20).

Error rates

For grammatical targets, the dataset was composed of 12,976 observations (3244 for *Same Structure/Same Verb*, 3246 for *Same Structure/Different Verb*, 3246 for *Different Structure/Same Verb,* 3240 for *Different Structure/Different Verb*). The effect of Structure was significant (b = -0.35, SE = 0.09, z = **3.74**), with more errors made when the structure of the prime and target were different. The effect of Verb was not significant (b = -0.11, SE = 0.08, z = 1.41), and neither was the Structure × Verb interaction (b = 0.24, SE = 0.15, z = 1.55).

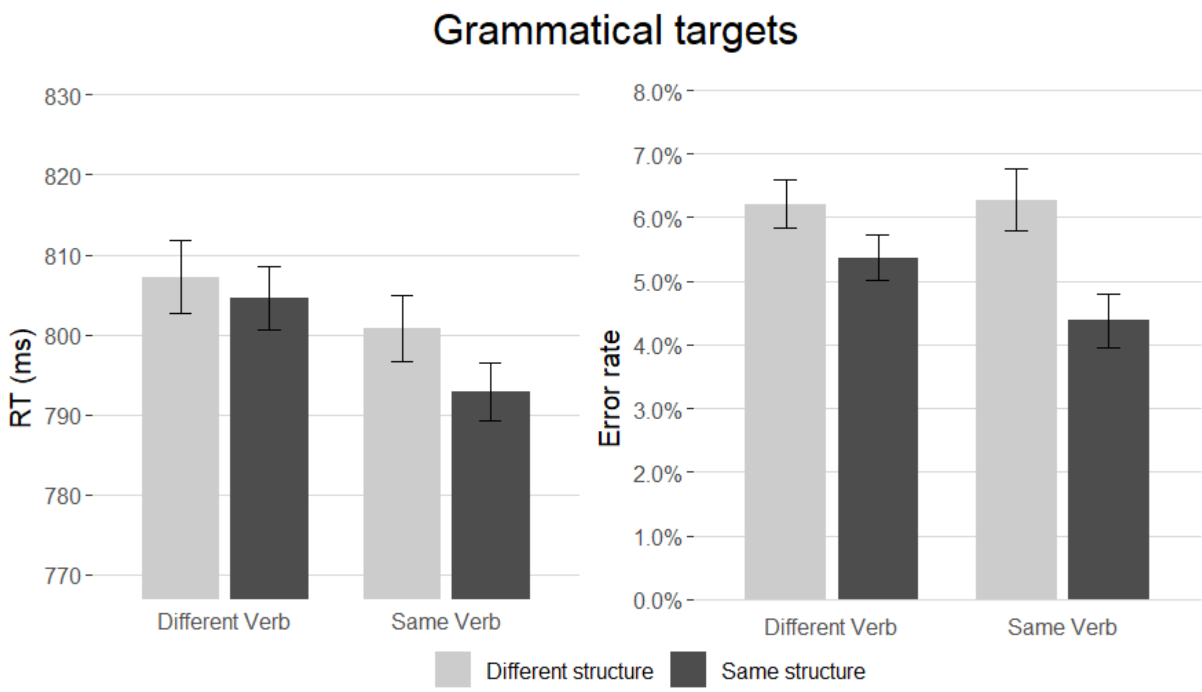

Figure 5. Mean RT (ms) and error rate (%) for the four priming conditions with the grammatical targets in Experiment 2. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005).

Ungrammatical targets

Response times

For ungrammatical targets, the dataset was composed of 10,245 observations (2567 for *Same Structure/Same Verb*, 2581 for *Same Structure/Different Verb*, 2543 for *Different Structure/Same Verb,* 2554 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = -0.30, SE = 1.98, t = 0.15), and neither was the effect of Verb (b = -1.31, SE = 2.00, t = 0.65). The interaction was not significant (b = -2.96, SE = 3.62, t = 0.82).

Error rates

For ungrammatical targets, the dataset was composed of 11,529 observations (2895 for *Same Structure/Same Verb*, 2880 for *Same Structure/Different Verb*, 2877 for *Different Structure/Same Verb,* 2877 for *Different Structure/Different Verb*). The effect of Structure was not significant (b = -0.02, SE = 0.09, z = 0.24), and neither was the effect of Verb (b = 0.10, SE = 0.07, z = 1.43). The Structure × Verb interaction was not significant (b = -0.02, SE = 0.14, z = 0.16).

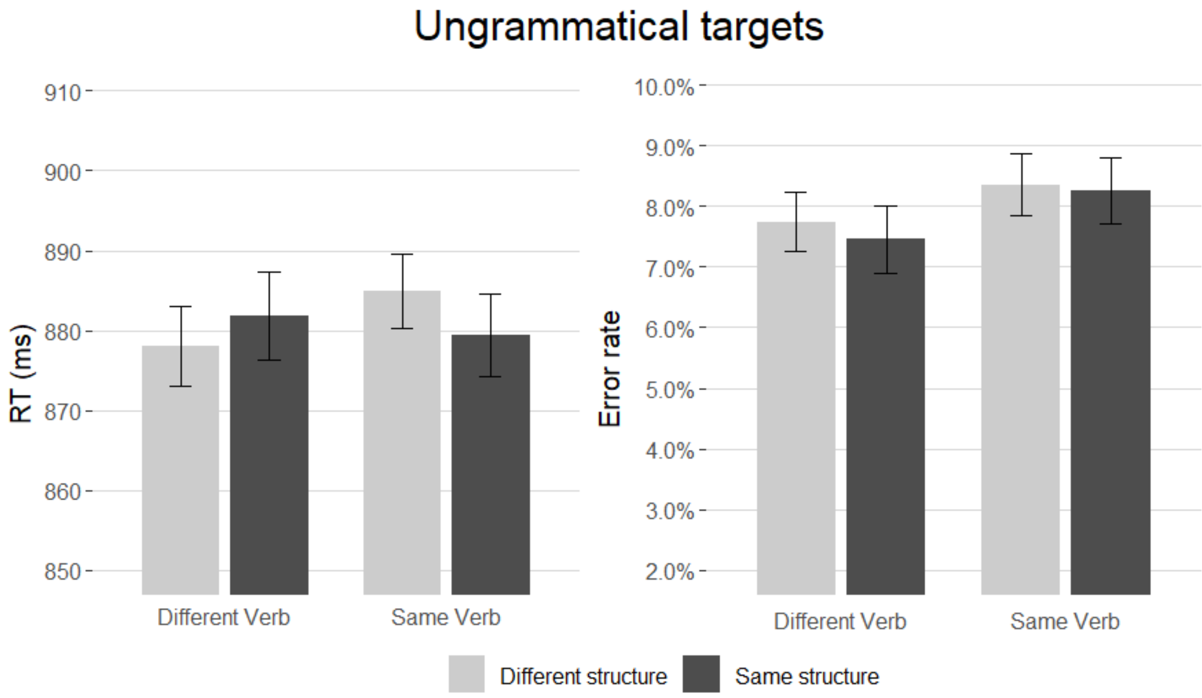

Figure 6. Mean RT (ms) and error rate (%) for the four priming conditions with the ungrammatical targets in Experiment 2. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005).

Discussion

Experiment 2 replicated the findings of Experiment 1, with an effect of structural priming in error rates. We also observed a significant effect of having the same verb in the prime and target sentences, but this time in the RT analysis and not in error rates. The impact of having a shared verb on structural priming effects was again not significant in Experiment 2 (i.e., no significant interactions). Finally, we succeeded in increasing the structural priming effect seen in error rates from Experiment 1 (0.44%) to Experiment 2 (1.36%) by reducing target presentation duration, which also led to an overall increase in error rates.

General Discussion

In two online experiments we examined, for the first time, fast structural priming during reading using the grammatical decision task. The task involved speeded decisions as to whether a sequence of four words was grammatically correct or not. The critical stimuli were the grammatically correct target sequences (the ungrammatical sequences were included for the purpose of the task), and the four types of prime sequence associated with these targets. Primes were presented for only 170 ms and could either have the same syntactic structure as targets and have the same verb (e.g., *you see a friend* as a prime for the target *they see the moon*) or a different verb (e.g., *she writes a book*), or could have a different syntactic structure and again either with the same verb (e.g., *he sees him now)* or not (e.g., *stay in our hotel*). Target sequences remained on screen until participants' response in Experiment 1 and for a fixed duration of 500 ms in Experiment 2. The key finding of the present study is the significant effect of structural priming seen in both experiments, with same structure primes leading to lower error rates on targets (the RTs showed the same numerical pattern). Sharing the same verb also facilitated grammatical decisions in error rates in Experiment 1 and RTs in Experiment 2. Crucially, in both Experiments, the size of structural priming was not significantly influenced by having the same verb in the prime and target sentences. Moreover, the significant effects were only obtained with grammatically correct targets.

The present findings align nicely with those of Giavazzi et al. (2018) who found structural priming in a sentence-picture matching task in conditions that minimized the role of participants' expectations, and this structural priming was obtained independently of whether or not primes shared the same verb as targets (see also Kim et al., 2014). However, our study goes beyond that of Giavazzi et al. (2018) in two important ways: 1) use of the grammatical decision task to study structural priming; and 2) use of very brief prime exposures. Use of the grammatical decision task ensures complete syntactic analysis of the critical grammatical targets and arguably provides a more direct measure of syntactic processing compared with sentence-picture matching for example. Use of very brief prime durations provides a much stricter control over the possible influence of strategic factors (i.e., controlled processing) in driving priming effects (Neely, 1977).

The fast-acting structural priming effects found in the present work are very much in line with the assumptions of activation-based accounts of structural priming (e.g., Ferreira & Bock, 2006; Pickering & Branigan, 1998) that provide a natural mechanism for automatic priming effects. Alternative learning-based accounts (e.g., Bock & Griffin, 2000; Fine & Jaeger, 2013; see Giavazzi et al., 2018, for discussion) do not provide a natural explanation for such fast-acting effects (see Reitter et al., 2011, for a computational model that implements both activation-based and learning-based mechanisms, and provides a highly relevant discussion of the conditions in which these mechanisms can operate). The logic here is that a very brief presentation of a prime sequence does not enable updating of connections strengths in LTM (that would generate learning-based structural priming) but does enable the temporary activation of a syntactic structure in STM (the source of automatic structural priming effects). This logic is based on prior work on priming with visually presented words, whereby long-term priming would require a greater depth of processing of the prime (i.e., conscious identification of the prime word) whereas fast-priming would not.

We therefore suggest that our prime stimuli were activating a primitive syntactic structure, possibly a simple linear combination of parts-of-speech (POS), with sufficient detail to at least partly activate syntactic structures stored in long-term memory, hence leading to the temporary activation of these structures in STM (see Mitchell et al., 1995 for an illuminating analysis of the different grain sizes that might be involved in syntactic parsing, and Bever, 1970, for an early proposal in line with what we have in mind). This temporary activation of syntactic representations in STM then facilitates the subsequent processing of target word sequences that partly match the pre-activated syntactic structure (i.e., a complete match is not necessary). The absence of an interaction with the shared verb manipulation provides additional evidence in favor of the relatively primitive (e.g., unstructured) nature of the syntactic structures driving the present effects. The evidence we found for an effect of shared verbs in the present study, would simply be occurring at a lexical level. Having a shared verb would boost the lexical activation of this word, hence facilitating the retrieval of the corresponding part-of-speech.

Although we had no specific hypotheses with respect to the effects obtained with ungrammatical targets, the fact that we did not see structural priming with such targets is in line with our proposed explanation. The highly ungrammatical nature of these targets (generated by randomly re-ordering grammatical sequences) would not provide a good-enough match with structures in long-term memory to generate the partial activation necessary to obtain a structural priming effect. In sum, much like fast-priming has revealed the automatic activation of letter identities and their positions during visual word recognition, we suggest that our findings reveal the rapid activation of multiple word identities, the corresponding parts-of-speech, and the order of these elements in a sequence of words. We suspect that such processes are key components in enabling the rapid interpretation of text by skilled readers.

Evidence for the rapid activation of parts-of-speech when reading short sequences of words has been obtained with other paradigms (e.g., Snell & Grainger, 2017; Snell et al., 2017; Wen et al., 2019). One such paradigm is particularly relevant here – the Rapid Parallel Visual Presentation (RPVP) procedure, whereby a sequence of words is briefly presented (200 ms), aligned horizontally as in normal text reading, and followed by a pattern mask accompanied by a post-cue that indicates the location of the word that must be reported. Participants simply have to report the identity of the word at the post-cued location. The key finding here is that word identification accuracy is higher when the target word is part of a correct sentence (e.g., the target *man* in *the man can run*) compared with an ungrammatical re-ordering of the same words (e.g., *run man the can*) – a sentence superiority effect (Snell & Grainger, 2017; Wen et al., 2019). We have suggested that the sentence superiority effect reflects the rapid retrieval of the parts-of-speech associated with partially activated word identities when processing a sequence of written words. This then leads to the generation of a primitive syntactic parse of the sequence of words being read (cf. the "good enough" representations proposed by Ferreira & Lowder, 2016), which in turn constrains on-going word identification processes in a cascaded, interactive processing framework. Particularly strong evidence for this approach was provided by Declerck et al. (2020) who showed that the sentence superiority effect can be observed in bilingual participants when presented with mixed-language sentences such as *ses feet sont big* (from the English *his feet are big* and the French *ses pieds sont grands*). Declerck et al. proposed that language-independent parts-of-speech are retrieved from the different words in the mixed-language sequences and could therefore activate a primitive language-independent syntactic structure (i.e., an ordered set of language-independent parts-of-speech without language-specific hierarchical structuring).

Conclusions

The present findings provide further support for the rapid, automatic activation of a syntactic representation upon reading a sequence of words. We suspect that this syntactic representation is initially a linear sequence of parts-of-speech associated with the word identities that are being processed. Syntactically legal (ordered) combinations of parts-of-speech would be stored in long-term memory, at least for relatively short and frequently occurring combinations. Hence activation of this primitive syntactic representation can be sustained long enough to facilitate the subsequent processing of grammatically correct target sequences having the same syntactic structure. However, it is clear that future explorations of fast structural priming are necessary in order to clarify why the effects only emerged in error rates in the present study, and in which conditions (if any) effects might also be found in RTs. Moreover, combining fast sentence priming with EEG recordings should provide a valuable means to specify the time-course of component processes in written sentence comprehension, much like the combination of fast-priming and EEG recordings have helped elucidate the time-course of component processes in visual word recognition (e.g., Grainger & Holcomb, 2009).

Declarations

Competing interests **-** The authors declare no conflicts of interest.

Ethics - Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (No. 17/051).

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Authors' contributions – CF: stimulus selection, programming, data analysis, writing. JM: supervision, data analysis; MD: design, writing. JG: design, writing, supervision.

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