

Sentence superiority in the reading brain

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SHORT TITLE

Neural sentence superiority

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ABSTRACT (N= 213)

A word is better recognized when presented in a grammatical sequence of words (e.g., within a sentence) than when presented in an ungrammatical sequence of words. This sentence superiority effect was recently demonstrated in a series of behavioral experiments where participants had better word identification rates for all positions in a sentence relative to an ungrammatical sequence of the same words. A previous EEG investigation of this phenomenon pointed toward an online, automatic processing of linguistic information starting at around 270 ms post-stimulus onset. Taken together, these results support the idea of an early role of the syntactic network in facilitating the recognition of a word presented in a sentence context, leading to the question of how this network is set in motion. To answer this question, we conducted an MEG experiment and source analysis of the brain areas implicated in syntactic processing. Source activations over time showed grammatical vs. ungrammatical differences first in the inferior frontal gyrus (325-400 ms), then the anterior middle temporal gyrus (475-525 ms), and finally in both in the inferior frontal gyrus and the posterior middle temporal gyrus (550-600 ms). We interpret the spatio-temporal dynamic of the sentence superiority effect in terms of an Interactive-Activation model with bottom-up activations and top-down influences operating between word and sentence-level representations.

KEYWORDS

Sentence superiority effect; Grammatical decision; Syntax; Reading; Parallel processing;

1. Introduction

The sentence superiority effect reflects the literate brain's ability to better recall a grammatically correct sequence of words compared with an ungrammatical sequence. Since its discovery by Cattell (1886, in Scheerer, 1981), it has been used to study the relational binding of words according to certain syntactic and grammatical rules (see Roverud et al., 2020, for an overview). Typically, in such studies, words are presented one after another (serially) either in a visual or auditory modality. Recently Snell and Grainger (2017) asked whether or not such an effect could be observed using a brief visual parallel—rather than serial—presentation of a sentence. In this paradigm—the Rapid Parallel Visual Presentation (RPVP) procedure—a word would be better recognized when it is embedded in a structurally coherent (grammatical) sequence. Such a finding would echo the word superiority effect, whereby a letter is better identified when presented embedded in a word rather than a random string of letters (Cattell, 1886, Reicher, 1969, Wheeler 1970). Snell and Grainger asked their participants to identify a single target word that was embedded either in a 4-word sentence or in an ungrammatical scrambled sequence of the same words. The authors were interested in knowing whether a 200-millisecond display of a word sequence was sufficient for a coarse syntactic structure to emerge, which could influence word identification accuracy. The results showed that words-in-sentences were recognised with better accuracy (+20%) than words in random sequences, regardless of their position in the sequence. This effect, initially studied in literate adults, was also found in 9-year-old primary school children who showed a smaller but significant accuracy gain of around 10% (Massol & Grainger, 2020).

The sentence superiority effect observed with the RPVP paradigm raises the question as to the mechanisms driving this effect. Snell and Grainger interpreted their finding in an Interactive-Activation framework (McClelland & Rumelhart, 1981) where a fast bottom-up activation of sentence-level structures (when these are available) would reinforce word identification processes via top-down feedback from sentence-level structures to words. This interpretation was further strengthened in Declerck et al. (2020) where bilingual participants performed a RPVP post-cued word identification task on stimuli mixing two languages (French and English). The authors found clear evidence that the sentence superiority effect was driven by the rapid association of word identities with their parts-of-speech (i.e., lemma access) followed by the computation of a primitive syntactic structure. However, an alternative explanation for the sentence superiority effect obtained with the RPVP paradigm could appeal to the sophisticated-guessing explanation of the word superiority effect (Johnston, 1978). That is, identification of part of the sentence context (one or two words and their feasible syntactic

relationship) would enable participants to make informed guesses about the identity of the post-cued target word given partial information about that word (one or two letters).

To put these two interpretations to test, an electroencephalography (EEG) experiment was conducted by Wen et al. (2019) using the same materials and procedure as Snell and Grainger (2017). The authors found a difference in the event-related potential (ERP) traces that started at around 270 ms with the bulk of the sentence superiority effect occurring in an early onset N400 component. Such an effect, emerging within the classical time-window of lexical access as revealed by EEG studies (see Grainger & Holcomb, 2009, for a review), pointed to online, automatic processing of linguistic information rather than offline guessing procedures as the source of the sentence superiority effect, thus advocating in favour of an Interactive Activation explanation of this phenomenon (see Wen et al., 2020, for a similar timing of ERP effects in the RPVP paradigm but with a grammatical decision task).

Here, we conducted a similar experiment to Wen et al. (2019) but using magnetoencephalography (MEG) rather than EEG in order to better characterize both the timing of the visual sentence superiority effect and its location in the literate brain. MEG affords much higher spatial resolution than EEG and is thus the gold standard technique for cortical source reconstruction. For the present experiment, we used the same materials and procedure as the two preceding studies (Snell & Grainger, 2017; Wen et al., 2019), however our participants had to report the post-cued target word out loud rather than write it with a keyboard (due to constraints of working with MEG).

The central hypothesis guiding the present study is that the sentence superiority effect is primarily a syntactic effect (Declerck et al., 2020). We therefore expected that syntactic cortical networks, previously identified in other modalities and procedures, would be activated under RPVP presentation conditions. In psycholinguistics, syntax is traditionally studied in the auditory modality where participants hear sentences. In this modality, the literature shows that syntax plays a 2-stage role in sentence processing: a recognition phase and an integration phase (Friederici, 2011). During the recognition phase, syntax acts first at the word or lemma level: a word is recognized along with its syntactic category (e.g., table-NOUN). This recognition process is local both in terms of visual features (recognition of a single word or a small group of words) and brain location. Early syntactic activation takes place in the inferior frontal gyrus (IFG), which includes Broca's area and is thought to be highly automatic in the sense that its activation is task-independent. ERP and MEG studies in the auditory modality suggest that syntactic violations (e.g., word category errors like "films about America" that is syntactically correct and "films America about" that is not) activate the IFG at around 120-200 ms

(Friederici et al., 2000, Gross et al. 1998, Herrmann et al., 2011). Subsequent activations during the early phase of building syntactic structures also involve the temporal cortex (posterior superior temporal gyrus (pSTG), overlapping with Wernicke's area). There, words and their associated parts-of-speech are integrated with each other to form a unique syntactic entity through online construction of linguistic hierarchies. This is thought to be the location of sentence-level syntactic processing (Pallier et al., 2011). In ERP studies, sentence-level processes are reflected by an N400 component that was first identified by Kutas and Hillyard (1980). Subsequent studies found, for example, that the N400 effect to semantic violations was increased by an additional gender-based syntactic violation (Hagoort, 2003), or that semantically incorrect sentences generated a more negative going waveform than correct sentences (e.g., Hahne & Friederici, 2002). The second step—the integration phase—combines the lexico-semantic and syntactic information to accomplish comprehension (Osterhout & Holcomb, 1992; Bornkessel & Schlesewsky, 2006). Although the least well-characterized of the processes involving syntax, this step is thought to involve a reanalysis of the syntactic structure that has been computed and eventually a syntactic repair. Such processes are reflected in the P600 ERP component that originates from the pSTG (Grodzinsky & Friederici, 2006). In addition to Friederici's model (for a detailed description, see Friederici, 2017), Price (2012) also described the anterior and posterior middle temporal gyrus (aMTG; pMTG) as playing a role in the processing of semantic information associated to syntactic entities. In the neuroscientific literature, aMTG has been identified as a semantic hub - a domain-general associative memory system that is modality-invariant and links visual and auditory features (Patterson & Ralph, 2016), while pMTG supports semantic processing during language comprehension (Lau et al., 2008).

In our MEG study, we compared source activations associated with visually presented syntactically valid 4-word sequences and those associated with scrambled ungrammatical sequences of the same words. From the literature reviewed above, we identified four regions of interest (ROIs) according to their potential role in the visual sentence superiority effect. We predicted that these ROIs would activate sequentially reflecting a multi-stage model of syntactic processing: IFG (word-level syntax) and pSTG (sentence-level syntax) are thought to activate first in a 120-600 ms time-window, followed by aMTG (syntactico-semantic integration, forming part of the anterior temporal lobe, ATL) and pMTG (comprehension). The final activation related to syntax would originate from the pSTG (syntactic control and repair) in a time window later than 600 ms.

2. Materials and methods

Material and methods exposed below closely follow those of the reported studies conducted in the MEG center of La Timone Hospital, Marseille, France.

2.1. *Participants.*

Twenty native French speaking adults (mean age= 23.65 years; range= [20;30]; SD= 3.01; 14 women; 6 men) were included in this research and earned EUR 50 for participation. All the participants were recruited from Aix-Marseille University (France). In order to prevent adding unnecessary noise in the MEG signal, participants with non-removable piercings or surgical implants were not included in this study. Participants were asked not to wear metallic or magnetic jewelry and to avoid using cosmetic products. Participants were monolingual French native speakers, had no record of neurological or psychiatric disorders and had regular or corrected hearing and vision. This study was carried out in accordance with the recommendations of the French ethics committee (Comité de Protection des Personnes SUD-EST IV No. 17/051). All participants gave written informed consent in accordance with the Declaration of Helsinki.

2.2. *Stimuli and experimental design.*

Materials from Snell and Grainger (2017) were used in this experiment. It consisted of four-hundred 4-word sequences that were either syntactically correct or not (word length, average= 4.03, SD= 0.82 letters; word frequency, average= 5.66, SD= 1.08 Zipf unit¹; 200 syntactically correct sequences). The set of sequences was built in the following way. First, two hundred syntactically correct sequences were constructed and tested using cloze probability measures to ensure that they were semantically neutral (for details, see Snell & Grainger, 2017). Syntactically incorrect sequences were then derived from the correct pool: each correct sequence was associated with an incorrect sequence that was composed of the same words but in a different order. Within each pair of sequences, a word was chosen as the target (used in the identification task; counter-balanced across trials using the 4 possible word positions) and remained in the same position within the two sequences while the three other words were randomly permuted to form the incorrect sequence. This procedure ensured that the obtained scrambled sequence was not syntactically correct while keeping intact the properties of the individual words composing the pair of sequences. To avoid within-participant stimulus repetition, two counterbalanced lists of 200 sequences each (100 syntactically correct and 100 syntactically incorrect sequences) were created, and participants were assigned to one of them. As such, all stimuli were presented in both syntactic conditions (across two participants) and each participant was presented a single member of a sequence pair. Each list of 200-word sequences was divided into 4 blocks of 50 sequences. A 2 (Grammatical vs. Ungrammatical) x 4 (within-sequence word target position) factorial design was used, and stimulus order was randomized within blocks.

2.3. Procedure.

We used E-Prime software (Psychology Software Tools, 1999) to implement a visual post-cued word-in-sequence identification task where 4 horizontally aligned words were briefly presented (RPVP paradigm). Each trial began with the visual presentation of a fixation sign in the centre of the screen consisting of 2 bars vertically separated by an empty space (see figure 1). After 500 milliseconds (ms), the empty space was filled by a sequence (either syntactically correct or incorrect) for 200 ms. The sequence's letters were then replaced by a post-mask formed of hash symbols (#) preserving between-word spaces and inter-letter spacing. The post-mask consisted of two colours: the hashes replacing the target word were displayed in yellow and the three other locations were displayed in white. The task consisted of naming the word which had appeared in the cued (yellow) position. The stimulus remained on screen until a verbal response was given. When E-Prime detected an oral response, the visual word sequence disappeared, leaving an empty screen for 100 ms followed by a stimulus composed of a single letter "C" (from the French word *cligner* – to blink) in the middle of the screen presented for 1500 ms. A trial ended with a final empty screen of 100 ms. Participants were instructed to fix the empty space in between bars at the beginning of the trial and to blink only during the "C" phase of a trial. Vertical bars remained on screen from the start of the trial to the display of the letter C. All visual stimuli were displayed using a white 18pt bold Courier New font on a black background.

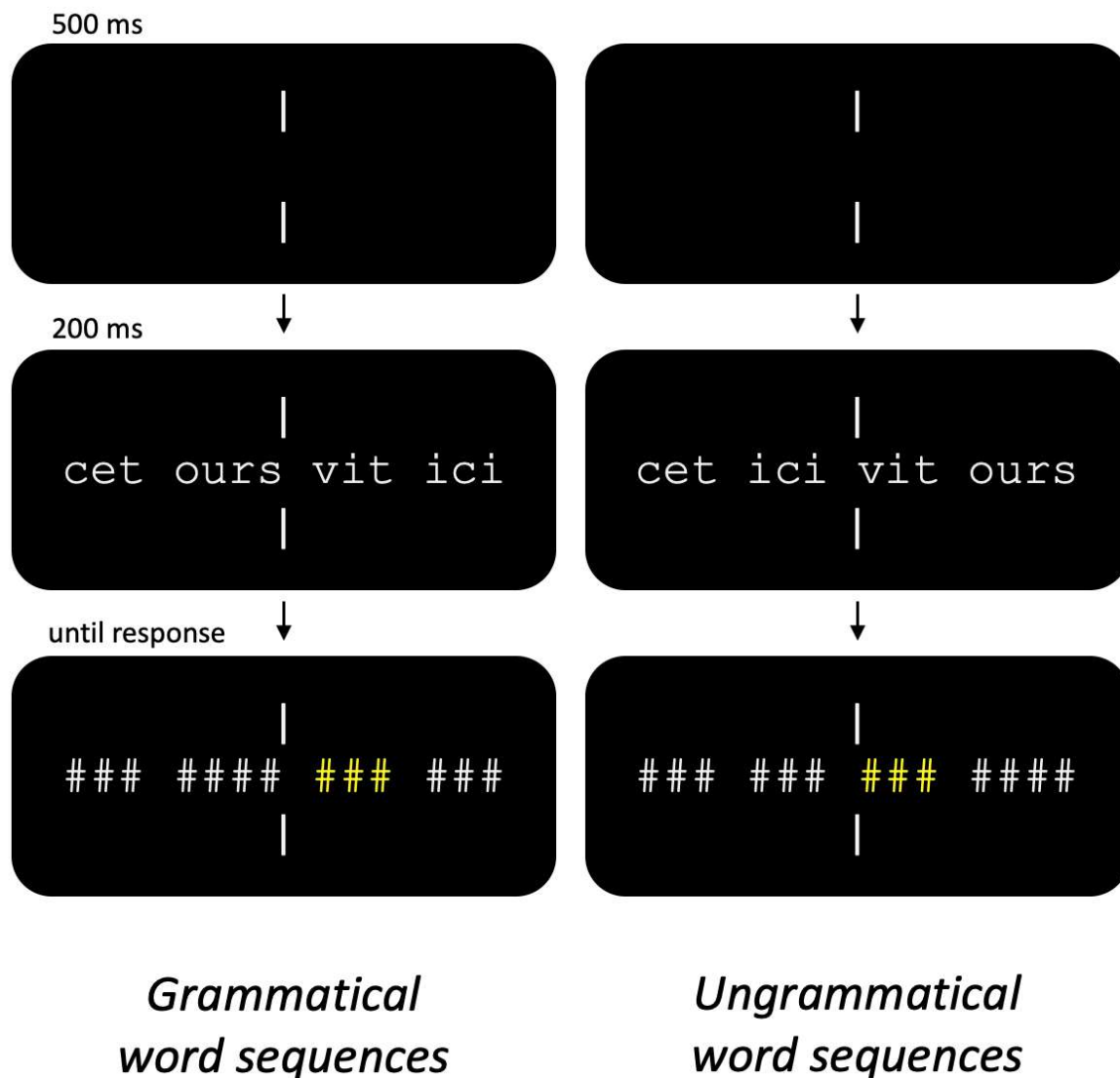


Figure 1. Trial description for the grammatical (left panel) and ungrammatical (right panel) word sequences. After an initial fixation stimulus was displayed for 500 milliseconds (ms; see Methods section 2.3), a word sequence appeared that was either syntactically correct (*cet ours vit ici* - this bear lives here) or not (*cet ici vit ours* - this here lives bear). The word sequence was visible for 200 ms.

2.4. Data acquisition and analysis. The data were acquired on a 248-channel whole-head 4D Neuroimaging MEG system at La Timone Hospital in Marseille, France (4D Neuroimaging, San Diego, CA). Sampling rate was 2035 Hz. Individual head shapes, consisting of the forehead, nose, and the location of the head-position coils were digitized using a 3D Polhemus Fastrak device (Polhemus Inc., Colchester, VT, USA). Five head-positioning coils were attached to the forehead and periauricular points to determine the position of the head. Head position was captured at the beginning of the first

and third block to check and possibly compensate for differences in head position between the first and second half of the stimuli set. Participants were lying inside a magnetically shielded room and were instructed to move as little as possible. Stimuli were presented on an 1024x768 resolution video-projector screen placed about 40 cm in front of participants. The exact timing of stimuli onset was captured using a photodiode that detected brightness changes on the presentation screen. A non-magnetic microphone (Sennheiser MO2000) was placed nearby the participant's mouth (without skin contact) to capture verbal responses. A stereo audio file was recorded during the entire experiment, with one channel dedicated to the participant's verbal output and another one to record clicks corresponding to the word sequence display onset timing. Verbal output was coded off-line for the correctness of the response. Following Gross et al. (2013), an electrooculogram was recorded throughout the experiment to capture the activity of eye movements as well as an electrocardiogram for heartbeats.

Continuous data processing was performed using Anywave (Colombet et al., 2015) for visual rejection of channels showing excessive noise, muscle, or SQUID jump artifacts, for filtering (1- to 300-Hz bandpass) and independent component analysis (runica algorithm) to identify and remove the heartbeat and blink artifacts. Brainstorm (Tadel et al., 2011) was used for additional filtering (25-Hz lowpass), for epoching signal segments time-locked to word sequence onset (-200 to 800 ms), trial rejection and averaging. Data processing and source reconstruction were performed independently for each participant. Artifact-free epochs were averaged separately for each experimental condition to obtain event-related fields (ERFs) for each participant. This average was then projected onto the cortical surface using a free orientation, cortically constrained minimum norm estimation (MNE) procedure (Hauk, 2004; Hämäläinen & Ilmoniemi, 1994). The MNE was weighted by a sample estimate of sensor noise covariance matrix obtained from empty room recordings for each of the participants, and used for improved data modelling as is typical in MNE approaches (Baillet et al., 2001; Dale et al., 2000). The MEG forward model was obtained from overlapping spheres fitted to each participant's scalp points (Huang et al., 1999). For all participants but three, cortical surface extraction was performed on individual MRI images using BrainSuite (Shattuck & Leahy, 2002). For the three participants having a non-conclusive extraction, sources were constrained to a cortical surface mesh template obtained from the MNI ICBM152 brain. Brainstorm was used with default parameters to warp the template to each participant's digitized head shape. The norm of the three source time series at each cortical voxel (i.e., conversion of orientation-unconstrained sources to flat maps, taking the norm of the three elementary dipoles at each time step, yielding only one value by vertex) was extracted. The difference was taken between the source projections for the two conditions for each

participant, then the difference was z-scored with respect to the $[-200, 0]$ milliseconds baseline, and absolute value transformed, thus yielding a single value corresponding to the difference in activation between conditions by vertex at each time point.

Four regions of interest (ROIs; see figure 2) corresponding to the brain areas discussed in the introduction were defined: inferior frontal gyrus (IFG; $x=47$, $y=143$, $z=85$, $N=287$ vertices), posterior superior temporal gyrus (pSTG; $x=30$, $y=90$, $z=93$, $N=227$ vertices), anterior temporal lobe (ATL; $x=28$, $y=121$, $z=58$, $N=184$ vertices) and posterior middle temporal gyrus (pMTG; $x=29$, $y=92$, $z=70$, $N=144$ vertices). To obtain the time course for each ROI, the average difference between the conditions (described above) was taken over all the vertices comprising that region. This ROI time course was then compared to the baseline using a t-test procedure¹ (one-tail, positive) with an alpha level of 0.05, and a Bonferroni correction for multiple comparisons over the time dimension. Only regions with at least 50ms continuously above the alpha threshold were considered significant.

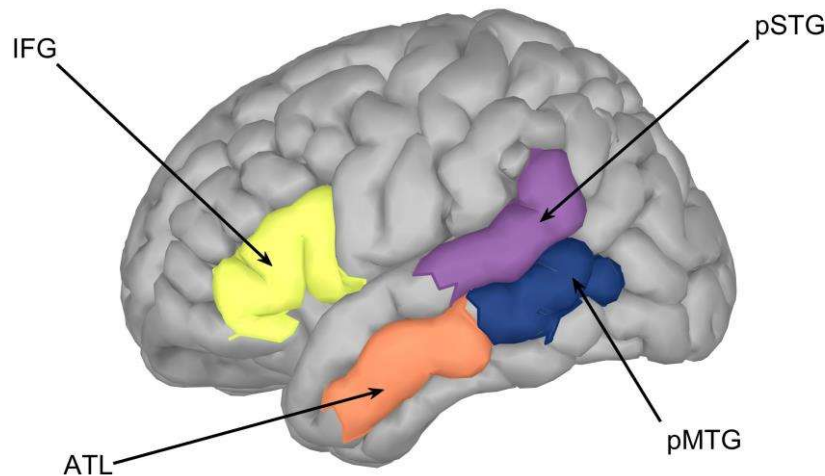


Figure 2. An illustration of the ROIs selected for their noted role in syntactic processing. IFG: inferior frontal gyrus; pSTG: posterior superior temporal gyrus; ATL: anterior temporal lobe; pMTG: posterior middle temporal gyrus.

3. Results

Accuracy results of the word-in-sequence identification task were analyzed in 2 (Grammatical, Ungrammatical) x 4 (Positions) logistic mixed-effects regression modeling (Jaeger, 2008). Overall, individual words were better identified when such words were presented in a syntactically-correct sequence (62.4% for Grammatical, 50.3% for Ungrammatical), $b=0.83$, $SD=0.36645$, $z=2.26$ ($\Pr(>|z|)=0.024$). The effect of Position and the interaction between Position and Grammaticality were not significant.

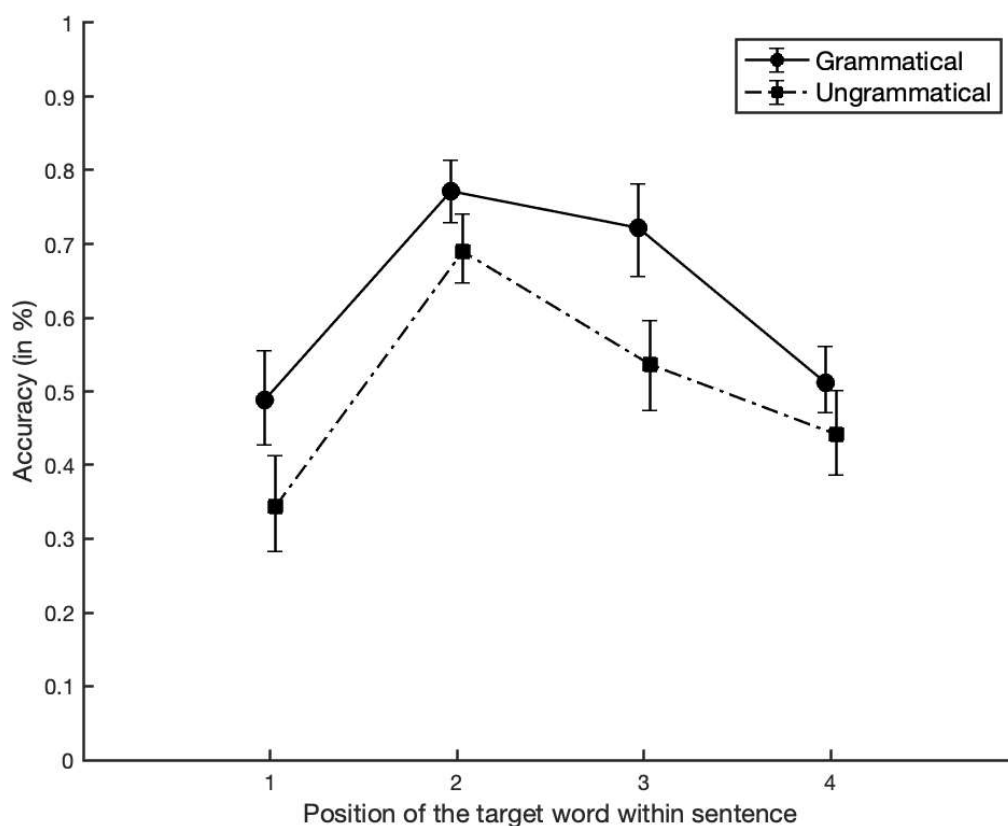


Figure 3. Mean accuracy per position of the target word (1: most leftward word of the horizontal sequence; 4: most rightward). Responses in the Grammatical condition (words in grammatical sequences) had a higher accuracy than responses in the Ungrammatical condition (words in ungrammatical sequences) in all the word positions. Error bars correspond to the bootstrapped by-participant 95% confidence interval standardized for participants across positions (Cousineau, 2005).

Cortical source activations for the Grammatical and Ungrammatical conditions in 4 ROIs (inferior frontal gyrus, IFG; posterior superior temporal gyrus, pSTG; anterior temporal lobe, ATL; posterior middle temporal gyrus, pMTG) were compared using a Bonferroni-corrected t-test at each time point. Three out of the four ROIs gave a significant difference (see figure 5): IFG in 2 time-windows (321-406 ms; 549-602 ms), ATL in a single time window (466-531 ms) and pSTG in a single time window as well (553-622 ms).

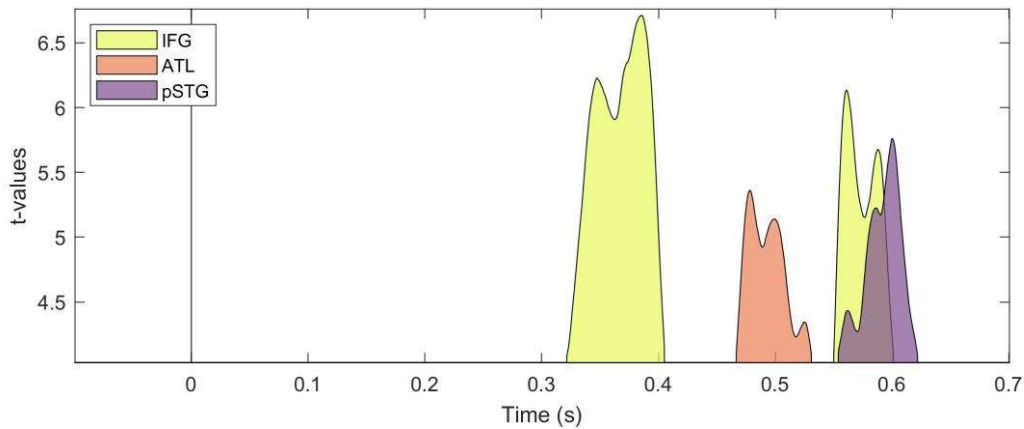


Figure 4. Results of a t-test comparing the Grammatical-Ungrammatical difference against baseline for the 4 ROIs in the [-100; 700] ms time window across participants (Bonferroni-corrected; minimum of 50 milliseconds of continuous positivity). Y-axis scale for t-values was cut at significance value (~ 4.1).

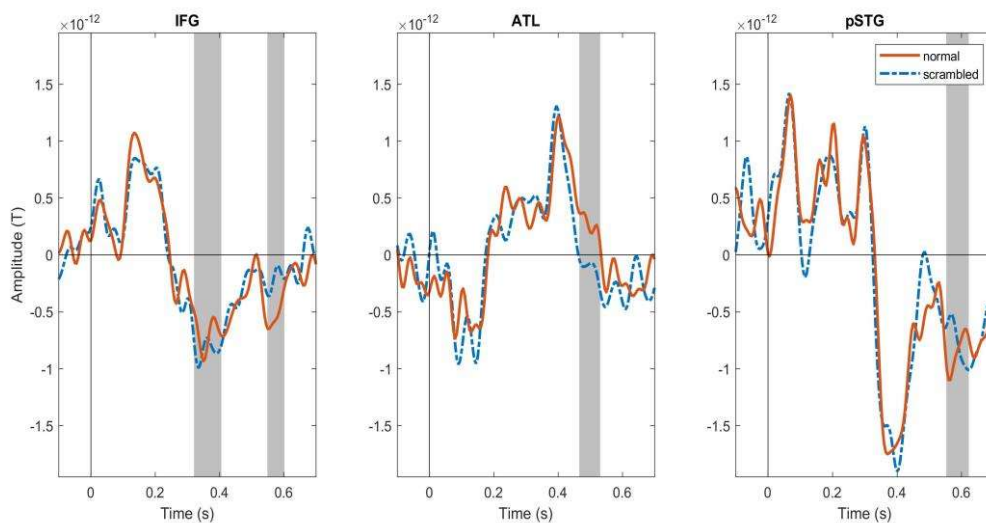


Figure 5. Average source activations for the Grammatical and Ungrammatical conditions for the 3 ROIs with significant differences between conditions. Gray areas represent regions of statistical significance of Bonferroni-corrected t-tests

4. Discussion

Presented in the context of a sequence of written words, a word is better recognized when the sequence is grammatical (i.e., within a sentence or a phrase) rather than an ungrammatical word sequence. This sentence superiority effect was recently brought to light in a series of behavioral and EEG experiments that used a post-cued partial report Rapid Parallel Visual Presentation (RPVP; Snell & Grainger, 2017; Wen et al., 2019). In these studies, an enhanced word identification rate was noted for all the 4 possible positions in the sequence.

Here, we used the materials and procedure of Snell and Grainger (2017) in an MEG setting to study the spatio-temporal dynamics of the sentence superiority effect. As expected, behavioral results revealed the standard sentence superiority effect (grammatical accuracy > ungrammatical). Accuracy curves displayed an inverted U-shaped function similar to the 2 previous studies where overall performance was higher for the second- and third-word positions relative to the first and last (although the overall effect of Position was not significant). Critically, the sentence superiority effect was not sensitive to the word location manipulation. That is, the effect was present in all 4 of the word positions within the sequence. This pattern is evidence that some form of sentence-level representation had been computed even with the very brief (200 ms) stimulus exposures used in the RPVP paradigm. Based on a review of the literature, we identified 4 ROIs as brain regions involved in syntactic processing. Source activations over time show grammatical vs. ungrammatical differences first in the IFG, then ATL, and finally in both IFG and pSTG.

First IFG activation. A previous EEG investigation using the same linguistic materials as in the present study found an effect in an early N400 window (274- 410 ms) where ungrammatical sequences produced more negative-going waveforms than the grammatical condition (Wen et al., 2019). Such a time scale is similar to our first significant time-window in the IFG (321-406 ms). However, in Friederici's (2017) model of syntax in the brain, the IFG processes the earliest phase of syntactic processing in an even earlier time window (120-200 ms). Is this timing difference an indication of

different cognitive processes? We think that this is likely given that in our study, words were displayed simultaneously for a brief duration, while the evidence for syntactic processing at 120 ms was obtained using spoken sentences in which a misplaced word of different part-of-speech disrupted the sentence's syntactic regularity as heard by the participant. Hagoort and Brown (2000) tested more directly comparable conditions across modalities, where spoken sentence processing was compared to sentence reading using rapid serial visual presentation (RSVP). They found an early left anterior negativity (ELAN) only in the spoken condition. In addition, other studies investigating the ELAN component in reading failed to find evidence for this, but described a later anterior negativity in the 300-500 ms window (see e.g., Newman et al., 2007; Roehm & Haider, 2009). Finally, Steinhauer and Drury (2012) questioned the reliability and validity of ERP data supporting "syntax-first" models based on the evidence for early syntactic activities such as ELAN. For these authors, the existence of the very first syntactic stage is not supported by a critical reading of the evidence published in the literature. They argued that syntactic processing starts at 300 ms even in spoken sentence processing. On the other hand, the difference in timing between Friederici's first stage and our MEG result does not mean that syntax is not processed first in IFG. There is no doubt that syntactic violations generate an activity in the IFG, and that this activation is modality-independent (for evidence, see the fMRI study of Constable et al., 2004). Whether or not this left anterior negativity arises as early as 100-300 ms or later (300-500 ms), Broca's area appears to play an integral role in early sentence processing.

ATL activation. Activation of anterior MTG has not been previously shown in syntactic experiments. Indeed, Friederici's model links the first IFG activation directly to pSTG. Our report therefore brings a new player in the game. As exposed in the introduction, aMTG has been identified as a memory hub linking visual and auditory features (Price, 2012). It is therefore not surprising that this structure should be involved in our recognition task. So why have activations of this structure not previously been documented? One hypothesis would be that the brain is wired for spoken language processing and therefore spoken material would not be required to be linked to any other form of modality. On the contrary, written material would be linked to its associated auditory counterpart representation

at some point to form a unique modality-independent representation. Since our experimental design relies on the difference between grammatical and ungrammatical sentences, aMTG activation reflects that one type of stimulus only is linked to its phonological counterpart, inferring that this type must be the grammatical stimuli. Intuitively, aMTG can only be activated after a first representation of syntax is built and serves as a hub linking visual- to auditory-based information.

pSTG and second activation of IFG. The final structures that played a role in our sentence superiority manipulation were more in line with the model of Friederici, with pSTG being thought to be the host of syntactic reanalysis and repairs. However, the second phase of IFG activation appears more surprising even if Yamada and Neville (2007) found an ERP P600 component that was anteriorly distributed. This activation might be related to a verification process at the word level where IFG stores the identity of a word along with its syntactic category.

5. Conclusion

Taken together, cortical activations elicited by a visual syntactic manipulation form a clear network when one thinks of cerebral processes within an Interactive-Activation model with bottom-up activations and top-down influences. In this hypothetical view, afferences from grammatical written word sequences activate the IFG within 300 ms from stimulus onset. In IFG, a first coarse representation for syntax is coded that would then be refined by neural structures in pSTG via a top-down influence. In our visual task, IFG would be modality-specific, coding the written material, while pSTG would be modality-independent, coding a general form of syntactic representation for both visual and auditory modalities. IFG would be a syntactic buffer and pSTG a syntactic memory storing long-term representations. The role of aMTG, linking IFG and pSTG, would be essential in transcoding a visually-based syntactic information to a general syntactic area.

Our proposed syntactic network slightly differs from Friederici's model that we described in the introduction, less in term of location than in term of timing of activations. Indeed, parallel visual

presentation of word sequences triggers cognitive processes that are specific to this presentation modality. In the present article, we capitalized on the literature of single- and multiple word recognition by framing such syntactic processes within a classical model of word recognition. It represents a first attempt to explore the rapid parallel visual presentation of grammatical and ungrammatical word sequences, and certainly more studies are needed to better characterize the underlying syntactic network.

FOOTNOTES

1. Comparison was made on the mean over all vertices in the ROI.

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