

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21

**Towards a causal role of Broca's area in language:  
A TMS-EEG study on syntactic prediction**

Matteo Maran<sup>a,b</sup>, Ole Numssen<sup>c</sup>, Gesa Hartwigsen<sup>c</sup>, Angela D. Friederici<sup>a</sup> & Emiliano Zaccarella<sup>a</sup>

<sup>a</sup>Max Planck Institute for Human Cognitive and Brain Sciences, Department of  
Neuropsychology, Stephanstraße 1a, 04103, Leipzig, Germany

<sup>b</sup>International Max Planck Research School on Neuroscience of Communication: Function,  
Structure, and Plasticity, Stephanstraße 1a, 04103, Leipzig, Germany

<sup>c</sup>Max Planck Institute for Human Cognitive and Brain Sciences, Lise Meitner Research Group  
Cognition and Plasticity, Stephanstraße 1a, 04103, Leipzig, Germany

Correspondence should be addressed to:

Matteo Maran

Stephanstraße 1a, 04103 Leipzig, Germany

Phone: +49 (0) 341 9940 2566

Fax: +49 (0) 341 9940 113

E-mail: [maran@cbs.mpg.de](mailto:maran@cbs.mpg.de)

1 **ABSTRACT**

2 Categorical predictions have been proposed as the key mechanism supporting the fast pace of  
3 syntactic composition in human language. Accordingly, grammar-based expectations facilitate the  
4 analysis of incoming syntactic information—e.g., hearing the determiner “the” enhances the  
5 prediction of a noun—which is then checked against a single or few other word categories. Previous  
6 functional neuroimaging studies point towards Broca’s area in the left inferior frontal gyrus (IFG)  
7 as one fundamental cortical region involved in categorical prediction during on-line language  
8 processing. Causal evidence for this hypothesis is however still missing. In this study, we combined  
9 Electroencephalography (EEG) and Transcranial Magnetic Stimulation (TMS) to test whether  
10 Broca’s area is functionally relevant in predictive mechanisms for language. Specifically, we  
11 transiently perturbed Broca’s area during the categorical prediction phase in two-word  
12 constructions, while simultaneously measuring the Event-Related Potential (ERP) correlates of  
13 syntactic composition. We reasoned that if Broca’s area is involved in predictive mechanisms for  
14 syntax, disruptive TMS during the processing of the first word (determiner/pronoun) would mitigate  
15 the difference in ERP responses for predicted and unpredicted categories when composing basic  
16 phrases and sentences. Contrary to our hypothesis, perturbation of Broca’s area at the predictive  
17 stage did not affect the ERP correlates of basic composition. The correlation strength between the  
18 electrical field induced by TMS and the magnitude of the EEG response on the scalp further  
19 confirmed this pattern. We discuss the present results in light of an alternative account of the role of  
20 Broca’s area in syntactic composition, namely the bottom-up integration of words into constituents.

21

22 **KEYWORDS**

23 Broca’s area, syntax, prediction, two-word, phrase, EEG, TMS

## 1 1. INTRODUCTION

2 The combination of words into larger units is a hallmark of the human language faculty. A  
3 compositional engine overcomes the size of the lexicon, making it possible to convey an infinite  
4 number of meanings from a limited set of words. Syntactic rules are at the basis of this process,  
5 binding words into hierarchically structured phrases and sentences according to grammatical  
6 categorical information (Berwick et al., 2013; Chomsky, 1995; Everaert et al., 2015; Friederici et  
7 al., 2017).

8 At the neural level, the analysis of grammatical category is prioritized over other linguistic  
9 information (Friederici, 2011), mirroring the central role of syntactic composition in language. This  
10 is reflected in the earliness of the Event-Related Potential (ERP) components elicited by syntactic  
11 categorical violations (e.g., *\*the forget<sup>1</sup>*), such as the Early Left Anterior Negativity (ELAN,  
12 Friederici et al., 1993; Neville et al., 1991), the Early Syntactic Negativity (ESN, Hasting & Kotz,  
13 2008) and the Syntactic Mismatch Negativity (sMMN, Hasting et al., 2007; Herrmann et al., 2009).  
14 The latencies of these components show that categorical analysis occurs in approximately 200-250  
15 milliseconds (ms), preceding thematic and semantic relations (Friederici, 2011). Syntactic effects  
16 are also observed on early perceptual components when the presence of closed-class morphemes or  
17 orthographic cues facilitates category recognition (Dikker et al., 2009, 2010). This first step of  
18 syntactic analysis occurs in a highly automatic fashion, as the sMMN and ESN effects are also  
19 elicited in the presence of distracting conditions (Batterink & Neville, 2013; Hasting et al., 2007;  
20 Hasting & Kotz, 2008; Herrmann et al., 2009). Moreover, the ELAN is not influenced by task-  
21 specific strategies or the probability of violation occurrence (Hahne & Friederici, 2002; Hahne &  
22 Friederici, 1999).

23 The earliness of categorical analysis has been proposed to rely on syntactic predictive  
24 mechanisms (Dikker et al., 2009, 2010; Jakuszeit et al., 2013; Lau et al., 2006). According to this

---

<sup>1</sup> The symbol \* is conventionally used in theoretical linguistics to indicate an ungrammatical construction.

1 hypothesis, syntactic predictions restrict the grammatical information to be checked against a target  
2 category (e.g., *The* → prediction for a noun) and allow fast analysis of incoming words.  
3 Computationally, this idea is reminiscent of left-corner parsing models (Abney & Johnson, 1991;  
4 Hale, 2014; Resnik, 1992), which perform incremental syntactic analysis by opening a phrase as  
5 soon as its leftmost element is encountered (e.g., *The* → opening of a determiner phrase and  
6 prediction for a noun). At the neural level, this hypothesis is grounded on the assumption that the  
7 brain minimizes the processing load of incoming input by top-down predictions, which are passed  
8 from higher to lower levels of the functional architecture (Friston, 2003; Friston & Kiebel, 2009;  
9 Rao & Ballard, 1999). When the current input does not correspond to the expected one, a mismatch  
10 signal (i.e., the prediction error) is generated and the internal model is updated (Den Ouden et al.,  
11 2012; Friston, 2005; Garrido et al., 2007). Accordingly, the earliness of the ELAN would then  
12 reflect an incremental parsing process in which syntactic information of incoming words is checked  
13 against a single predicted candidate category (e.g., noun) or its left-side modifiers (e.g., adjectives).  
14 Overall, the use of structural information driving categorical expectations converges on data  
15 showing that preceding context facilitates different stages of linguistic analysis, including  
16 orthographic or phonological processing, lexical access and semantic integration (see Kuperberg &  
17 Jaeger, 2016 and Pickering & Gambi, 2018 for two recent reviews).

18 Evidence for the existence of categorical predictions in language comes from behavioural,  
19 neurophysiological and hemodynamic data. At the behavioural level, predictions driven by syntactic  
20 structure have been shown to influence fixation times when reading sentences (Boston et al., 2008).  
21 A second eye-tracking study, in which the final word of a sentence was displayed in one of two  
22 positions on the screen according to its grammatical category, found anticipatory eye-movements  
23 towards the correct target position, suggesting that participants used syntactic structures to inform  
24 categorical predictions (Bonhage et al., 2015). Going to the most basic two-word level, recent data  
25 showed faster recognition of target categories (noun or verb) when they were coherent with the  
26 expectation triggered by the primes (determiners and pronouns), independently of whether the

1 primes were presented above or below awareness threshold (Berkovitch & Dehaene, 2019). At the  
2 neurophysiological level, Lau and colleagues (2006) showed that the amplitude of the ELAN  
3 depends on the strength of categorical predictions induced by the previous context. The authors  
4 observed that an ungrammatical sentence continuation elicited a smaller ELAN than the control  
5 condition when an ellipsis configuration softened the expectancy for a noun. Converging evidence  
6 comes from electroencephalography (EEG) studies employing narratives, which showed that  
7 metrics reflecting grammar-based expectations predict the signal elicited by incoming words  
8 (Brennan & Hale, 2019; Hale et al., 2018). Finally, at the two-word level increased oscillatory  
9 synchronization was observed before pseudo-verbs preceded by pronouns (Segaert et al., 2018),  
10 possibly reflecting the expectation for syntactic composition to occur with an upcoming verb  
11 element (see Lewis et al., 2015, 2016 and Meyer, 2018 for reviews on the oscillatory dynamics of  
12 linguistic analysis and prediction).

13 At the neuroanatomical level, syntactic violations are known to engage the left perisylvian cortex  
14 (Friederici et al., 2003; Herrmann et al., 2012; Suzuki & Sakai, 2003; Vandenberghe et al., 2002).  
15 Activity in these regions seems to be modulated by surprisal, a metrics reflecting how much the  
16 current grammatical information is unexpected given the previous context (Brennan et al., 2016;  
17 Henderson et al., 2016; Shain et al., 2020). However, it is unclear whether these studies isolated  
18 brain regions involved in generating or checking grammatical predictions. To the best of our  
19 knowledge, we are aware of only one study that directly investigated the generation of categorical  
20 prediction at neural level (Bonhage et al., 2015). In this experiment, the fMRI analysis was  
21 constrained by the timing of prediction generation, indicated by the anticipatory eye-movements  
22 towards the position of a target category. When only the structural information could be extracted  
23 from the context, increased activation as a function of syntactic prediction was observed in Broca's  
24 area. Broca's area is a region situated in the left inferior frontal gyrus (IFG), and its structural (Finkl  
25 et al., 2020) and functional (Trettenbrein et al., 2020) profile point towards a role in modality-  
26 independent linguistic computations, based on grammar (Chen et al., 2019; Chen, Goucha, et al.,

1 2021; Chen, Wu, et al., 2021). This region is well-known to support linguistic composition, as  
2 shown by numerous fMRI studies (Graessner et al., 2021; Makuuchi et al., 2009; Pallier et al.,  
3 2011; Schell et al., 2017; Snijders et al., 2009; Tyler et al., 2010; van der Burght et al., 2019;  
4 Zaccarella, Meyer, et al., 2017), lesion data (Friederici et al., 1998, 1999) and meta-analytical  
5 findings (Hagoort & Indefrey, 2014; Zaccarella, Schell, et al., 2017). Within Broca's area, the pars  
6 opercularis (Brodmann area, BA, 44) has been specifically linked to syntactic composition based on  
7 abstract categorical representations, as structure-building effects in this region are also observed  
8 during the processing of jabbberwocky phrases or sentences (Goucha & Friederici, 2015; Zaccarella  
9 & Friederici, 2015a). Given that in jabbberwocky conditions content elements (e.g., nouns, verbs,  
10 adjectives) are replaced by pseudowords, activity in BA44 might be amplified by the highly  
11 predictive nature of the functional elements (determiners, prepositions, morphological particles)  
12 retained within the stimuli. Furthermore, increased directed connectivity from BA44 to the left  
13 middle temporal gyrus (MTG) is observed when two-word phrases start with a function word  
14 compared to a non-predictive element (Wu et al., 2019), possibly reflecting the top-down  
15 transmission of a categorical expectation.

16 The hypothesis that Broca's area and specifically BA44 is involved in generating categorical  
17 predictions appears to be coherent with computational parsing models and functional data from the  
18 neuroimaging literature, and is in line with the existence of domain specific circuits supporting  
19 predictive processes in language (Shain et al., 2020). However, conflicting evidence and theoretical  
20 views not supporting this notion have also being reported. First, words whose grammatical category  
21 is not expected, but which can nonetheless be integrated in a grammatical construction, do not seem  
22 to elicit an ELAN (Friederici et al., 1996). This early independence between grammaticality and  
23 predictive mechanisms has been also reported in sMMN-based studies, where the neural response to  
24 different grammatically correct phrases is not modulated by the frequency of occurrence of the  
25 phrase under analysis (Herrmann et al., 2009; Pulvermüller & Assadollahi, 2007). Secondly, given  
26 that increased activity in Broca's area is also observed for syntactic categorical violations

1 (Friederici et al., 2003; Herrmann et al., 2012), it is not possible to exclude that this brain region  
2 licenses syntactic structures via a bottom-up process rather than predict them. As a matter of fact, a  
3 very recent fMRI study showed that Broca’s area activity correlates with indexes of bottom-up  
4 integration during naturalistic listening (Bhattasali et al., 2019). Similarly, increased activity in the  
5 left IFG has been reported as a function of whether a word can be integrated or not in the syntactic  
6 context (Hultén et al., 2019). Third, recent data suggest that a careful examination of apparent pre-  
7 activation effects is necessary. While initial data supported the notion that probabilistic information  
8 can be used to anticipate properties of upcoming words up to the phonological level (DeLong et al.,  
9 2005), a recent large-scale replication study showed that this effect might be absent or much smaller  
10 than originally thought (Nieuwland et al., 2018). Finally, theoretical views have emerged which put  
11 forward the notion that this process might not be a necessary component of linguistic  
12 comprehension (Huettig, 2015; Huettig & Mani, 2016).

13 At present, no causal evidence exists for or against the existence of categorical predictive  
14 processes located in Broca’s area. The absence of the ELAN in patients with lesions in Broca’s area  
15 (Friederici et al., 1998, 1999) supports a causal role of this region in syntactic composition, but does  
16 not discriminate between predictive and bottom-up processes. Both accounts are compatible with  
17 the absence of the ELAN, either because no categorical expectation is formed or because the  
18 integration phase is disrupted. A similar argument applies to a clinical study of Jakuszeit and  
19 colleagues (2013). Here we begin to address the computational role of Broca’s area in syntactic  
20 composition by testing one of the two competing hypotheses. In particular, we tested the causal role  
21 of Broca’s area in generating categorical predictions by using focal perturbations induced by short  
22 trains of Transcranial Magnetic Stimulation (TMS). When delivered “online” (i.e., during the task),  
23 TMS allows to test causal relationships between the targeted area and a specific cognitive process  
24 of interest (Hartwigsen, 2015; Pascual-Leone et al., 1999; Siebner et al., 2009; Walsh & Cowey,  
25 2000). Our experiment represents the first investigation of the causal involvement of Broca’s area in  
26 generating syntactic predictions by combining three elements:

- 1        1. An ESN paradigm in which syntactic categorical predictions are generated at the basic two-
- 2            word level (determiner → prediction for a noun, pronoun → prediction for a verb), and
- 3            fulfilled (grammatical constructions) or violated (ungrammatical constructions).
- 4        2. An ERP analysis measuring the different brain responses to prediction fulfilment and
- 5            violation.
- 6        3. A TMS approach with high temporal resolution to causally link Broca's area to a specific
- 7            stage of syntactic analysis (i.e., the generation of predictions).

8

9    We reasoned that, if Broca's area is causally involved in syntactic predictive processes, TMS-

10 induced disruption of this region during the prediction phase (determiner or pronoun processing)

11 will attenuate the difference between expected and unexpected categories (nouns or verbs), which

12 appear as second words in grammatical and ungrammatical constructions, respectively. More

13 specifically we expect to find evidence for a Grammaticality\*TMS interaction on the ESN

14 amplitude, which we will further quantify using Bayesian statistics. At the most fine-grained level,

15 we characterize the effect of TMS on categorical predictive processes by looking at the correlation

16 between the strength of the electrical field induced by the stimulation in Broca's area and changes

17 in the ESN amplitude. If, conversely, our experiment will not support a causal role of Broca's area

18 in syntactic composition at the predictive stage, a reversed account relying on bottom-up integration

19 processes can be instead proposed for the region.

20

## 21    **2. METHODS**

### 22    **2.1 Participants**

23    Thirty native German speakers were recruited for the experiment. Due to the presence of strong

24 artifacts in the EEG signal, one subject was excluded from the analysis. Therefore, twenty-nine

25 subjects were included in the statistical analysis (fifteen female; mean age: 27.1 years, standard

26 deviation: 4.1 years). All participants were right-handed (mean laterality quotient: 93.3, standard



1 deviation: 9.5), as assessed with the Edinburgh handedness test (Oldfield, 1971), had normal or  
2 corrected-to-normal vision, and no colour blindness. None of the participants presented  
3 contraindications against TMS or had history of psychiatric or neurological disorders. Participants  
4 gave their written informed consent and were reimbursed 12€ per hour for participating in the study.  
5 The study was approved by the local ethics committee (University of Leipzig) and was conducted in  
6 compliance with the Declaration of Helsinki guidelines.

7

## 8 **2.2 Paradigm**

9 Our experiment employed an adapted version of a standard two-word auditory ESN paradigm with  
10 syntactic categorical violations, previously published in the literature and frequently used to test  
11 neural sensitivity to syntactic composition (Hasting et al., 2007; Hasting & Kotz, 2008; Herrmann  
12 et al., 2009, 2012; Jakuszeit et al., 2013). The first word of each utterance was the German  
13 determiner “Ein” (*a*) or the personal pronoun “Er” (*he*), while the second word could be either a  
14 noun or verb. Thirty-two pairs of nouns and verbs with an ambiguous stem were used (e.g., “Fech-  
15 ter”, *fencer*, and “fech-tet”, *fences*, see section 2.3). Each second word was presented once  
16 following the determiner and once following the personal pronoun, resulting in four possible types  
17 of trials, two grammatical (*a + noun*, *he + verb*) and two ungrammatical (*a + verb*, *he + noun*). The  
18 grammatical and ungrammatical conditions consisted of sixty-four trials each, as thirty-two pairs of  
19 nouns and verbs were used. The conditions of the paradigm are summarised in Table 1.

20 Grammaticality constitutes the first factor in our experimental design, reflecting whether the second  
21 word matched the categorical prediction triggered by the first one (grammatical items) or not  
22 (ungrammatical items). Importantly, with this paradigm, grammaticality is orthogonal to both the  
23 identity of the first word (“Ein” or “Er”) and the grammatical category of the second word (noun or  
24 verb), therefore ruling out potential confounding factors. As previously shown (Hasting & Kotz,  
25 2008), ungrammatical items result in an increased ESN response, functionally equivalent to the  
26 ELAN observed with longer stimuli (Friederici, 2011).

Experimental conditions	
Grammatical	Ungrammatical
Ein Falter ( <i>a butterfly</i> )	Ein faltet ( <i>a folds</i> )
Er faltet ( <i>he folds</i> )	Er Falter ( <i>he butterfly</i> )

**Table 1:** Conditions included in the experimental paradigm. The design crossed Grammaticality (grammatical vs. ungrammatical) and TMS (Brodmann Area (BA) 44, superior parietal lobe (SPL) and sham).

### 2.3 Stimuli

As in the original version of the paradigm (Hasting & Kotz, 2008), we used nouns and verbs with ambiguous stems in which the category information can only be assessed once the suffix is processed (e.g., “Fech-ter”, *fencer*, and “fech-tet”, *fences*) as second words. In this way, we could precisely time-lock the ERP analysis to the point of categorical access of the second word, which is represented by the suffix onset time. While in the original study (Hasting & Kotz, 2008) the category of most of the nouns was expressed with zero marking (e.g., “Kegel-Ø<sup>2</sup>”, *cone*, compared to the verb “kegel-t”, *bowls*), we decided to include only nouns with the category overtly marked by a suffix. Our decision was motivated by studies which showed no syntactic categorical violation effects when nouns with zero marking were used (Dikker et al., 2009; Herrmann et al., 2009). Furthermore, syntactic violations realised with an offending suffix (e.g., “\*Er kegel-st”, *\*he bowl*) are more robust against conditions of reduced statistical power such as small or heterogeneous sample sizes than unmarked ones (e.g., “\*Er Kegel- Ø”, *\*he cone*, Jakuszeit et al., 2013).

<sup>2</sup> Ø denotes a so-called zero form, i.e., an absence of a suffix.

1 The thirty-two pairs of nouns and verbs with ambiguous stems used in our experiment are the  
2 result of a four-step selection procedure. First, we extracted from CELEX corpus (Baayen,  
3 Piepenbrock, & Gulikers, 1995) masculine and neuter German disyllabic nouns ending in “-er”. We  
4 used only masculine and neuter nouns in the nominative case as they follow the determiner “Ein”,  
5 while feminine nouns and other cases would have required explicit agreement processes. Secondly,  
6 for each noun we constructed a potential verb “candidate” in the infinitive form, by replacing the  
7 suffix “-er” with the infinite form ending “-en” (e.g., “Fecht-er”, *fencer* → “fecht-en”, *to fence*). For  
8 nouns ending with “-ler”, we constructed an additional infinite candidate form using the ending “-  
9 eln” (e.g., “Schwin-dler”, *cheater* → “schwin-deln”, *to cheat*). Nouns for which the respective verb  
10 candidate was not found in CELEX corpus were excluded at this step. In the third step, the verbs  
11 were inflected in the present tense third-person singular form. Pairs in which the verb became  
12 monosyllabic when inflected (e.g., “spinnen”, *to spin* → “spinnt”, *spins*) were excluded from the  
13 list. Finally, as in German “Ein” and “Er” can form compounds prefixing both nouns and verbs, we  
14 removed pairs of nouns and verbs in which the ungrammatical forms could exist as a compound  
15 (i.e., “ein+verb” or “er+noun”) according to the majority of eight independent native German  
16 speakers. The auditory stimuli used in the experiment were prepared adapting the cross-splicing  
17 procedure described by Hasting and Kotz (2008). For each pair of nouns and verbs a trained  
18 German native speaker was asked to read several times three utterances:

- 19 a. The correct determiner phrase (e.g., “Ein Fech-ter”, *A fencer*);
- 20 b. The correct verb phrase (e.g., “Er fecht-tet”, *he fences*);
- 21 c. The stem embedded in a meaningless pseudo-word phrase (e.g., “Lub fecht-tek”).

22 The recordings were acquired in a soundproof cabin using Audacity software (sampling rate:  
23 44100 Hz). The most similar determiner phrase, verb phrase and pseudo-word phrase were then  
24 selected for the cross-splicing procedure. From the determiner phrase, the word “Ein” and the noun  
25 suffix (e.g., “-ter”) were extracted. The pronoun “Er” and the verb suffix (e.g., “-tet”) were then  
26 extracted from the verb phrase. When the two first words (“Ein” and “Er”) were extracted from the

1 recordings, also the silence extending up to 600 ms (the closest zero-crossing sample) from word  
2 onset was included. Similarly, the stem (e.g., “Fech”) was extracted from the pseudo-word phrase.  
3 To avoid clicking sounds, the recordings were cut only at points of zero crossing. The grammatical  
4 and ungrammatical utterances (e.g., |Ein |Fech|-ter|, \*|Ein |Fech|-tet|, |Er |Fech|-tet|, \*|Er |Fech|-ter|)  
5 were then created by concatenating one of the two first words (e.g., |Ein| or |Er|), the stem (e.g.,  
6 |Fech|), and one of the two possible suffixes (e.g., |-ter|, |-tet|). Finally, the constructed utterances  
7 were normalized to 65 dB and 7 ms of silence were added at the beginning of each stimulus. Since  
8 TMS pulses produce a loud click noise, concatenated items were normalized to adjust the volume  
9 of the stimuli at the beginning of the experiment so that all the utterances could be heard clearly.  
10 Manipulation of the recordings was performed using Praat software (Boersma, 2001). Our  
11 procedure strongly reduced acoustic differences between grammatical and ungrammatical  
12 utterances up to the divergence point (DVP), after which the suffix occurs and the category of the  
13 second word is revealed (e.g., Ein Fech<sub>[DVP]</sub>ter, \*Ein fech<sub>[DVP]</sub>tet, Er fech<sub>[DVP]</sub>tet, \*Er Fech<sub>[DVP]</sub>ter).  
14 A t-test on the root mean square amplitude of the recordings up to the DVP revealed no significant  
15 difference between grammatical (Ein + Noun, Er + Verb) and ungrammatical (Ein + Verb, Er +  
16 Noun) items ( $p = .99$ ).

17

## 18 **2.4 Transcranial Magnetic Stimulation (TMS)**

19 Transcranial magnetic stimulation was applied during the task (“online”) to investigate the causal  
20 role of BA44 in syntactic predictive processes. We delivered 10 Hz trains of five TMS pulses  
21 during the first word of each item (“Ein”, *a*, or “Er”, *he*) to perturb the stage of syntactic categorical  
22 prediction (determiner → prediction for a noun, pronoun → prediction for a verb). The first pulse of  
23 each TMS train was time-locked to the onset of the first word and each burst lasted 400 ms. Since  
24 the second word of each item started 600 ms after the first word onset and potential after-effects of  
25 online TMS are thought to last approximately half of the stimulation time (Rotenberg, Horvath, &

1 Pascual-Leone, 2014), our stimulation protocol and stimuli materials ensured that the perturbation  
2 was limited to the stage of syntactic prediction only.

3 We included three TMS conditions: BA44 (MNI: -48, 17, 16), the left superior parietal lobe  
4 (SPL, MNI: -34, -42, 70) as an active control site, and a sham condition (Figure 1). Each participant  
5 took part in three experimental sessions, one for each TMS condition, which were separated at least  
6 by 7 days (mean distance: 7.89 days, standard deviation: 2.96 days). The order of conditions was  
7 counterbalanced across subjects. The MNI coordinates for BA44 were defined according to the  
8 results of Zaccarella and Friederici (2015), who found increased activation for phrases compared to  
9 word lists in this region. This target is located in the most anterior and ventral part of BA44, which  
10 is functionally specialized in syntactic computations (Papitto et al., 2020; Zaccarella et al., 2021).  
11 The SPL coordinates were based on a TMS experiment on degraded speech comprehension in  
12 which this region served as a control condition (Hartwigsen et al., 2015). In the sham condition, no  
13 effective stimulation of the brain occurred. The vertex was chosen as a target for sham TMS to  
14 perform the neuronavigation procedure as in the other TMS conditions (Friehs et al., 2020; Klaus &  
15 Hartwigsen, 2019; Kuhnke et al., 2020). In the sham condition, a disconnected coil was navigated  
16 over the electrode Cz and an active coil was placed above it with an angle of 90°, therefore not  
17 stimulating the brain. This procedure allows to produce the same acoustic noise as the other two  
18 TMS conditions, but without an actual stimulation of the brain (Friehs et al., 2020; Kroczeck et al.,  
19 2019; Kuhnke et al., 2017, 2020; Meyer et al., 2018).

20 We used stereotactic neuronavigation (TMS Navigator software version 3.0.33, Localite GmbH,  
21 Sankt Augustin, Germany) to position and maintain the TMS coil over the target regions during the  
22 experiment. Individual structural T1-weighted MRI images were previously acquired for each  
23 participant. The coordinates of the target regions were converted from the MNI standard to the  
24 individual subject space using SPM12 software (Wellcome TrustCenter for Neuroimaging,  
25 University College London, United Kingdom), using an established procedure (Friehs et al., 2020;  
26 Klaus & Hartwigsen, 2019; Kuhnke et al., 2017, 2020). After EEG preparation, the head of each

1 participant was co-registered to their MRI image, allowing for precise positioning of the TMS coil  
2 over the target coordinates as defined in the individual anatomical image.

3 TMS was delivered using a figure-of-eight coil (C-B60) connected to a MagVenture MagPro  
4 X100 stimulator (MagVenture, Farum, Denmark). The coil handle was oriented with an angle of  
5 45° and 0° relative to the sagittal plane when stimulating BA44 and the SPL respectively, as in  
6 previous studies (Hartwigsen et al., 2015; Klaus & Hartwigsen, 2019; Kroczeck et al., 2019; Kuhnke  
7 et al., 2017; Meyer et al., 2018). The intensity of the stimulation was set to 90% of the individual  
8 resting motor threshold (RMT), defined during the first session for each participant. RMT was  
9 defined as the minimum intensity at which TMS could evoke at least 5 motor evoked potentials  
10 (MEP) with an amplitude  $\geq 50 \mu\text{V}$  in the relaxed first dorsal interosseous muscle out of 10  
11 consecutive pulses (Rothwell et al., 1999). To this end, the TMS coil was navigated over the  
12 coordinates of the left hand motor area (MNI: -37, -21, 58, Mayka et al., 2006) and the hotspot was  
13 identified with a standard threshold hunting procedure. If necessary, stimulation intensity for BA44  
14 was corrected for the scalp-to-cortex distance relative to the motor cortex as described previously  
15 (e.g., Kuhnke et al., 2017). In short, the adjusted intensity was calculated using the formula by  
16 Stokes and colleagues (2005), as adapted for applications with 90% of the RMT (Kuhnke et al.,  
17 2017):  $BA44 \text{ intensity (stimulator output)} = 90\% \text{ RMT} + 3 * (\text{Distance}_{BA44} - \text{Distance}_{M1})$ , where  
18  $\text{Distance}_{BA44}$  and  $\text{Distance}_{M1}$  correspond to the distance in mm between the scalp and BA44 and M1  
19 respectively. The stimulation intensity for the sham condition was the same as the one used for  
20 BA44. Finally, the stimulation intensity for the SPL condition corresponded to the 90% of the  
21 RMT, as for no subject it required to be adjusted. If stimulation was too unpleasant, intensity was  
22 gradually decreased in steps of 1%.

23

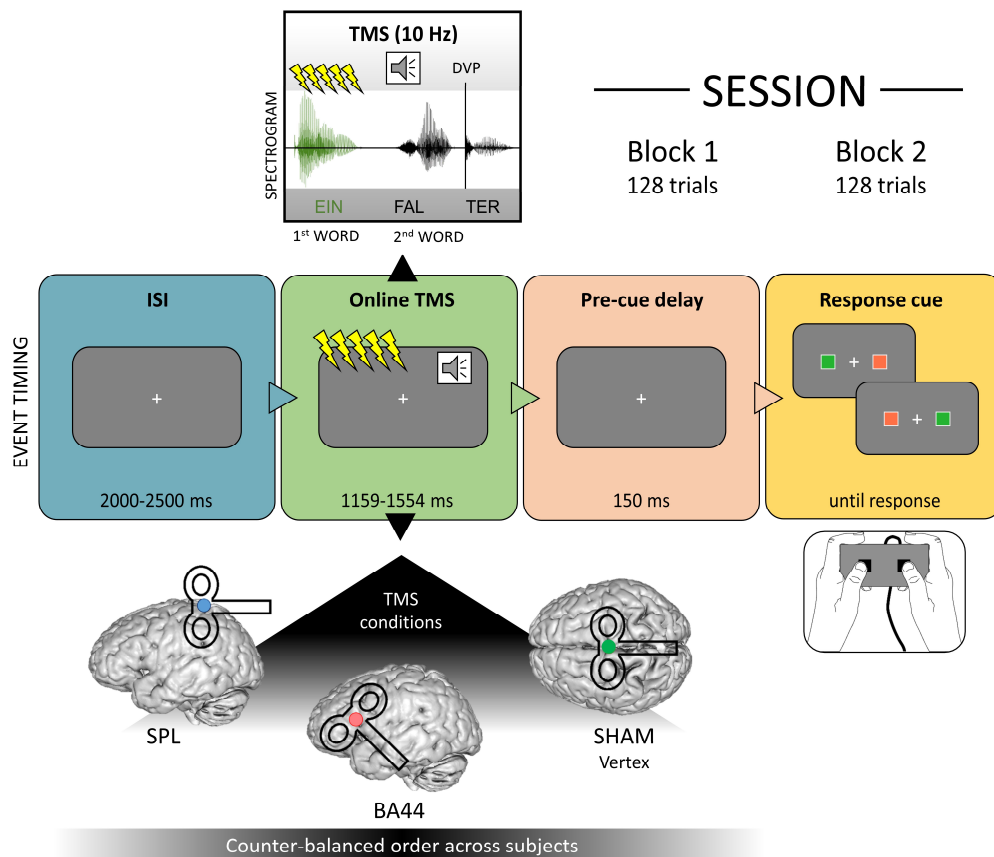
## 24 **2.5 Procedure and timing of events**

25 At the beginning of the TMS-EEG sessions, each participant filled in a short TMS safety  
26 questionnaire and received the task instructions. After EEG preparation, the participant was moved

1 into an electrically shielded cabin where the head surface was co-registered to the structural MRI  
2 image for TMS neuronavigation. Subjects sat comfortably approximately 140 cm from the  
3 computer monitor. During the first TMS-EEG session, the individual RMT was defined. To  
4 familiarize the subject with the sensory stimulation associated with each TMS condition, some test  
5 pulses on the target region were delivered. Before the experiment, subjects were provided with in-  
6 ear headphones and after reading a reminder of the instructions they underwent a short practice,  
7 consisting of 12 trials with items excluded from the main task. The trial structure of the practice  
8 block was the same as the one of the main task, but feedback was provided after each response to  
9 ensure that subjects understood the instructions. To provide comparable conditions, TMS was also  
10 delivered during the practice trials, allowing the subject to indicate if sound volume needed to be  
11 adjusted due to the TMS-induced noise.

12 During the task, the TMS coil was manually positioned and maintained over the target region.  
13 Subjects performed a grammaticality judgement task, indicating if the two-word utterance they  
14 heard was grammatically correct or not via a button-box press. A fixation cross was displayed at the  
15 centre of the monitor, and after an inter-stimulus interval randomly jittered between 2 and 2.5  
16 seconds (s) the two-word item was presented acoustically. The TMS train was delivered during the  
17 first word. After the acoustic item ended, a delay of 150 ms was included to avoid an overlap of  
18 language-related and motor-related evoked responses in the EEG signal. A response cue was then  
19 presented, consisting of two coloured squares presented to the left and right of the fixation cross.  
20 One of the squares was red and one green, with the colours being assigned pseudo-randomly for  
21 each trial. The green colour was associated to the position of the response button for “grammatical”,  
22 similarly the red colour coded for “ungrammatical”. We used a red and a green colour with a similar  
23 luminance ( $L = 64.39$  and  $64.37$  respectively in CIE Luv color-space) to avoid that differences in  
24 brightness might bias the behavioural data analysis. Relative luminance was calculated  
25 implementing the formula defined in the Web Content Accessibility Guidelines (WCAG) 2.0  
26 (<https://www.w3.org/TR/WCAG20/Overview.html#sRGB>, see Supplementary Materials). The

1 timing of TMS bursts and stimulus presentation was controlled using Presentation Software version  
 2 17.2 (NeurobehavioralSystems, Inc., Albany, CA, USA). Figure 1 illustrates the structure of a trial.  
 3 In each session, subjects performed the task twice (in two blocks), with the same 128 items  
 4 presented in a different pseudo-randomized order. Short breaks were included every 32 trials, to  
 5 cool down and switch the TMS coil if needed. After the experiments, the position of the electrodes  
 6 was digitized using the TMS Navigator software. Considering EEG-TMS preparation, the first  
 7 experimental session lasted on average approximately 3.5 hours, while the other two lasted  
 8 approximately 2.5 hours.



10

11

12 **Figure 1:** Timing of events including an illustration of the online stimulation during the first  
 13 word (above the event timeline) and the three target regions for the neuro-navigation system (below  
 14 the event timeline). Divergence Point (DVP); Interstimulus Interval (ISI); Superior parietal lobe  
 15 (SPL); Brodmann Area (BA) 44.



## 1 **2.6 Behavioural data analysis**

2 Behavioural data were analysed with repeated measures analysis of variance (ANOVA), including  
3 as factors Grammaticality (grammatical and ungrammatical), TMS (BA44, SPL and sham) and  
4 Block (first and second). Repeated measures ANOVA was conducted on the subjects' mean  
5 responses times and accuracy rates for each condition, following the removal of trials with RTs  
6 shorter than 150 ms or longer than 1 s. Analysis of the RTs was based on trials with correct  
7 response only.

8

### 9 **2.7.1 EEG recording and analysis**

10 TMS pulses result in a series of artifacts on the concurrent EEG signal which need to be controlled  
11 during both data collection and pre-processing. Electromagnetic artifacts are commonly observed  
12 following each TMS pulse (Ilmoniemi & Kičić, 2010; Rogasch et al., 2013, 2014; Veniero et al.,  
13 2009), and depending on the target location additional large cranial muscular activity can  
14 contaminate the EEG signal. Muscle artifacts are particularly pronounced when the target site is a  
15 lateral brain region (Mutanen et al., 2013; Rogasch et al., 2013), such as the IFG and the posterior  
16 temporal lobe (Salo et al., 2020). Given the series of potential artifacts during online TMS-EEG, the  
17 employed procedure for data collection and pre-processing in the present study differs from  
18 traditional EEG studies.

19 EEG signal was recorded using 63 Ag/AgCl monopolar electrodes (61 electrodes embedded in  
20 an EEG cap, EC80, EasyCap GmbH, Germany, and A1 and A2 on the left and right mastoids  
21 respectively), which were placed according to the international extended 10-20 system. Two  
22 additional pairs of bipolar electrodes were placed to monitor vertical and horizontal eye movements.  
23 EEG signal was amplified using REFA8 68-channel amplifier system (TMSi, Oldenzaal, the  
24 Netherlands) and recorded at a sampling rate of 2000 Hz using BrainVision Recorder software  
25 version 1.02.0001 (Brain Products GmbH, Gilching, Germany). The average of the 63 monopolar  
26 electrodes served as an online reference. The ground electrode was placed on the sternum.

1 Electromagnetic artifacts following each TMS pulse were reduced by arranging the direction of the  
2 electrode wires orthogonally to the TMS coil handle (Sekiguchi et al., 2011). Impedance was kept  
3 below 5 k $\Omega$ .

4 Pre-processing was performed using the Matlab FieldTrip toolbox version fieldtrip-20200115  
5 (Oostenveld et al., 2011). Given that the TMS trains were time-locked to the first word onset, EEG  
6 signal in this time-window was strongly contaminated by the large electromagnetic and muscular  
7 artifacts described at the beginning of this section. The presence of these artifacts could have  
8 resulted in large signal distortions when applying common EEG pre-processing steps like filtering  
9 on the raw data (Rogasch et al., 2017). Since our ERP component of interest is time-locked to the  
10 DVP of the second word, we applied cubic interpolation of the continuous EEG signal from -2 to  
11 450 ms relative to the first pulse of each TMS train (first word onset). Cubic interpolation was  
12 based on the 300 ms time-window before and after the segments to be interpolated. The continuous  
13 EEG signal obtained after interpolation was high-pass filtered with a cutoff frequency of 0.5 Hz  
14 (onepass-zero phase, order 4460, kaiser-windowed sinc FIR, 6 dB attenuation at the cutoff  
15 frequency, transition width 1.0 Hz, stopband 0-0.0 Hz, passband 1.0-1000 Hz, max passband  
16 deviation 0.0100, stopband attenuation 40 dB). Epochs from -250 ms to 2 s relative to the DVP of  
17 the second word were then extracted. Participants were instructed to delay, if possible, blinks and  
18 eye-movements until after the behavioural response, however ocular artifacts were present also in  
19 earlier parts of the trial. Therefore, this extended time-window for epoching allowed us to have a  
20 sufficient number of blinks and eye-movement events for well characterizing ocular artifacts with  
21 Independent Component Analysis (ICA) in a later step. Before ICA, epochs were visually inspected  
22 and trials and channels with excessive artifacts were removed (trials removed per block: mean =  
23 3.4, std = 3.5; channels removed per block: mean = 0.9, std = 0.9). The common average reference  
24 of the good channels was then computed, and ICA using the RunICA algorithm was run, accounting  
25 for data rank reduction due to bad channel exclusion. ICA components were visually inspected and  
26 bad components reflecting ocular, cardiac and muscle artifacts were removed. If present,

1 components reflecting the exponential decay after TMS were removed as well. After the removal of  
2 bad ICA components (number of components kept per block: mean = 27.1, standard deviation =  
3 5.2), EEG data were re-referenced to the common average and the signal of the channels removed  
4 during visual inspection was interpolated using spherical spline interpolation (Perrin et al., 1989),  
5 an approach recently used in a TMS-EEG experiment targeting Broca's area (Kroczek et al., 2019).  
6 EEG data were then re-referenced to the new common average reference and trials with an incorrect  
7 response were removed. The clean trials with a correct response were low-pass filtered with a cut-  
8 off frequency of 44 Hz (onepass-zero phase, order 408, kaiser-windowed sinc FIR, 6 dB attenuation  
9 at the cutoff frequency, transition width 11.0 Hz, passband 0-38.5 Hz, stopband 49.5-1000 Hz, max  
10 passband deviation 0.0100, stopband attenuation 40 dB). These pre-processing steps were repeated  
11 for each of the two blocks in each session. The trials from the two blocks were then merged in one  
12 unique dataset per TMS condition for each subject and re-referenced to the average of A1 and A2  
13 electrodes. No baseline correction was applied, as the use of our high-pass filter already attenuated  
14 direct-current offset (Widmann et al., 2015). From each dataset two ERP waveforms were then  
15 calculated, averaging separately the trials belonging to the grammatical and ungrammatical  
16 conditions. This procedure resulted in six ERP waveforms per subject, reflecting the six cells of our  
17 Grammaticality\*TMS within-subject design. ERP waveforms were then calculated to test three  
18 effects of interest: the main effect of Grammaticality (averaged across TMS conditions), the main  
19 effect of TMS (averaged across stimulus conditions in each session) and the interaction between  
20 Grammaticality and TMS.

21 The statistical analysis of EEG data was performed using non-parametric cluster-based  
22 permutation tests (Maris & Oostenveld, 2007) implemented in the FieldTrip toolbox (Oostenveld et  
23 al., 2011). This method is based on cluster formation according to test values and spatial and  
24 temporal contiguity after sample-by-sample statistical comparison. A cluster-level statistic is then  
25 calculated and, by comparing it against its distribution in random partitions via the Monte Carlo  
26 approximation, a significance probability value is obtained (for a detailed presentation, see Maris &

1 Oostenveld, 2007). The dependent sample T-statistic (“depsamplesT”) was used for cluster  
2 formation when analysing the main effect of Grammaticality. For the analysis of the main effect of  
3 TMS and the Grammaticality\*TMS interaction, the dependent sample F-statistic  
4 (“depsamplesFunivariate”) was used, as three levels were present in the independent variable<sup>3</sup>. The  
5 cluster-level statistic was calculated as the maximum of the cluster-level summed T- or F-values of  
6 each cluster. The critical alpha level for the Monte Carlo significance probability was set to 0.025  
7 when testing the main effect of Grammaticality (two-tailed hypothesis) and to 0.05 for the analysis  
8 of the main effect of TMS and the Grammaticality\*TMS interaction (one-tailed hypothesis). In each  
9 of the three statistical tests conducted (two main effects and one interaction), the Montecarlo  
10 estimation was based on 5000 random partitions and the time-window of interest was defined from  
11 0 to 1000 ms relative to the DVP.

12

### 13 **2.7.2 Bayesian repeated measures ANOVA on the ESN amplitude**

14 To quantify the evidence for and against the presence of a Grammaticality\*TMS interaction in our  
15 EEG data, we performed an additional Bayesian repeated measures ANOVA on the mean amplitude  
16 of the ESN. Bayesian analysis allows to quantify evidence for both the null and the alternative  
17 hypotheses, describing how informative data from a given experiment are (Keysers et al., 2020;  
18 Wagenmakers, Marsman, et al., 2018). Bayes factors (BF) indicate how likely the data are under  
19 these two hypotheses. For example, a  $BF_{10}$  equal to 5 indicates that the current data are five times  
20 more likely under the alternative than the null hypothesis.  $BF_{01}$  is equal to  $1/BF_{10}$  and indicates how  
21 many times the data are more likely under the null hypothesis.

22 In a Bayesian repeated measures ANOVA, Bayes Factors are obtained by comparing the  
23 predictive performance of two models (van den Bergh et al., 2020; Wagenmakers, Love, et al.,  
24 2018). Bayes Factors  $BF_{10}$  and  $BF_{01}$  quantify how much the data are more likely according to one of

---

<sup>3</sup> In the case of the interaction, the independent variable to be considered is the grammaticality effect within each TMS condition, which has three levels: BA44 grammaticality effect, SPL grammaticality effect, sham grammaticality effect.

1 the two competing models (e.g., an alternative model against the null model or the best model). For  
2 example, a  $BF_{10} = 5$  relative to a null model (e.g., a model that only accounts for the presence of  
3 different subjects) means that the data are predicted five times better by the given alternative model.  
4 A  $BF_{01} = 5$  relative to a null model means that the null model predicts the data five times better than  
5 the alternative one.

6 The analysis was conducted using JASP software version 0.14 (JASP Team, 2020; <https://jasp->  
7 [stats.org/](https://jasp-stats.org/); for theoretical and practical introductions see Dablander et al., 2020; Faulkenberry et al.,  
8 2020; Keyesers et al., 2020; Wagenmakers, Love, et al., 2018; Wagenmakers, Marsman, et al.,  
9 2018). The Bayesian repeated measures ANOVA included Grammaticality and TMS as factors.  
10 This analysis compared the performance of five models: a null model (M0: coding only the  
11 presence of different subjects) and four alternative models (M1: subject + Grammaticality, M2:  
12 subject + TMS, M3: subject + Grammaticality + TMS, M4: subject + Grammaticality + TMS +  
13 Grammaticality\*TMS). The default uninformed prior distribution was used. We planned to test the  
14 Grammaticality\*TMS interaction in two ways:

- 15 1. By comparing model M4 including the interaction against the models which included only  
16 the main effect of Grammaticality (M1) and the two main effects (M2). This comparison  
17 quantifies how much adding an interaction term improves the predictive performance of the  
18 model.
- 19 2. By performing an analysis of the effects via Bayesian Model Averaging, which allows to  
20 quantify the evidence for including factors and interactions by considering all the models  
21 according to their predictive power (Hinne et al., 2020; Keyesers et al., 2020; van den Bergh  
22 et al., 2020; Wagenmakers, Love, et al., 2018). With this analysis  $BF_{incl}$  and  $BF_{excl}$  are  
23 obtained, indicating respectively how much more likely the data are under models which  
24 include and exclude a given factor or interaction. The analysis of effects was computed  
25 across all models.

1 For the Bayesian repeated measures ANOVA, we extracted the mean amplitude of the ESN  
2 component averaging signal between 190 ms and 430 ms at 40 electrodes: AF3, AFz, AF4, F5, F3,  
3 F1, Fz, F2, F4, F6, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3,  
4 CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, P6, PO3, POz and PO4. The electrodes and time-  
5 points included are based on the results of the main effect of Grammaticality and by the rather  
6 spread topography of our ERP component of interest (see section 3.2 below). Henceforth we refer  
7 to this as the Full ESN. Crucially, the criterion used for selecting the electrodes and time-points  
8 included does not make circular the analysis, which addresses a different research question  
9 (interaction) compared the test used for defining them (main effect of Grammaticality).

10

### 11 **2.7.3 ESN and induced electrical field simulation**

12 Together with stimulation intensity and coil orientation (Laakso et al., 2014; Weise et al., 2020),  
13 neuroanatomical factors such as individual gyrification patterns (Thielscher et al., 2011) and the  
14 distribution of tissue types (Lee et al., 2018; Opitz et al., 2011) affect the spread and strength of the  
15 electrical field induced by TMS pulses. To precisely characterize the impact of BA44 stimulation  
16 on the amplitude of the ESN, we performed an additional analysis on the EEG data including the  
17 strength of the electrical field in this target region for each subject. By modelling the extent to  
18 which TMS interfered with the target region it is possible to account for anatomical factors (Lee et  
19 al., 2018; Thielscher et al., 2011) which, differing between subjects, might otherwise hide the  
20 presence of an effect of TMS if not included in the analysis (Kuhnke et al., 2020).

21 The calculation of the induced electrical fields was implemented using a recently established  
22 pipeline (Weise et al., 2020). For each subject and each active TMS condition we performed an  
23 electrical field simulation based on individual T1-weighted images, additional T2-weighted images  
24 if available, and the coil position recorded during the experimental session. Individual head meshes  
25 were constructed using the headreco pipeline (Nielsen et al., 2018) and Simnibs software (Windhoff  
26 et al., 2013) was used to calculate the electric fields. The electric field models were visually

1 inspected to ensure good quality of the head models. At this stage, two subjects were excluded from  
2 the analysis, due to an unrealistic field reconstruction. For each of the remaining 27 subject we  
3 extracted the average electrical field intensity from nine regions of interest (ROIs), two in Broca's  
4 area (BA44 and BA45; Amunts et al., 1999, 2004), and seven in the SPL (BA5L, BA5M, BA5Ci,  
5 BA7A, BA7PC, BA7M, BA7P; Scheperjans, Eickhoff, et al., 2008; Scheperjans, Hermann, et al.,  
6 2008) using maximum probability maps from the SPM Anatomy Toolbox version 2.2c (Eickhoff et  
7 al., 2005, 2006, 2007). The inclusion of BA45 as a ROI is motivated by its involvement, together  
8 with BA44, in categorical prediction (Bonhage et al., 2015) and by its close proximity to this region  
9 in the left IFG<sup>4</sup>. The average electrical fields in Broca's area (BA44 and BA45) and in SPL (BA5L,  
10 BA5M, BA5Ci, BA7A, BA7PC, BA7M, BA7P) ROIs were extracted from the BA44 and SPL TMS  
11 sessions respectively.

12 To test whether TMS affected the ESN, we computed a Pearson correlation between the induced  
13 electrical field in the abovementioned ROIs and the sham-normalized amplitude of Full ESN. The  
14 two sham-normalized Full ESN amplitudes were obtained in a two-step procedure:

- 15 1. First, for all the three TMS conditions we calculated the mean amplitude of the difference  
16 wave (ungrammatical – grammatical), resulting in three mean amplitude values: Full  
17  $ESN_{BA44}$ , Full  $ESN_{SPL}$  and Full  $ESN_{sham}$ ;
- 18 2. We then obtained the sham-normalized mean amplitudes (Full  $ESN_{BA44}$  effect, Full  $ESN_{SPL}$   
19 effect) by subtracting Full  $ESN_{sham}$  from Full  $ESN_{BA44}$  and Full  $ESN_{SPL}$  respectively (Full  
20  $ESN_{BA44}$  effect = Full  $ESN_{BA44}$  - Full  $ESN_{sham}$ ). As the induced electrical field for the sham  
21 condition is zero (no electrical stimulation of the brain), this subtraction isolated the effect  
22 of the induced field in a given ROI on the ESN amplitude for each of the two active TMS  
23 conditions.

---

4 The coordinates used as target for stimulating BA44 (Zaccarella & Friederici, 2015a) lie indeed in the most anterior and ventral part of the region, very close to BA45.

1 Additionally, as our main effect of Grammaticality is characterized by an early frontal component  
2 and a second centro-parietal component (see Results section and Figure 3), we performed an  
3 exploratory analysis focusing on each component separately. This additional analysis is motivated  
4 by ERP studies showing the presence of two subsequent negativities for agreement (Barber &  
5 Carreiras, 2005; Hanna et al., 2014; Jakuszeit et al., 2013; Pulvermüller & Shtyrov, 2003) and  
6 categorical (Hasting et al., 2007) marked syntactic violations at the two-word level, which might  
7 reflect different stages of analysis. Crucially, by analysing the two effects separately we could test  
8 whether TMS selectively affected only one of them. We subdivided the Full ESN in two parts:

- 9 1. First ESN: average of signal from 190 ms to 310 ms at 17 anterior electrodes AF3, AFz,  
10 AF4, F5, F3, F1, Fz, F2, F4, F6, FC5, FC3, FC1, FCz, FC2, FC4 and FC6. The time-points  
11 included correspond to the first half of the Full ESN effect. Only anterior electrodes are  
12 included, in light of the topography of the main effect of grammaticality in this time-  
13 window (see Figure 3);
- 14 2. Second ESN: average of signal from 310 ms to 430 ms at 17 posterior electrodes CP5, CP3,  
15 CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, P6, PO3, POz and PO4 (second half of  
16 the time window of the Full ESN effect). Only posterior electrodes are included, since in  
17 this time-window the effect is mostly pronounced at these sites (see Figure 3).

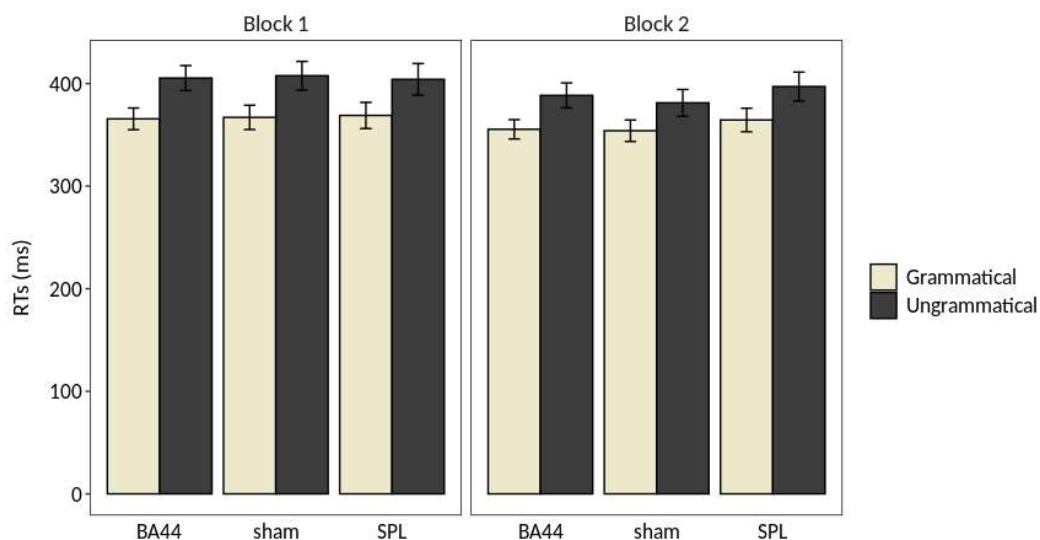
18 First ESN<sub>BA44</sub> effect, First ESN<sub>SPL</sub>, Second ESN<sub>BA44</sub> effect and Second ESN<sub>SPL</sub> effect were obtained  
19 with the same procedure described above for the full time-window, normalizing First ESN<sub>BA44/SPL</sub>  
20 and Second ESN<sub>BA44/SPL</sub> with the subtraction of First ESN<sub>sham</sub> and Second ESN<sub>sham</sub> respectively.  
21 The NHST correlational analysis was complemented by Bayesian inference using JASP software  
22 (JASP Team, 2020), to quantify both evidence for the alternative and the null hypotheses. The  
23 default uninformed prior distribution was used.



### 1 3. RESULTS

#### 2 3.1 Behavioural data

3 The performance of the participants was at ceiling (mean accuracy = 97%, range = 75-100%), and  
4 the analysis of the accuracy revealed no significant main effect or interaction involving the factors  
5 Grammaticality, TMS and Block. The analysis of response times (RTs) showed a main effect of  
6 Grammaticality ( $F(1,28) = 92.43, p < 5e-10, \eta^2_G = 0.0655$ ), with RTs for the grammatical items  
7 being on average 35 ms faster than for the ungrammatical ones. The main effect of Block was  
8 significant ( $F(1,28) = 11.35, p < 0.005, \eta^2_G = 0.0097$ ), with RTs being on average 13 ms faster in  
9 the second block. Finally, the interaction Grammaticality\*Block was significant ( $F(1,28) = 7.20, p$   
10  $< 0.05, \eta^2_G = 0.0008$ ). A post-hoc analysis revealed that this interaction was driven by a significant  
11 difference between the RTs for the ungrammatical conditions of Block 1 and Block 2 ( $p < 0.001$ ,  
12 Bonferroni-corrected), which was absent for the grammatical counterpart ( $p > .05$ , Bonferroni-  
13 corrected). No main effect of TMS and no interaction including this factor was significant. Figure 2  
14 illustrates the results of the repeated measures ANOVA.



24 **Figure 2:** Results of the repeated measures ANOVA on the Response Times (RTs). The error bar  
25 indicates the standard error of the mean.

26

## 1 **3.2 EEG data**

2 The ERP waveforms of grammatical and ungrammatical conditions at selected electrodes, collapsed  
3 across TMS sites, are shown in Figure 3. Additional electrodes are displayed in the Supplementary  
4 Materials (Figure S1). Visual inspection of the ERP waveforms reveals an increased negativity for  
5 the ungrammatical condition from approximately 200 ms to 450 ms, followed by a late positivity  
6 from 450 to 800 ms. The cluster-based permutation test revealed a main effect of Grammaticality,  
7 with the presence of a significant negative ( $P < 0.0005$ , cluster-corrected) and positive ( $P < 0.0005$ ,  
8 cluster-corrected) cluster. The negative cluster, reflecting increased negativity for the  
9 ungrammatical condition relative to the grammatical one, extended approximately from 190 to 430  
10 ms after the DVP<sup>5</sup> (Figure 3). The positive cluster, reflecting an effect in the opposite direction,  
11 extended approximately from 440 to 800 ms after the DVP. Both the effects were mostly  
12 pronounced over fronto-central and centro-parietal electrodes (Figure 3). A marginally non-  
13 significant effect of TMS was also found ( $P = 0.05$ , cluster-corrected).

14 The Grammaticality\*TMS interaction of interest was not significant ( $P > 0.5$ , cluster-corrected).  
15 The ERP waveforms of grammatical and ungrammatical conditions within each TMS are shown in  
16 Figure 4. Additional electrodes are displayed in Figures S2, S3 and S4 in the Supplementary  
17 Materials. The absence of the interaction is evidenced by the presence of an increased negativity  
18 and a late positivity for the ungrammatical condition in each TMS condition. Indeed, within each  
19 TMS condition significant negative and positive clusters were found (BA44: first negative cluster  $P$   
20  $< 0.005$ , second negative cluster  $P < 0.005$ , first positive cluster  $P < 0.005$ , second positive cluster  $P$   
21  $< 0.05$ ; sham: negative cluster  $P < 0.0005$ , positive cluster  $P < 0.0005$ ; SPL: negative cluster  $P <$   
22  $0.0005$ , positive cluster  $P < 0.005$ ). The extent of the clusters in two selected time-windows is  
23 shown in Figure 4. The full extent of the clusters within each TMS condition is shown in Figures  
24 S5, S6, S7 and S8 in the Supplementary Materials. The absence of the critical Grammaticality\*TMS

---

<sup>5</sup> We describe the temporal and spatial extent only in approximate terms, as recommended by methodological papers on this topic (Maris, 2012; Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019).

1 interaction shows that TMS over Broca's area during the first word did not affect the amplitude of  
2 the ESN.

3

4

5

6

7

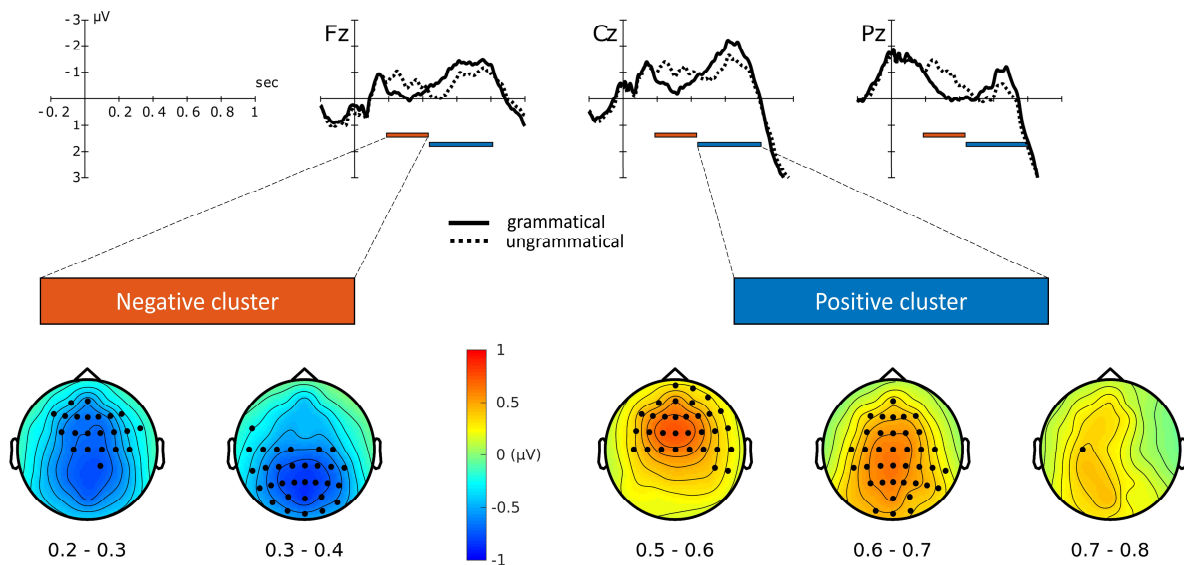
8

9

10

11

12

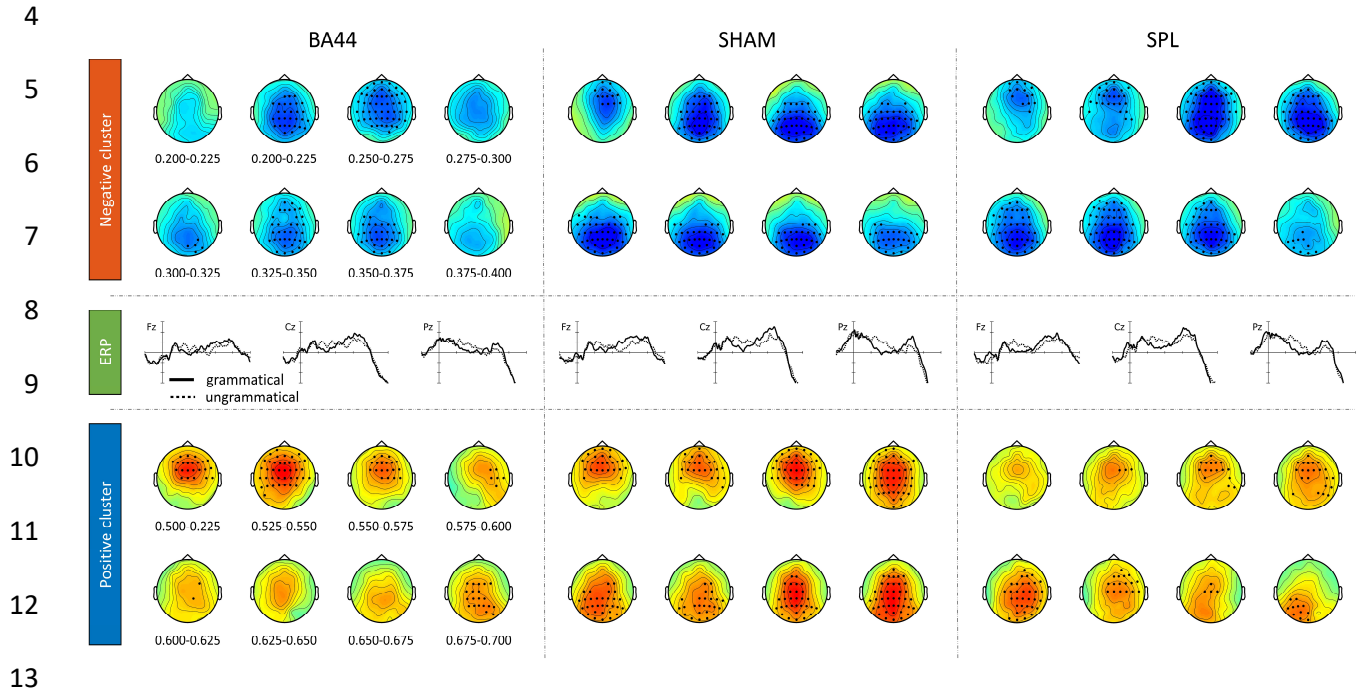


13 **Figure 3:** ERP waveforms for grammatical and ungrammatical waveforms ( $\mu V$  over seconds,  
14 collapsed across TMS conditions at selected electrodes), together with electrodes and time-points  
15 showing highest contributions to the significance of the negative (bottom left) and positive (bottom  
16 right) clusters.

17

18 Visual inspection of the ERP waveforms of the SPL condition shows an increased positivity for the  
19 ungrammatical items approximately 50 ms before the DVP. Crucially, this difference is short-lived,  
20 with the waveforms of grammatical and ungrammatical condition being aligned approximately 30  
21 ms after the DVP. Furthermore, in the other two TMS conditions the waveforms are already aligned  
22 before the DVP. Differences between conditions can be problematic if they are sustained effects  
23 and are “masked” by baseline-correction procedure (Steinhauer & Drury, 2012). We did not  
24 perform a baseline-correction procedure, which would have artificially increased the  
25 Grammaticality effect for this TMS condition. To statistically confirm that this pre-DVP difference  
26 in the ERP waveforms is not a sustained effect, we performed a cluster-based permutation test on

1 grammatical and ungrammatical conditions in the time-window -5 to 180 ms relative to the DVP.  
2 This analysis revealed no significant cluster ( $P > 0.5$ ), in line with the non-sustained nature of this  
3 difference.



14 **Figure 4:** Grammaticality effect within each TMS condition. Electrodes and time-points providing  
15 the highest contribution to the significance of the negative cluster (top rows, 0.2-0.4 s time-window)  
16 and positive clusters (bottom rows, 0.5-0.7 s time-window) are highlighted. Colorbar and axes  
17 dimensions are the same as the ones shown in Figure 3.

18

### 19 3.3 Bayesian repeated measures ANOVA on the ESN amplitude

20 The results of the Bayesian repeated measures ANOVA on the ESN amplitude are summarized in  
21 Table 2. The best model included only the factors subject and Grammaticality ( $BF_M = 5.651$ ). The  
22 model including the Grammaticality\*TMS interaction was approximately 10 times less likely than  
23 the model with only the main effect of Grammaticality given the data ( $BF_{01} = 10.295$ ). Direct  
24 comparison of the interaction model against the one including the two main effects showed that the  
25 former was approximately 6 times less likely given the data ( $BF_{01} = 6.287$ ).

26

Models	P(M)	P(M data)	BF <sub>M</sub>	BF <sub>10</sub>	BF <sub>01</sub>	Error %
Grammaticality (Gram)	0.200	0.586	5.651	1.000	1.000	-
Gram + TMS	0.200	0.358	2.226	0.611	1.683	2.829
Gram + TMS + Gram*TMS	0.200	0.057	0.241	0.097	10.295	2.985
Null model	0.200	3.145e-9	1.258e-8	5.371e-9	1.862e+8	2.521
TMS	0.200	1.073e-9	4.291e-9	1.832e-9	5.459e+8	2.634

1

2 **Table 2:** Summary of the results of the Bayesian repeated measure ANOVA conducted on the Full  
3 ESN.  $P(M)$  = prior model probability;  $P(M|data)$  = posterior model probability;  $BF_M$  = posterior  
4 model odds;  $BF_{10}$  and  $BF_{01}$  show the Bayes factors for the comparison of each model against the  
5 best one (Grammaticality).

6

7 The analysis of the effects is summarized in Table 3. The data are approximately  $1.5 \cdot 10^7$  times  
8 more likely under models which include the Grammaticality factor ( $BF_{incl} = 1.539e+8$ ) and two  
9 times more likely under models which do not include the TMS factor ( $BF_{excl} = 2.047$ ). Crucially,  
10 the data are four times more likely under models which do not include the Grammaticality\*TMS  
11 interaction ( $BF_{excl} = 4.058$ ). Therefore, the additional analysis provide evidence against an effect of  
12 TMS over Broca's area on the amplitude of the ESN component.

13

Effects	P(incl)	P(excl)	P(incl data)	P(excl data)	BF <sub>incl</sub>	BF <sub>excl</sub>
Grammaticality	0.600	0.400	1.000	4.218e-9	1.581e+8	6.326e-9
TMS	0.600	0.400	0.414	0.586	0.472	2.119
Grammaticality*TMS	0.200	0.800	0.057	0.943	0.241	4.145

14

1 **Table 3:** Summary of the analysis of the effects across all models.  $P(incl)$  = prior probability of  
 2 including a predictor;  $P(excl)$  = prior probability of excluding a predictor;  $P(incl|data)$  = posterior  
 3 probability of including a predictor;  $P(excl|data)$  = posterior probability of excluding a predictor;  
 4  $BF_{incl}$  = Bayes factor for including a predictor;  $BF_{excl}$  = Bayes factor for excluding a predictor.

5  
 6 **3.4 ERP and induced electrical field simulation**

7 The average intensity of the induced electrical fields in each ROI is summarized in Table 4. Within  
 8 Broca’s area, the average electrical field was higher in BA45 (80.05 V/m) than BA44 (59.68 V/m).  
 9 Within the SPL, the ROI in which TMS induced the highest electrical field were BA7PC (52.60  
 10 V/m), BA5L (41.66 V/m) and BA7A (41.33V/m). The reconstructed electrical fields for each  
 11 subject, mapped to fsaverage space, are shown in Figures S9 and S10 in the Supplementary  
 12 Materials.

13

Mean electrical field (SD)			
Broca’s area		Superior Parietal Lobe	
BA44	59.68 (12.65)	BA5Ci	15.76 (3.03)
BA45	80.05 (16.10)	BA5L	41.66 (6.69)
		BA5M	17.52 (2.97)
		BA7A	41.33 (7.16)
		BA7M	13.02 (2.44)
		BA7P	23.29 (3.90)
		BA7PC	52.60 (12.15)

14  
 15 **Table 4:** Mean and standard deviation of the induced electrical field (V/m) in the nine ROIs of  
 16 interest

17

1 Considering the Full ESN time-window, no significant correlation was found between Full ESN<sub>BA44</sub>  
 2 effect and the induced electrical field in BA44 (Table 5 and Figure 5,  $r = 0.142$ ,  $p > 0.1$ ,  $BF_{01} =$   
 3  $3.302$ , with median posterior  $\delta = 0.128$ , 95% Credible Interval  $CI = [-0.239, 0.473]$ ). The  $BF_{01}$   
 4 indicates that the data are 3.302 times more likely under the null hypothesis compared to the  
 5 alternative one. Similarly, no significant correlation was found between Full ESN<sub>BA44</sub> effect and the  
 6 induced electrical field in BA45 ( $r = 0.114$ ,  $p > 0.5$ ,  $BF_{01} = 3.588$ , with median posterior  $\delta = 0.103$ ,  
 7 95%  $CI = [-0.264, 0.452]$ ). No significant correlation was found between Full ESN<sub>SPL</sub> effect and the  
 8 induced electrical field in BA7PC ( $r = 0.011$ ,  $p > 0.5$ ,  $BF_{01} = 4.178$ , with median posterior  $\delta =$   
 9  $0.010$ , 95%  $CI = [-0.352, 0.370]$ ), in BA5L ( $r = 0.261$ ,  $p > 0.1$ ,  $BF_{01} = 1.845$ , with median posterior  
 10  $\delta = 0.236$ , 95%  $CI = [-0.128, 0.560]$ ) or in BA7A ( $r = 0.157$ ,  $p > 0.1$ ,  $BF_{01} = 3.126$ , with median  
 11 posterior  $\delta = 0.142$ , 95%  $CI = [-0.225, 0.484]$ ). No significant correlation was found between Full  
 12 ESN<sub>SPL</sub> effect and the other SPL ROIs (see Table S1 in Supplementary Materials).

13

ESN effect	ROI eField	$r$	$p$	$BF_{10}$	$BF_{01}$
Full ESN <sub>BA44</sub> effect	BA44	0.142	0.480	0.303	3.302
Full ESN <sub>BA44</sub> effect	BA45	0.114	0.570	0.279	3.588
First ESN <sub>BA44</sub> effect	BA44	0.032	0.874	0.242	4.134
First ESN <sub>BA44</sub> effect	BA45	-0.006	0.975	0.239	4.182
Second ESN <sub>BA44</sub> effect	BA44	0.196	0.327	0.378	2.648
Second ESN <sub>BA44</sub> effect	BA45	0.120	0.549	0.283	3.529

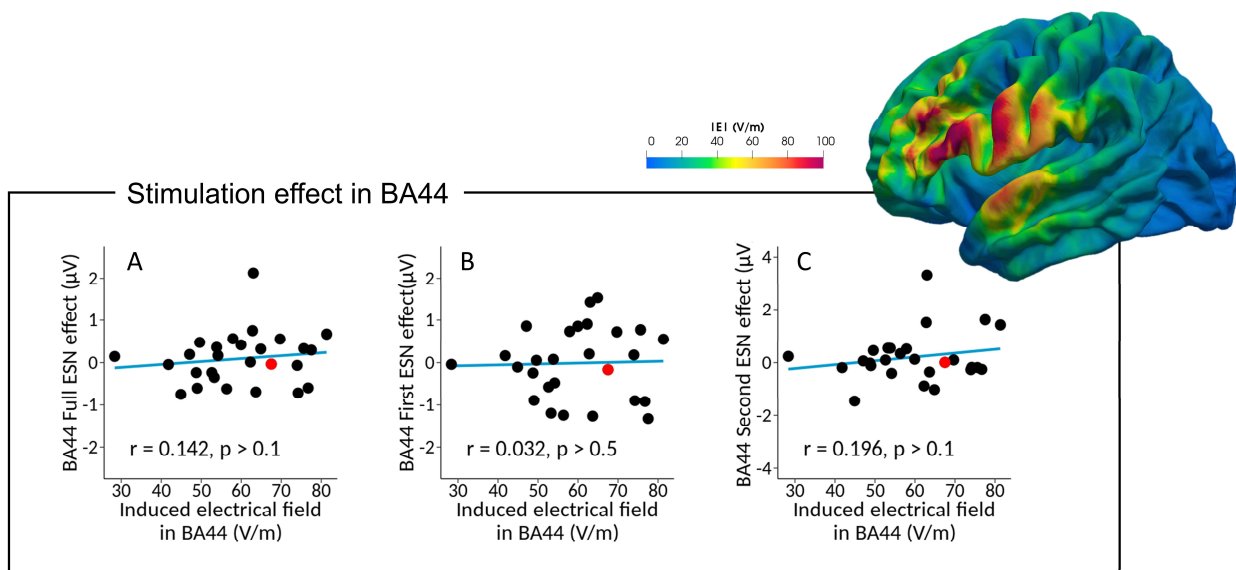
14

15 **Table 5:** Correlational analysis between the induced electrical field in the subregions of Broca's  
 16 area and the three ESN effects of interest

17

18

1 Considering the first part of the ESN effect, no significant correlation was found between First  
2  $ESN_{BA44}$  effect and the induced electrical field in BA44 ( $r = 0.032$ ,  $p > 0.5$ ,  $BF_{01} = 4.134$ , with  
3 median posterior  $\delta = 0.029$ , 95% CI = [-0.334, 0.387]) and BA45 ( $r = -0.006$ ,  $p > 0.5$ ,  $BF_{01} = 4.182$ ,  
4 with median posterior  $\delta = -0.006$ , 95% CI = [-0.366, 0.356]). Similarly, no significant correlation  
5 was found between First  $ESN_{SPL}$  effect and the electrical field induced in BA7PC ( $r = -0.008$ ,  $p >$   
6  $0.5$ ,  $BF_{01} = 4.182$ , with median posterior  $\delta = -0.007$ , 95% CI = [-0.367, 0.355]), in BA5L ( $r =$   
7  $0.294$ ,  $p > 0.1$ ,  $BF_{01} = 1.459$ , with median posterior  $\delta = 0.267$ , 95% CI = [-0.095, 0.583]) or in  
8 BA7A ( $r = 0.149$ ,  $p > 0.1$ ,  $BF_{01} = 3.217$ , with median posterior  $\delta = 0.135$ , 95% CI = [-0.233,  
9  $0.478$ ]). No significant correlation was found between First  $ESN_{SPL}$  effect and the other SPL ROIs  
10 (see Table S2 in Supplementary Materials).



20 **Figure 5:** Correlation analysis between the Full  $ESN_{BA44}$  effect (Full  $ESN_{BA44}$  - Full  $ESN_{sham}$ ) and  
21 the induced electrical field in BA44 (A), together with separate correlation analyses for the First  
22  $ESN_{BA44}$  effect (B) and Second  $ESN_{BA44}$  effect (C), respectively. The plotted brain illustrates the  
23 reconstructed TMS-induced electrical field from the BA44 session for a single subject, highlighted  
24 in red in the scatter plots.

25

26



1 Finally, considering the second half of the ESN effect, no significant correlation was found between  
2 Second ESN<sub>BA44</sub> effect and the induced electrical field in BA44 ( $r = 0.196$ ,  $p > 0.1$ ,  $BF_{01} = 2.648$ ,  
3 with median posterior  $\delta = 0.177$ , 95% CI = [-0.189, 0.513]) or in BA45 ( $r = 0.120$ ,  $p > 0.5$ ,  $BF_{01} =$   
4  $3.529$ , with median posterior  $\delta = 0.109$ , 95% CI = [-0.258, 0.456]). Similarly, no significant  
5 correlation was found between Second ESN<sub>SPL</sub> effect and the electrical field induced in BA7PC ( $r =$   
6  $0.014$ ,  $p > 0.5$ ,  $BF_{01} = 4.174$ , with median posterior  $\delta = 0.013$ , 95% CI = [-0.349, 0.373]), in BA5L  
7 ( $r = 0.221$ ,  $p > 0.1$ ,  $BF_{01} = 2.337$ , with median posterior  $\delta = 0.200$ , 95% CI = [-0.166, 0.531]) or in  
8 BA7A ( $r = 0.172$ ,  $p > 0.1$ ,  $BF_{01} = 2.949$ , with median posterior  $\delta = 0.155$ , 95% CI = [-0.212,  
9  $0.495$ ]). No significant correlation was found between Second ESN<sub>SPL</sub> effect and the other SPL  
10 ROIs (see Table S3 in Supplementary Materials).

11 To summarize the analysis, even when accounting for the induced electrical field and the spatio-  
12 temporal profile of our ERP effect, our data show that TMS over Broca's area did not affect the  
13 amplitude of the ESN component when inducing a virtual lesion during the online processing of the  
14 first word in our two-word paradigm.

15

#### 16 **4. DISCUSSION**

17 Lesion studies provide evidence for a causal role of Broca's area in syntactic composition,  
18 (Friederici et al., 1998, 1999), but leave open the question of whether this region is involved in  
19 predicting words' grammatical categories or integrating them into constituents. A disruption of  
20 either of these processes would result in the absence of the ELAN in patients with left IFG lesion.  
21 In this study, we used TMS in healthy individuals to disentangle these processes by perturbing  
22 activity in Broca's area during the first word (determiner or pronoun) of two-word  
23 phrasal/sentential structures. The high temporal resolution of the perturbation in our experiment  
24 allowed for the first time to specifically test the causal involvement of Broca's area at the stage of  
25 syntactic prediction (determiner → prediction for a noun, pronoun → prediction for a verb). State-  
26 of-the-art modelling of the induced electrical field (Kuhnke et al., 2020; Weise et al., 2020) further

1 quantified the impact of TMS in Broca’s area. Crucially, the online combination of EEG and TMS  
2 allowed to isolate the stimulation effect on both early automatic (ESN) and late controlled (late  
3 positivity) syntactic processes, further specifying the neuro-cognitive architecture of phrasal  
4 building. The present EEG-TMS data provided two main results. First, a main effect of  
5 Grammaticality revealed early automatic (ESN) and late controlled (late positivity) syntactic effects  
6 at the two-word level, functionally equivalent to those observed for longer and more complex  
7 stimuli (ELAN and P600, Friederici, 2002, 2011; Friederici & Kotz, 2003). Secondly, the absence  
8 of the critical Grammaticality\*TMS interaction indicated that the transient disruption of Broca’s  
9 area at the stage of categorical prediction did not affect the generation of the ESN (prediction error,  
10 according to a predictive coding perspective). In the following sections, we discuss both findings in  
11 light of the previous literature.

12

#### 13 **4.1 Early and late main effects of grammaticality**

14 The analysis of the main effect of Grammaticality revealed the presence of the ESN (approximately  
15 between 190 and 430 ms), followed by a late positivity (approximately between 440 and 800 ms).  
16 The presence of the ESN replicates previous work (Hasting & Kotz, 2008) and provides further  
17 evidence for an early analysis of categorical information at the most fundamental two-word level.  
18 The onset latency of the ESN in our experiment (~200 ms) was slightly delayed compared to the  
19 original ESN study (Hasting & Kotz, 2008), in which the ERP waveforms for grammatical and  
20 ungrammatical constructions diverged already between 100 and 200 ms. Crucially, in the original  
21 ESN study the grammatical category was marked by the presence or absence of a single phoneme  
22 after the DVP (e.g., “Kegel<sub>[DVP]Ø</sub>”, *cone*, “kegel<sub>[DVP]t</sub>”, *bowls*) for the majority of the items (34/50  
23 pairs of nouns and verbs). In our experiment, the grammatical category was always marked by a full  
24 syllable (e.g., “Fech<sub>[DVP]ter</sub>”, *fencer*, and “fech<sub>[DVP]tet</sub>”, *fences*), which unfolds over a longer time  
25 interval compared to a single phoneme. As a consequence, the detection of the grammatical  
26 violation is shifted in time. Another difference between the previous and present study is the offset

1 time. While in the original ESN paradigm the effect lasted until 300 ms, our ESN effect lasted  
2 approximately 140 ms longer. There are two possible explanations for this discrepancy. On the one  
3 hand, considering that a full syllable and not a single phoneme marks the category in our stimulus  
4 set, the delayed offset time could simply be a consequence of the shift in onset latency of the ESN.  
5 On the other hand, the extended duration of our main effect might reflect the concatenation of two  
6 processes, indexed by a first anterior negativity (ESN) and a second N400. This pattern has  
7 previously been reported for agreement violations (Barber & Carreiras, 2005; Hanna et al., 2014;  
8 Jakuszeit et al., 2013) and marked categorical (Hasting et al., 2007) when realized at the two-word  
9 level. The presence of an N400 in agreement violations, where the meaning of grammatical and  
10 ungrammatical constructions is extremely similar (e.g., “a boat/\*boats”), suggests that this  
11 component might reflect a process at the two-word level which is not purely semantic. Our stimuli  
12 match agreement violations paradigms with respect to the presence of a suffix indicating whether a  
13 given construction is grammatical or not. Therefore, the second negativity (N400) in our dataset  
14 could reflect an additional process in which a given suffix is compared against an expected one,  
15 which can be used to detect grammaticality for categorical violations overtly marked.

16 While functionally equivalent to the ELAN, the ESN does not show a left-lateralized  
17 topography. The early effect in our dataset has a rather non-lateralized and distributed topography,  
18 similar to the ESN reported by Hasting and Kotz (2008). In this regard, an fMRI study employing  
19 an adapted version of the original paradigm showed that categorical violations at the two-word level  
20 engage the bilateral temporal cortices, in addition to BA44 in the left hemisphere (Herrmann et al.,  
21 2012). These results are compatible with the presence of dipoles in both temporal cortices in ESN  
22 paradigms, which would explain the non-lateralized topography of the component. Interestingly,  
23 several ERP studies using two-word stimuli did not show a left-lateralized topography for  
24 categorical or agreement violation effects (Barber & Carreiras, 2005; Hasting & Kotz, 2008;  
25 Jakuszeit et al., 2013). Our results converge with these studies, indicating that the left-lateralized

1 topography observed for syntactic effects in long sentences (Friederici, 2011) could become more  
2 central at the two-word level.

3 Finally, the ESN was followed by a late positivity, approximately between 440 and 800 ms. This  
4 late positivity aligns well with the profile of the P600 (Osterhout et al., 1994; Osterhout &  
5 Holcomb, 1993), an ERP component indexing repairing and re-analysis processes (Friederici,  
6 2011). At the two-word level, the presence of a late positivity has been reported for agreement  
7 (Barber & Carreiras, 2005; Hasting & Kotz, 2008) and categorical (Jakuszeit et al., 2013)  
8 violations. This component was observed when a grammaticality judgement task was performed  
9 (agreement violations, Barber & Carreiras, 2005 and Hasting & Kotz, 2008) or during passive  
10 listening (categorical violations, Jakuszeit et al., 2013). However, when participants were actively  
11 distracted, this component was absent (Hasting & Kotz, 2008). In our experiment, participants were  
12 actively engaged in a repairing process, as they were performing a grammatical judgement task.  
13 Thus, the late positivity reflects a late and non-automatic process, as the P600 observed for longer  
14 stimuli (Anjia Hahne & Friederici, 1999). The present data converge with earlier studies  
15 demonstrating that the late syntactic processes observed with longer sentential stimuli (Anjia Hahne  
16 & Friederici, 1999) can be observed already at the minimal two-word level (Barber & Carreiras,  
17 2005; Hasting & Kotz, 2008; Jakuszeit et al., 2013). Overall, our findings suggest that the  
18 recursivity that characterizes syntactic composition (Everaert et al., 2015; Friederici et al., 2017)  
19 can be observed at the neurophysiological level, with functionally equivalent processes at the basis  
20 of building both minimal phrases and more complex structures.

21

## 22 **4.2 No evidence for Broca's area's causal role in categorical prediction**

23 We perturbed activity in Broca's area at the stage of syntactic prediction, by delivering TMS at the  
24 onset of a function word ("Ein", *a*, and "Er", *he*). We initially expected that disruption of Broca's  
25 area would interfere with the formation of a categorical prediction (determiner → noun, pronoun →  
26 verb), leading to the absence of the ESN effect elicited by an ungrammatical continuation of the

1 utterance (\*determiner + verb, \*pronoun + noun). However, the non-significant interaction between  
2 Grammaticality and TMS in our data does not support a causal role of Broca's area in categorical  
3 prediction. At a more fine-grained level, modelling of the induced electrical field showed no  
4 relation between the ESN amplitude change and individual interference in Broca's area. The  
5 additional Bayesian analysis provided initial evidence for the absence of the critical interaction  
6 effect, with the null hypothesis explaining our data approximately three times better than the  
7 alternative one. These results are compatible with two interpretations: either other brain regions  
8 outside of the left IFG are involved in generating syntactic categorical predictions, or automatic  
9 phrasal building does not rely on top-down expectations. We will discuss the first interpretation  
10 here, while we concentrate more closely on the second interpretation in the concluding paragraph of  
11 the discussion section.

12 In visual attention reading paradigm Bonhage and colleagues (2015) showed that categorical  
13 predictions engaged additional regions outside Broca's area, such as the bilateral superior temporal  
14 cortices and insulae, the left frontal operculum, the intraparietal sulcus, the right caudate and the  
15 anterior cingulate. Some of these activations might reflect increased attentional demands triggered  
16 by the employed jabberwocky stimuli, which were used to highlight brain regions predicting an  
17 abstract category but not a specific word. Yet, other studies speak against the localization of  
18 categorical predictions in these regions. Activity in the frontal operculum and the insula increases as  
19 a function of the number of words presented, irrespectively of whether they are predictive or not  
20 (Zaccarella & Friederici, 2015a, 2015b). Similarly, the inferior parietal lobe shows increased  
21 activity for lists relative to constituents (Pallier et al., 2011), even if clear categorical predictions  
22 can be formed only in the latter type of stimuli. In this regard, direct comparison of sentences  
23 against lists showed that, once semantic processes are carefully subtracted, increased activation is  
24 found in BA44 only (Goucha & Friederici, 2015). Finally, conflicting evidence exists regarding an  
25 involvement of the superior temporal lobe in categorical predictions. Structural effects in the  
26 anterior temporal lobe (ATL) have been reported in the literature (Brennan & Pykkänen, 2012;

1 Brennan et al., 2016), and activity in this region has been linked to left-corner predictive parsing  
2 analysis (Brennan & Pykkänen, 2012). However, these studies used narratives and sentences with  
3 real words, therefore it is unclear whether they isolated syntactic or semantic processes. Indeed,  
4 studies employing jabberwocky stimuli did not find a consistent involvement of the ATL in  
5 processing abstract categorical information (Goucha & Friederici, 2015; Matchin et al., 2019;  
6 Pallier et al., 2011; Zaccarella & Friederici, 2015a), and recent data point towards a role of this  
7 region in semantic/conceptual processing (Pykkänen, 2020). The posterior temporal lobe has been  
8 shown to support top-down predictive processes in the semantic domain (Gastaldon et al., 2020),  
9 but it is unclear if this region subserves the automatic generation of categorical predictions. Recent  
10 fMRI and MEG data showed that the posterior superior temporal gyrus (pSTG) rather supports  
11 active syntactic predictive processes, which are generated at the sentential but not at phrasal level  
12 (Matchin et al., 2017, 2019). Since Bonhage and colleagues (2015) used sentence stimuli and  
13 included a long delay (five seconds) at the predictive stage, it cannot be excluded that the reported  
14 activity in the pSTG reflected a controlled process in this study. Such an active process cannot  
15 account for the fast and automatic nature of syntactic composition, and indeed lesion of the  
16 posterior temporal lobe does not affect the ELAN response (Friederici et al., 1998). Thus, while we  
17 only tested the causal involvement of Broca's area in categorical prediction, previous functional and  
18 lesion data do not provide strong evidence for the involvement of the abovementioned brain regions  
19 in this process.

20

### 21 **4.3 The role of Broca's area role in syntactic composition**

22 While our results do not support a causal role of Broca's area in categorical predictions, they appear  
23 to be compatible with the alternative hypothesis that this region might be involved in the bottom-up  
24 integration of words into syntactic structures. Accordingly, in our experiment the ESN was not  
25 affected by TMS over Broca's area simply because the stimulation occurred before this region was

1 involved in the compositional process, as no syntactic rule could be evaluated on an isolated  
2 function word.

3 A first line of evidence supporting bottom-up syntactic composition in Broca's area comes from  
4 studies which compared sentences and phrases against control conditions containing function  
5 words. Maguire and Frith (2004) showed increased activation in Broca's area pars opercularis for  
6 sentences than lists, even if both conditions contained predictive function words. Similarly,  
7 Zaccarella and Friederici (2015) reported increased activity in BA44 not only for two-word pseudo-  
8 phrases relative to lists (e.g., "Diese Flirk", *this flirk*, against "Apfel Flirk", *apple flirk*), but also for  
9 determiner phrases compared to a single determiner ("Diese Flirk", *this flirk*, against "Diese", *this*).  
10 These studies support the notion that Broca's area, and specifically BA44, is involved in the  
11 bottom-up integration of words into structures, as categorical predictions could be generated also in  
12 the control condition. Converging evidence comes from an fMRI study which investigated  
13 categorical violations at the two-word level (Herrmann et al., 2012). Herrmann and colleagues  
14 (2012) observed increased activity in BA44 for categorical violations (\*pronoun + noun,  
15 \*preposition + verb) compared to the grammatical items (pronoun + verb, preposition + noun).  
16 Crucially, the grammatical and ungrammatical items differed only in whether the second word  
17 violated a syntactic rule or not, as syntactic predictions triggered by the first word would in  
18 principle be present in both conditions. Therefore, the increased activation of BA44 in this  
19 experiment might reflect the bottom-up detection of an error, indexing that no grammatical rule to  
20 be applied is found. In this regard, recent electrocorticography and fMRI studies showed that the  
21 number of operations applied to integrate a word in the syntactic structure (bottom-up node count)  
22 correlated with activity in Broca's area during language comprehension (Bhattasali et al., 2019;  
23 Nelson et al., 2017). Finally, preliminary comparison of bottom-up and predictive left-corner  
24 parsers showed that the former model provided a better account of activity in Broca's area (Nelson  
25 et al., 2017).

1 In light of the discussion above, we advance the hypothesis that Broca's area processes  
2 grammatical rules in a bottom-up fashion as words are incrementally encountered. Accordingly,  
3 words are temporarily stored until a grammatical rule can be applied to combine them into a  
4 syntactic structure. This notion is in line with the existence of distinct circuits maintaining words in  
5 memory and binding them into hierarchical structures (Iwabuchi et al., 2019; Makuuchi et al.,  
6 2009). At the two-word level, such a dissociation might be reflected in the distinct functional profile  
7 of the frontal operculum/adjacent insula and BA44 (Zaccarella & Friederici, 2015a, 2015b). The  
8 frontal operculum and insula increase their activity as a function of the number of words presented  
9 (Zaccarella & Friederici, 2015a, 2015b), while increased activation in BA44 is observed only when  
10 a grammatical rule can be invoked to combine two elements into a constituent (Zaccarella &  
11 Friederici, 2015a).

12 To the best of our knowledge, no study has directly tested the causal role of Broca's area in  
13 bottom-up syntactic composition. However, evidence from agreement paradigms suggests that the  
14 left IFG might be involved in the bottom-up application of syntactic rules. Increased activity has  
15 been observed in the left IFG for agreement violations (Carreiras et al., 2010; Heim et al., 2010) and  
16 lesions in this region result in the absence of the ESN in this domain (Jakuszeit et al., 2013). While  
17 some authors linked the damage of the left IFG to the generation of predictions (Jakuszeit et al.,  
18 2013), the ESN would be absent even if the lesion affected the bottom-up evaluation of  
19 grammaticality. Data from a TMS study with two-word agreement violations support the latter  
20 hypothesis (Carreiras et al., 2012): stimulation of Broca's area during the second word of a phrase  
21 causally affected bottom-up morphosyntactic processes, as indicated by a reduced advantage for a  
22 grammatical condition compared to an ungrammatical one.

23 Before concluding, we would like to point out that we are not suggesting that structural  
24 predictions are never generated, but rather that they do not necessarily constitute an automatic  
25 mechanism which incrementally builds syntactic structures (Matchin et al., 2017, 2019). In this  
26 respect, it is noteworthy considering whether predictive coding (Friston, 2003, 2005; Friston &



1 Kiebel, 2009; Rao & Ballard, 1999) provides an adequate framework for syntactic composition.  
2 Grammar consists of a set of rules which are not probabilistic but deterministic – either something  
3 is correct or not – and which are not defined by the individuals. In other words, grammatical rules  
4 constitute a model which is not internal and is not constantly updated, contrary to the processes well  
5 described under a predictive coding perspective (Zaccarella et al., 2021). Therefore, automatic  
6 syntactic processes treat common and uncommon constructions equally, as long as they are  
7 grammatical (Friederici et al., 1996; Herrmann et al., 2009; Pulvermüller & Assadollahi, 2007).  
8 Individuals can construct internal probabilistic models of how likely it is that specific syntactic  
9 structures will be produced (Kroczek & Gunter, 2017), but the pure application of grammatical  
10 rules might just be a binary process: either something is correct or it is not. A similar dissociation  
11 seems to exist at the neural level, where brain regions sensitive to the probabilistic structural  
12 expectation appear to be located outside of the left-lateralized language network (Kroczek &  
13 Gunter, 2020).

14

## 15 **5. LIMITATIONS**

16 In line with the reviewed literature, we have proposed a bottom-up integration role for this region in  
17 syntactic composition. An alternative account may posit that the TMS effect in the region might  
18 have been either short-lived or rapidly compensated, thus only minimally affecting the prediction  
19 phase in our study. Evidence from online (Klaus & Hartwigsen, 2019; Kuhnke et al., 2017; Meyer  
20 et al., 2018) and offline (Acheson & Hagoort, 2013) TMS studies, however, seems to speak against  
21 this explanation, since TMS application over Broca's area has been conversely shown to affect  
22 linguistic processing. The estimation of the TMS-induced electrical fields in our participants is a  
23 first-time quantification of the realized IFG stimulation. To the best of our knowledge, this new  
24 perturbation quantification (Weise et al., 2020) has not been used elsewhere in the TMS literature  
25 on the left IFG. However, a recent study with stimulation of the parietal lobe showed that induced  
26 electrical fields weaker than the ones reported in our study were sufficient to induce a TMS effect

1 on cognitive processes (Kuhnke et al., 2020). Thus, the available evidence suggests that the  
2 stimulation protocol and intensities used in the present study may have been well-suited for  
3 disrupting Broca's area functioning at the predictive phase. Future studies targeting syntactic  
4 processes in Broca's area, possibly exploiting novel methods for estimating TMS effects on neural  
5 processing (Kuhnke et al., 2020; Numssen et al., 2021; Weise et al., 2020), might provide useful  
6 insights, either by replicating the present results or by providing evidence for alternative  
7 hypotheses.

8

## 9 **6. CONCLUSIONS**

10 In this EEG-TMS study, we tested whether Broca's area is causally involved during the categorical  
11 prediction phase in two-word phrasal/sentential constructions. Contrary to our hypothesis,  
12 perturbation of Broca's area at the predictive stage did not affect the ERP correlates of basic  
13 syntactic composition. Our data are compatible with the proposal that phrasal building in Broca's  
14 area might be accomplished in a bottom-up fashion (Bhattachali et al., 2019; Nelson et al., 2017),  
15 with words being integrated into constituents whilst the linguistic stream unfolds. They also  
16 converge on fMRI and TMS data implying bottom-up evaluation of grammatical rules in this region  
17 (Carreiras et al., 2010, 2012; Heim et al., 2010; Herrmann et al., 2012; Zaccarella & Friederici,  
18 2015a). As such, future studies addressing this neurocognitive hypothesis are awaited to provide  
19 further insights into the mechanisms of incremental linguistic composition.

## 1 **ACKNOWLEDGMENTS**

2 We wish to thank Philipp Kuhnke for assisting in the calculation of the target coordinates in subject  
3 space, Ina Koch and Joëlle Schroën for their help during data acquisition, Maren Grigutsch and  
4 Burkhard Maess for the fruitful discussions on the pre-processing pipeline, Giorgio Papitto, Elena  
5 Pyatigorskaya and Patrick Trettenbrein for their insightful comments on a previous version of this  
6 manuscript.

7

## 8 **FUNDING**

9 Matteo Maran was supported by the International Max Planck Research School on Neuroscience of  
10 Communication: Function, Structure, and Plasticity (IMPRS NeuroCom) and by direct funding  
11 from the Department of Neuropsychology (Max Planck Institute for Human Cognitive and Brain  
12 Sciences).

13

## 14 **CREDIT AUTHOR STATEMENT**

15 **Matteo Maran:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation,  
16 Writing - Original Draft, Writing - Review & Editing, Visualization; **Ole Numssen:** Formal  
17 Analysis (Electrical field simulations), Writing - Review & Editing, Visualization (Electrical field  
18 simulations); **Gesa Hartwigsen:** Resources, Writing - Review & Editing; **Angela D. Friederici:**  
19 Conceptualization, Resources, Writing - Review & Editing, Funding acquisition, Supervision;  
20 **Emiliano Zaccarella:** Conceptualization, Writing - Review & Editing, Visualization, Supervision.

1 **REFERENCE LIST**

- 2 Abney, S. P., & Johnson, M. (1991). Memory requirements and local ambiguities of parsing  
3 strategies. *Journal of Psycholinguistic Research*, 20(3), 233–250.
- 4 Acheson, D. J., & Hagoort, P. (2013). Stimulating the Brain’s Language Network: Syntactic  
5 Ambiguity Resolution after TMS to the Inferior Frontal Gyrus and Middle Temporal Gyrus.  
6 *Journal of Cognitive Neuroscience*, 25(10), 1664–1677. [https://doi.org/10.1162/jocn\\_a\\_00430](https://doi.org/10.1162/jocn_a_00430)
- 7 Amunts, K., Schleicher, A., Bürgel, U., Mohlberg, H., Uylings, H., & Zilles, K. (1999). Broca ’ s  
8 Region Revisited : Cytoarchitecture and Intersubject. *The Journal of Comparative Neurology*,  
9 412, 319–341.
- 10 Amunts, K., Weiss, P. H., Mohlberg, H., Pieperhoff, P., Eickhoff, S., Gurd, J. M., Marshall, J. C.,  
11 Shah, N. J., Fink, G. R., & Zilles, K. (2004). Analysis of neural mechanisms underlying verbal  
12 fluency in cytoarchitectonically defined stereotaxic space - The roles of Brodmann areas 44  
13 and 45. *NeuroImage*, 22(1), 42–56. <https://doi.org/10.1016/j.neuroimage.2003.12.031>
- 14 Baayen, R. H., Piepenbrock, R., and Gulikers, L. (1995). *The CELEX Lexical Database*.  
15 Philadelphia, PA: Linguistics Data Consortium; University of Pennsylvania.
- 16 Barber, H., & Carreiras, M. (2005). Grammatical gender and number agreement in Spanish: An  
17 ERP comparison. *Journal of Cognitive Neuroscience*, 17(1), 137–153.  
18 <https://doi.org/10.1162/0898929052880101>
- 19 Batterink, L., & Neville, H. J. (2013). The Human Brain Processes Syntax in the Absence of  
20 Conscious Awareness. *Journal of Neuroscience*, 33(19), 8528–8533.  
21 <https://doi.org/10.1523/jneurosci.0618-13.2013>
- 22 Berkovitch, L., & Dehaene, S. (2019). Subliminal syntactic priming. *Cognitive Psychology*,  
23 109(December 2018), 26–46. <https://doi.org/10.1016/j.cogpsych.2018.12.001>
- 24 Berwick, R. C., Friederici, A. D., Chomsky, N., & Bolhuis, J. J. (2013). Evolution, brain, and the

- 1 nature of language. *Trends in Cognitive Sciences*, 17(2), 98.
- 2 <https://doi.org/10.1016/j.tics.2012.12.002>
- 3 Bhattasali, S., Fabre, M., Luh, W. M., Al Saied, H., Constant, M., Pallier, C., Brennan, J. R.,  
4 Spreng, R. N., & Hale, J. (2019). Localising memory retrieval and syntactic composition: an  
5 fMRI study of naturalistic language comprehension. *Language, Cognition and Neuroscience*,  
6 34(4), 491–510. <https://doi.org/10.1080/23273798.2018.1518533>
- 7 Boersma, P. (2001). Praat, a system for doing phonetics by computer. *Glott International*, 5(9/10),  
8 341–345.
- 9 Bonhage, C. E., Mueller, J. L., Friederici, A. D., & Fiebach, C. J. (2015). Combined eye tracking  
10 and fMRI reveals neural basis of linguistic predictions during sentence comprehension. *Cortex*,  
11 68, 33–47. <https://doi.org/10.1016/j.cortex.2015.04.011>
- 12 Boston, M. F., Hale, J., & Kliegl, R. (2008). Parsing costs as predictors of reading difficulty: An  
13 evaluation using the Potsdam Sentence Corpus. *Parsing Costs as Predictors of Reading*  
14 *Difficulty: An Evaluation Using the Potsdam Sentence Corpus*, 2(1), 1–12.  
15 <https://doi.org/10.16910/jemr.2.1.1>
- 16 Brennan, J., & Pylkkänen, L. (2012). The time-course and spatial distribution of brain activity  
17 associated with sentence processing. *NeuroImage*, 60(2), 1139–1148.  
18 <https://doi.org/10.1016/j.neuroimage.2012.01.030>
- 19 Brennan, J. R., & Hale, J. T. (2019). Hierarchical structure guides rapid linguistic predictions during  
20 naturalistic listening. *Plos One*, 14(1), e0207741.  
21 <https://doi.org/10.1371/journal.pone.0207741>
- 22 Brennan, J. R., Stabler, E. P., Van Wagenen, S. E., Luh, W. M., & Hale, J. T. (2016). Abstract  
23 linguistic structure correlates with temporal activity during naturalistic comprehension. *Brain*  
24 *and Language*, 157–158, 81–94. <https://doi.org/10.1016/j.bandl.2016.04.008>

- 1 Carreiras, M., Carr, L., Barber, H. A., & Hernandez, A. (2010). Where syntax meets math: Right  
2 intraparietal sulcus activation in response to grammatical number agreement violations.  
3 *NeuroImage*, 49(2), 1741–1749. <https://doi.org/10.1016/j.neuroimage.2009.09.058>
- 4 Carreiras, M., Pattamadilok, C., Meseguer, E., Barber, H., & Devlin, J. T. (2012). Broca’s area  
5 plays a causal role in morphosyntactic processing. *Neuropsychologia*, 50(5), 816–820.  
6 <https://doi.org/10.1016/j.neuropsychologia.2012.01.016>
- 7 Chen, L., Goucha, T., Männel, C., Friederici, A. D., & Zaccarella, E. (2021). Hierarchical syntactic  
8 processing is beyond mere associating: Functional magnetic resonance imaging evidence from  
9 a novel artificial grammar. *Human Brain Mapping, March*, hbm.25432.  
10 <https://doi.org/10.1002/hbm.25432>
- 11 Chen, L., Wu, J., Fu, Y., Kang, H., & Feng, L. (2019). Neural substrates of word category  
12 information as the basis of syntactic processing. *Human Brain Mapping*, 40(2), 451–464.  
13 <https://doi.org/10.1002/hbm.24386>
- 14 Chen, L., Wu, J., Hartwigsen, G., Li, Z., Wang, P., & Feng, L. (2021). The role of a critical left  
15 fronto-temporal network with its right-hemispheric homologue in syntactic learning based on  
16 word category information. *Journal of Neurolinguistics*, 58(July 2020), 100977.  
17 <https://doi.org/10.1016/j.jneuroling.2020.100977>
- 18 Chomsky, N. (1995). *The Minimalist Program*. Cambridge, Massachusetts: The MIT Press.
- 19 Dablander, F., Derks, K., Draws, T., Etz, A., Evans, N. J., Gronau, Q. F., Haaf, J. M., Hinne, M.,  
20 Ly, A., Marsman, M., Matzke, D., Komarlu, A. R., Gupta, N., Sarafoglou, A., Stefan, A., &  
21 Voelkel, J. G. (2020). The JASP guidelines for conducting and reporting a Bayesian analysis.  
22 *Psychonomic Bulletin & Review*. <https://doi.org/https://doi.org/10.3758/s13423-020-01798-5>
- 23 DeLong, K. A., Urbach, T. P., & Kutas, M. (2005). Probabilistic word pre-activation during  
24 language comprehension inferred from electrical brain activity. *Nature Neuroscience*, 8(8),

- 1 1117–1121. <https://doi.org/10.1038/nm1504>
- 2 Den Ouden, H. E. M., Kok, P., & de Lange, F. P. (2012). How prediction errors shape perception,  
3 attention, and motivation. *Frontiers in Psychology*, 3(DEC), 1–12.  
4 <https://doi.org/10.3389/fpsyg.2012.00548>
- 5 Dikker, S., Rabagliati, H., Farmer, T. A., & Pylkkänen, L. (2010). Early occipital sensitivity to  
6 syntactic category is based on form typicality. *Psychological Science*, 21(5), 629–634.  
7 <https://doi.org/10.1177/0956797610367751>
- 8 Dikker, S., Rabagliati, H., & Pylkkänen, L. (2009). Sensitivity to syntax in visual cortex. *Cognition*,  
9 110(3), 293–321. <https://doi.org/10.1016/j.cognition.2008.09.008>
- 10 Eickhoff, S. B., Heim, S., Zilles, K., & Amunts, K. (2006). Testing anatomically specified  
11 hypotheses in functional imaging using cytoarchitectonic maps. *NeuroImage*, 32, 570–582.  
12 <https://doi.org/10.1016/j.neuroimage.2006.04.204>
- 13 Eickhoff, S. B., Paus, T., Caspers, S., Grosbras, M., Evans, A. C., Zilles, K., & Amunts, K. (2007).  
14 Assignment of functional activations to probabilistic cytoarchitectonic areas revisited. *Human*  
15 *Brain Mapping Journal*, 36(3), 511–521. <https://doi.org/10.1016/j.neuroimage.2007.03.060>
- 16 Eickhoff, S. B., Stephan, K. E., Mohlberg, H., Grefkes, C., Fink, G. R., Amunts, K., & Zilles, K.  
17 (2005). A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional  
18 imaging data. *NeuroImage*, 25, 1325–1335. <https://doi.org/10.1016/j.neuroimage.2004.12.034>
- 19 Everaert, M. B. H., Huybregts, M. A. C., Chomsky, N., Berwick, R. C., & Bolhuis, J. J. (2015).  
20 Structures, Not Strings: Linguistics as Part of the Cognitive Sciences. *Trends in Cognitive*  
21 *Sciences*, 19(12), 729–743. <https://doi.org/10.1016/j.tics.2015.09.008>
- 22 Faulkenberry, T. J., Ly, A., & Wagenmakers, E. J. (2020). Bayesian inference in numerical  
23 cognition: A tutorial using jasp. *Journal of Numerical Cognition*, 6(2), 231–259.

- 1 <https://doi.org/10.5964/jnc.v6i2.288>
- 2 Finkl, T., Hahne, A., Friederici, A. D., Gerber, J., Mürbe, D., & Anwander, A. (2020). Language  
3 Without Speech: Segregating Distinct Circuits in the Human Brain. *Cerebral Cortex (New*  
4 *York, N.Y. : 1991)*, 30(2), 812–823. <https://doi.org/10.1093/cercor/bhz128>
- 5 Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in*  
6 *Cognitive Sciences*, 6(2), 78–84. [http://tics.trends.com/1364-6613/02/\\$-see-front-matter](http://tics.trends.com/1364-6613/02/$-see-front-matter)
- 7 Friederici, A. D. (2011). The brain basis of language processing: From structure to function.  
8 *Physiological Reviews*, 91(4), 1357–1392. <https://doi.org/10.1152/physrev.00006.2011>
- 9 Friederici, A. D., Chomsky, N., Berwick, R. C., Moro, A., & Bolhuis, J. J. (2017). Language, mind  
10 and brain. *Nature Human Behaviour*, 1(October). <https://doi.org/10.1038/s41562-017-0184-4>
- 11 Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal structure of syntactic parsing:  
12 early and late event-related brain potential effects. *J. Exp. Psychol. Learn. Mem. Cogn.*, 22(5),  
13 1219–1248. <https://doi.org/10.1037/0278-7393.22.5.1219>
- 14 Friederici, A. D., Hahne, A., & Von Cramon, D. Y. (1998). First-pass versus second-pass parsing  
15 processes in a Wernicke's and a Broca's aphasic: Electrophysiological evidence for a double  
16 dissociation. *Brain and Language*, 62(3), 311–341. <https://doi.org/10.1006/brln.1997.1906>
- 17 Friederici, A. D., & Kotz, S. A. (2003). The brain basis of syntactic processes: Functional imaging  
18 and lesion studies. *NeuroImage*, 20(SUPPL. 1), 8–17.  
19 <https://doi.org/10.1016/j.neuroimage.2003.09.003>
- 20 Friederici, A. D., Pfeifer, E., & Hahne, A. (1993). Event-related brain potentials during natural  
21 speech processing: effects of semantic, morphological and syntactic violations. *Cognitive*  
22 *Brain Research*, 1(3), 183–192. [https://doi.org/10.1016/0926-6410\(93\)90026-2](https://doi.org/10.1016/0926-6410(93)90026-2)
- 23 Friederici, A. D., Rüschemeyer, S. A., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior



- 1 frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and  
2 semantic processes. *Cerebral Cortex*, 13(2), 170–177. <https://doi.org/10.1093/cercor/13.2.170>
- 3 Friederici, A. D., Von Cramon, D. Y., & Kotz, S. A. (1999). Language related brain potentials in  
4 patients with cortical and subcortical left hemisphere lesions. *Brain*, 122(6), 1033–1047.  
5 <https://doi.org/10.1093/brain/122.6.1033>
- 6 Friehs, M. A., Klaus, J., Singh, T., Frings, C., & Hartwigsen, G. (2020). Perturbation of the right  
7 prefrontal cortex disrupts interference control. *NeuroImage*, 222(August), 117279.  
8 <https://doi.org/10.1016/j.neuroimage.2020.117279>
- 9 Friston, K. (2003). Learning and inference in the brain. *Neural Networks*, 16(9), 1325–1352.  
10 <https://doi.org/10.1016/j.neunet.2003.06.005>
- 11 Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society*  
12 *B: Biological Sciences*, 360(1456), 815–836. <https://doi.org/10.1098/rstb.2005.1622>
- 13 Friston, K., & Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philosophical*  
14 *Transactions of the Royal Society B: Biological Sciences*, 364, 1211–1221.  
15 <https://doi.org/https://doi.org/10.1098/rstb.2008.0300>
- 16 Garrido, M. I., Kilner, J. M., Kiebel, S. J., & Friston, K. J. (2007). Evoked brain responses are  
17 generated by feedback loops. *Proceedings of the National Academy of Sciences of the United*  
18 *States of America*, 104(52), 20961–20966. <https://doi.org/10.1073/pnas.0706274105>
- 19 Gastaldon, S., Arcara, G., Navarrete, E., & Peressotti, F. (2020). Commonalities in alpha and beta  
20 neural desynchronizations during prediction in language comprehension and production.  
21 *Cortex*. <https://doi.org/10.1016/j.cortex.2020.09.026>
- 22 Goucha, T., & Friederici, A. D. (2015). The language skeleton after dissecting meaning: A  
23 functional segregation within Broca’s Area. *NeuroImage*, 114, 294–302.

- 1 <https://doi.org/10.1016/j.neuroimage.2015.04.011>
- 2 Graessner, A., Zaccarella, E., & Hartwigsen, G. (2021). Differential contributions of left-  
3 hemispheric language regions to basic semantic composition. *Brain Structure and Function*,  
4 *0123456789*. <https://doi.org/10.1007/s00429-020-02196-2>
- 5 Hagoort, P., & Indefrey, P. (2014). The neurobiology of language beyond single words. *Annual*  
6 *Review of Neuroscience*, *37*, 347–362. <https://doi.org/10.1146/annurev-neuro-071013-013847>
- 7 Hahne, Anja, & Friederici, A. D. (2002). Differential task effects on semantic and syntactic  
8 processes as revealed by ERPs. *Cognitive Brain Research*, *13*(3), 339–356.  
9 [https://doi.org/10.1016/S0926-6410\(01\)00127-6](https://doi.org/10.1016/S0926-6410(01)00127-6)
- 10 Hahne, Anja, & Friederici, A. D. (1999). Electrophysiological evidence for two steps in syntactic  
11 analysis. Early automatic and late controlled processes. *Journal of Cognitive Neuroscience*,  
12 *11*(2), 194–205.
- 13 Hale, J. (2014). *Automaton theories of human sentence comprehension*. CSLI Publications.
- 14 Hale, J., Dyer, C., Kuncoro, A., & Brennan, J. R. (2018). *Finding Syntax in Human*  
15 *Encephalography with Beam Search*. 2014. <https://doi.org/10.1023/A:1019527211183>
- 16 Hanna, J., Mejias, S., Schelstraete, M. A., Pulvermüller, F., Shtyrov, Y., & van der Lely, H. K. J.  
17 (2014). Early activation of Broca’s area in grammar processing as revealed by the syntactic  
18 mismatch negativity and distributed source analysis. *Cognitive Neuroscience*, *5*(2), 66–76.  
19 <https://doi.org/10.1080/17588928.2013.860087>
- 20 Hartwigsen, G. (2015). The neurophysiology of language: Insights from non-invasive brain  
21 stimulation in the healthy human brain. *Brain and Language*, *148*, 81–94.  
22 <https://doi.org/10.1016/j.bandl.2014.10.007>
- 23 Hartwigsen, G., Golombek, T., & Obleser, J. (2015). Repetitive transcranial magnetic stimulation

- 1 over left angular gyrus modulates the predictability gain in degraded speech comprehension.  
2 *Cortex*, 68, 100–110. <https://doi.org/10.1016/j.cortex.2014.08.027>
- 3 Hasting, A. S., & Kotz, S. A. (2008). Speeding up syntax: On the relative timing and automaticity  
4 of local phrase structure and morphosyntactic processing as reflected in event-related brain  
5 potentials. *Journal of Cognitive Neuroscience*, 20(7), 1207–1219.  
6 <https://doi.org/10.1162/jocn.2008.20083>
- 7 Hasting, A. S., Kotz, S. A., & Friederici, A. D. (2007). Setting the stage for automatic syntax  
8 processing: The mismatch negativity as an indicator of syntactic priming. *Journal of Cognitive  
9 Neuroscience*, 19(3), 386–400. <https://doi.org/10.1162/jocn.2007.19.3.386>
- 10 Heim, S., Van Ermingen, M., Huber, W., & Amunts, K. (2010). Left cytoarchitectonic BA 44  
11 processes syntactic gender violations in determiner phrases. *Human Brain Mapping*, 31(10),  
12 1532–1541. <https://doi.org/10.1002/hbm.20957>
- 13 Henderson, J. M., Choi, W., Lowder, M. W., & Ferreira, F. (2016). Language structure in the brain:  
14 A fixation-related fMRI study of syntactic surprisal in reading. *NeuroImage*, 132, 293–300.  
15 <https://doi.org/10.1016/j.neuroimage.2016.02.050>
- 16 Herrmann, B., Maess, B., Hasting, A. S., & Friederici, A. D. (2009). Localization of the syntactic  
17 mismatch negativity in the temporal cortex: An MEG study. *NeuroImage*, 48(3), 590–600.  
18 <https://doi.org/10.1016/j.neuroimage.2009.06.082>
- 19 Herrmann, B., Obleser, J., Kalberlah, C., Haynes, J. D., & Friederici, A. D. (2012). Dissociable  
20 neural imprints of perception and grammar in auditory functional imaging. *Human Brain  
21 Mapping*, 33(3), 584–595. <https://doi.org/10.1002/hbm.21235>
- 22 Hinne, M., Gronau, Q. F., van den Bergh, D., & Wagenmakers, E.-J. (2020). A Conceptual  
23 Introduction to Bayesian Model Averaging. *Advances in Methods and Practices in  
24 Psychological Science*, 3(2), 200–215. <https://doi.org/10.1177/2515245919898657>

- 1 Huettig, F. (2015). Four central questions about prediction in language processing. *Brain Research*,  
2 1626, 118–135. <https://doi.org/10.1016/j.brainres.2015.02.014>
- 3 Huettig, F., & Mani, N. (2016). Is prediction necessary to understand language? Probably not.  
4 *Language, Cognition and Neuroscience*, 31(1), 19–31.  
5 <https://doi.org/10.1080/23273798.2015.1072223>
- 6 Hultén, A., Schoffelen, J. M., Uddén, J., Lam, N. H. L., & Hagoort, P. (2019). How the brain makes  
7 sense beyond the processing of single words – An MEG study. *NeuroImage*, 186(November  
8 2018), 586–594. <https://doi.org/10.1016/j.neuroimage.2018.11.035>
- 9 Ilmoniemi, R. J., & Kičić, D. (2010). Methodology for combined TMS and EEG. *Brain*  
10 *Topography*, 22(4), 233–248. <https://doi.org/10.1007/s10548-009-0123-4>
- 11 Iwabuchi, T., Nakajima, Y., & Makuuchi, M. (2019). Neural architecture of human language:  
12 Hierarchical structure building is independent from working memory. *Neuropsychologia*,  
13 132(July), 107137. <https://doi.org/10.1016/j.neuropsychologia.2019.107137>
- 14 Jakuszeit, M., Kotz, S. A., & Hasting, A. S. (2013). Generating predictions: Lesion evidence on the  
15 role of left inferior frontal cortex in rapid syntactic analysis. *Cortex*, 49(10), 2861–2874.  
16 <https://doi.org/10.1016/j.cortex.2013.05.014>
- 17 Keysers, C., Gazzola, V., & Wagenmakers, E. J. (2020). Using Bayes factor hypothesis testing in  
18 neuroscience to establish evidence of absence. *Nature Neuroscience*, 23(7), 788–799.  
19 <https://doi.org/10.1038/s41593-020-0660-4>
- 20 Klaus, J., & Hartwigsen, G. (2019). Dissociating semantic and phonological contributions of the left  
21 inferior frontal gyrus to language production. *Human Brain Mapping*, 40(11), 3279–3287.  
22 <https://doi.org/10.1002/hbm.24597>
- 23 Kroczek, L. O. H., & Gunter, T. C. (2017). Communicative predictions can overrule linguistic

- 1 priors. *Scientific Reports*, 7(1), 1–9. <https://doi.org/10.1038/s41598-017-17907-9>
- 2 Kroczek, L. O. H., & Gunter, T. C. (2020). Distinct Neural Networks Relate to Common and  
3 Speaker-Specific Language Priors. *Cerebral Cortex Communications*, 1, 1–11.  
4 <https://doi.org/10.1093/texcom/tgaa021>
- 5 Kroczek, L. O. H., Gunter, T. C., Rysop, A. U., Friederici, A. D., & Hartwigsen, G. (2019).  
6 Contributions of left frontal and temporal cortex to sentence comprehension: Evidence from  
7 simultaneous TMS-EEG. *Cortex*, 115, 86–98. <https://doi.org/10.1016/j.cortex.2019.01.010>
- 8 Kuhnke, P., Beaupain, M. C., Cheung, V. K. M., Weise, K., Kiefer, M., & Hartwigsen, G. (2020).  
9 Left posterior inferior parietal cortex causally supports the retrieval of action knowledge.  
10 *NeuroImage*, 219(March), 117041. <https://doi.org/10.1016/j.neuroimage.2020.117041>
- 11 Kuhnke, P., Meyer, L., Friederici, A. D., & Hartwigsen, G. (2017). Left posterior inferior frontal  
12 gyrus is causally involved in reordering during sentence processing. *NeuroImage*,  
13 148(January), 254–263. <https://doi.org/10.1016/j.neuroimage.2017.01.013>
- 14 Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language  
15 comprehension? *Language, Cognition and Neuroscience*, 31(1), 32–59.  
16 <https://doi.org/10.1080/23273798.2015.1102299>
- 17 Laakso, Ii., Hirata, A., & Ugawa, Y. (2014). Effects of coil orientation on the electric field induced  
18 by TMS over the hand motor area Effects of coil orientation on the electric field induced by  
19 TMS over the hand. *Physics in Medicine and Biology*, 59, 203–218.  
20 <https://doi.org/10.1088/0031-9155/59/1/203>
- 21 Lau, E., Stroud, C., Plesch, S., & Phillips, C. (2006). The role of structural prediction in rapid  
22 syntactic analysis. *Brain and Language*, 98(1), 74–88.  
23 <https://doi.org/10.1016/j.bandl.2006.02.003>

- 1 Lee, E. G., Rastogi, P., Hadimani, R. L., Jiles, D. C., & Camprodon, J. A. (2018). Clinical  
2 Neurophysiology Impact of non-brain anatomy and coil orientation on inter- and intra-subject  
3 variability in TMS at midline. *Clinical Neurophysiology*, *129*(9), 1873–1883.  
4 <https://doi.org/10.1016/j.clinph.2018.04.749>
- 5 Lewis, A. G., Schoffelen, J.-M., Schriefers, H., & Bastiaansen, M. (2016). A Predictive Coding  
6 Perspective on Beta Oscillations during Sentence-Level Language Comprehension. *Frontiers*  
7 *in Human Neuroscience*, *10*(March), 1–6. <https://doi.org/10.3389/fnhum.2016.00085>
- 8 Lewis, A. G., Wang, L., & Bastiaansen, M. (2015). Brain & Language Fast oscillatory dynamics  
9 during language comprehension : Unification versus maintenance and prediction ? *Brain and*  
10 *Language*, *148*, 51–63. <https://doi.org/10.1016/j.bandl.2015.01.003>
- 11 Maguire, E. A., & Frith, C. D. (2004). The brain network associated with acquiring semantic  
12 knowledge. *Neuroimage*, *22*, 171–178. <https://doi.org/10.1016/j.neuroimage.2003.12.036>
- 13 Makuuchi, M., Bahlmann, J., Anwender, A., & Friederici, A. D. (2009). Segregating the core  
14 computational faculty of human language from working memory. *Proceedings of the National*  
15 *Academy of Sciences of the United States of America*, *106*(20), 8362–8367.  
16 <https://doi.org/10.1073/pnas.0810928106>
- 17 Maris, E. (2012). Statistical testing in electrophysiological studies. *Psychophysiology*, *49*(4), 549–  
18 565. <https://doi.org/10.1111/j.1469-8986.2011.01320.x>
- 19 Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data.  
20 *Journal of Neuroscience Methods*, *164*(1), 177–190.  
21 <https://doi.org/10.1016/j.jneumeth.2007.03.024>
- 22 Matchin, W., Brodbeck, C., Hammerly, C., & Lau, E. (2019). The temporal dynamics of structure  
23 and content in sentence comprehension: Evidence from fMRI-constrained MEG. *Human Brain*  
24 *Mapping*, *40*(2), 663–678. <https://doi.org/10.1002/hbm.24403>

- 1 Matchin, W., Hammerly, C., & Lau, E. (2017). The role of the IFG and pSTS in syntactic  
2 prediction: Evidence from a parametric study of hierarchical structure in fMRI. *Cortex*, 88,  
3 106–123. <https://doi.org/10.1016/j.cortex.2016.12.010>
- 4 Mayka, M. A., Corcos, D. M., Leurgans, S. E., & Vaillancourt, D. E. (2006). Three-dimensional  
5 locations and boundaries of motor and premotor cortices as defined by functional brain  
6 imaging: A meta-analysis. *NeuroImage*, 31(4), 1453–1474.  
7 <https://doi.org/10.1016/j.neuroimage.2006.02.004>
- 8 Meyer, L. (2018). The neural oscillations of speech processing and language comprehension: state  
9 of the art and emerging mechanisms. *European Journal of Neuroscience*, 48(7), 2609–2621.  
10 <https://doi.org/10.1111/ejn.13748>
- 11 Meyer, L., Elsner, A., Turker, S., Kuhnke, P., & Hartwigsen, G. (2018). Perturbation of left  
12 posterior prefrontal cortex modulates top-down processing in sentence comprehension.  
13 *NeuroImage*, 181(May), 598–604. <https://doi.org/10.1016/j.neuroimage.2018.07.059>
- 14 Mutanen, T., Mäki, H., & Ilmoniemi, R. J. (2013). The effect of stimulus parameters on TMS-EEG  
15 muscle artifacts. *Brain Stimulation*, 6(3), 371–376. <https://doi.org/10.1016/j.brs.2012.07.005>
- 16 Nelson, M. J., El Karoui, I., Giber, K., Yang, X., Cohen, L., Koopman, H., Cash, S. S., Naccache,  
17 L., Hale, J. T., Pallier, C., & Dehaene, S. (2017). Neurophysiological dynamics of phrase-  
18 structure building during sentence processing. *Proceedings of the National Academy of  
19 Sciences of the United States of America*, 114(18), E3669–E3678.  
20 <https://doi.org/10.1073/pnas.1701590114>
- 21 Neville, H., Nicol, J. L., Barss, A., Forster, K. I., & Garrett, M. F. (1991). Syntactically based  
22 sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive  
23 Neuroscience*, 3(2), 151–165. <https://doi.org/10.1162/jocn.1991.3.2.151>
- 24 Nielsen, J. D., Madsen, K. H., Puonti, O., Siebner, H. R., Bauer, C., Camilla, G., Saturnino, G. B.,

- 1 & Thielscher, A. (2018). *NeuroImage Automatic skull segmentation from MR images for*  
2 *realistic volume conductor models of the head : Assessment of the state-of-the-art.*  
3 *174*(March), 587–598. <https://doi.org/10.1016/j.neuroimage.2018.03.001>
- 4 Nieuwland, M. S., Politzer-Ahles, S., Heyselaar, E., Segaert, K., Darley, E., Kazanina, N., Von  
5 Grebmer Zu Wolfsturn, S., Bartolozzi, F., Kogan, V., Ito, A., Mézière, D., Barr, D. J.,  
6 Rousselet, G. A., Ferguson, H. J., Busch-Moreno, S., Fu, X., Tuomainen, J., Kulakova, E.,  
7 Husband, E. M., ... Huettig, F. (2018). Large-scale replication study reveals a limit on  
8 probabilistic prediction in language comprehension. *ELife*, *7*, 1–24.  
9 <https://doi.org/10.7554/eLife.33468>
- 10 Numssen, O., Zier, A.-L., Thielscher, A., Hartwigsen, G., Knösche, T. R., & Weise, K. (2021).  
11 Efficient high-resolution TMS mapping of the human motor cortex by nonlinear regression.  
12 *BioRxiv*, 2021.03.11.434996. <https://doi.org/10.1101/2021.03.11.434996>
- 13 Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory.  
14 *Neuropsychologia*, *9*(1), 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- 15 Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software  
16 for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational*  
17 *Intelligence and Neuroscience*, *2011*. <https://doi.org/10.1155/2011/156869>
- 18 Opitz, A., Windhoff, M., Heidemann, R. M., Turner, R., & Thielscher, A. (2011). How the brain  
19 tissue shapes the electric field induced by transcranial magnetic stimulation. *NeuroImage*,  
20 *58*(3), 849–859. <https://doi.org/10.1016/j.neuroimage.2011.06.069>
- 21 Osterhout, L., & Holcomb, P. J. (1993). Event-related potentials and syntactic anomaly: Evidence  
22 of anomaly detection during the perception of continuous speech. *Language and Cognitive*  
23 *Processes*, *8*(4), 413–437. <https://doi.org/10.1080/01690969308407584>
- 24 Osterhout, L., Holcomb, P. J., & Swinney, D. A. (1994). Brain potentials elicited by garden-path



- 1 sentences: Evidence of the application of verb information during parsing. *Journal of*  
2 *Experimental Psychology: Learning, Memory, and Cognition*, 20(4), 786–803.  
3 <https://doi.org/10.1037//0278-7393.20.4.786>
- 4 Pallier, C., Devauchelle, A. D., & Dehaene, S. (2011). Cortical representation of the constituent  
5 structure of sentences. *Proceedings of the National Academy of Sciences of the United States*  
6 *of America*, 108(6), 2522–2527. <https://doi.org/10.1073/pnas.1018711108>
- 7 Papitto, G., Friederici, A. D., & Zaccarella, E. (2020). The topographical organization of motor  
8 processing: An ALE meta-analysis on six action domains and the relevance of Broca’s region.  
9 *NeuroImage*, 206(June 2019), 116321. <https://doi.org/10.1016/j.neuroimage.2019.116321>
- 10 Pascual-Leone, A., Bartres-Faz, D., & Keenan, J. P. (1999). Transcranial magnetic stimulation:  
11 Studying the brain-behaviour relationship by induction of “virtual lesions.” *Philosophical*  
12 *Transactions of the Royal Society B: Biological Sciences*, 354(1387), 1229–1238.  
13 <https://doi.org/10.1098/rstb.1999.0476>
- 14 Perrin, F., Pernier, J., & Bertrand, O. (1989). Spherical splines for scalp potential and current  
15 density mapping. *Electroencephalography and Clinical Neurophysiology*, 72, 184–187.  
16 [https://doi.org/10.1016/0013-4694\(89\)90180-6](https://doi.org/10.1016/0013-4694(89)90180-6)
- 17 Pickering, M. J., & Gambi, C. (2018). Predicting while comprehending language: A theory and  
18 review. *Psychological Bulletin*, 144(10), 1002–1044. <https://doi.org/10.1037/bul0000158>
- 19 Pulvermüller, F., & Assadollahi, R. (2007). Grammar or serial order?: discrete combinatorial brain  
20 mechanisms reflected by the syntactic mismatch negativity. *Journal of Cognitive*  
21 *Neuroscience*, 19(6), 971–980. <https://doi.org/10.1162/jocn.2007.19.6.971>
- 22 Pulvermüller, F., & Shtyrov, Y. (2003). Automatic processing of grammar in the human brain as  
23 revealed by the mismatch negativity. *NeuroImage*, 20(1), 159–172.  
24 [https://doi.org/10.1016/S1053-8119\(03\)00261-1](https://doi.org/10.1016/S1053-8119(03)00261-1)

- 1 Pykkänen, L. (2020). Neural basis of basic composition: What we have learned from the red-boat  
2 studies and their extensions. *Philosophical Transactions of the Royal Society B: Biological*  
3 *Sciences*, 375(1791). <https://doi.org/10.1098/rstb.2019.0299>
- 4 Rao, R. P. N., & Ballard, D. H. (1999). Hierarchical Predictive Coding Model Hierarchical  
5 Predictive Coding of Natural Images. *Nature Neuroscience*, 2(1), 79.  
6 <http://neurosci.nature.com>
- 7 Resnik, P. (1992). Left-Corner Parsing and Psychological Plausibility. *Proceedings of the 14th*  
8 *Conference on Computational Linguistics - Volume 1*, 191–197.  
9 <https://doi.org/10.3115/992066.992098>
- 10 Rogasch, N. C., Sullivan, C., Thomson, R. H., Rose, N. S., Bailey, N. W., Fitzgerald, P. B., Farzan,  
11 F., & Hernandez-Pavon, J. C. (2017). Analysing concurrent transcranial magnetic stimulation  
12 and electroencephalographic data: A review and introduction to the open-source TESA  
13 software. *NeuroImage*, 147(June 2016), 934–951.  
14 <https://doi.org/10.1016/j.neuroimage.2016.10.031>
- 15 Rogasch, N. C., Thomson, R. H., Daskalakis, Z. J., & Fitzgerald, P. B. (2013). Short-latency  
16 artifacts associated with concurrent TMS-EEG. *Brain Stimulation*, 6(6), 868–876.  
17 <https://doi.org/10.1016/j.brs.2013.04.004>
- 18 Rogasch, N. C., Thomson, R. H., Farzan, F., Fitzgibbon, B. M., Bailey, N. W., Hernandez-Pavon, J.  
19 C., Daskalakis, Z. J., & Fitzgerald, P. B. (2014). Removing artefacts from TMS-EEG  
20 recordings using independent component analysis: Importance for assessing prefrontal and  
21 motor cortex network properties. *NeuroImage*, 101, 425–439.  
22 <https://doi.org/10.1016/j.neuroimage.2014.07.037>
- 23 Rotenberg, A., Horvath, J.C., & Pascual-Leone, A. (2014). *Transcranial Magnetic Stimulation*.  
24 Springer: New York.

- 1 Rothwell, J. C., Hallett, M., Berardelli, A., Eisen, A., Rossini, P., & Paulus, W. (1999). Magnetic  
2 stimulation: motor evoked potentials. *The International Federation of Clinical*  
3 *Neurophysiology. Electroencephalography and Clinical Neurophysiology. Supplement, 52,*  
4 *97–103.*
- 5 Salo, K. S. T., Mutanen, T. P., Vaalto, S. M. I., & Ilmoniemi, R. J. (2020). EEG Artifact Removal  
6 in TMS Studies of Cortical Speech Areas. *Brain Topography, 33*(1), 1–9.  
7 <https://doi.org/10.1007/s10548-019-00724-w>
- 8 Sassenhagen, J., & Draschkow, D. (2019). Cluster-based permutation tests of MEG/EEG data do  
9 not establish significance of effect latency or location. *Psychophysiology, 56*(6), 1–8.  
10 <https://doi.org/10.1111/psyp.13335>
- 11 Schell, M., Zaccarella, E., & Friederici, A. D. (2017). Differential cortical contribution of syntax  
12 and semantics: An fMRI study on two-word phrasal processing. *Cortex, 96*, 105–120.  
13 <https://doi.org/10.1016/j.cortex.2017.09.002>
- 14 Scheperjans, F., Eickhoff, S. B., Hömke, L., Mohlberg, H., Hermann, K., Amunts, K., & Zilles, K.  
15 (2008). Probabilistic maps, morphometry, and variability of cytoarchitectonic areas in the  
16 human superior parietal cortex. *Cerebral Cortex, 18*(9), 2141–2157.  
17 <https://doi.org/10.1093/cercor/bhm241>
- 18 Scheperjans, F., Hermann, K., Eickhoff, S. B., Amunts, K., Schleicher, A., & Zilles, K. (2008).  
19 Observer-independent cytoarchitectonic mapping of the human superior parietal cortex.  
20 *Cerebral Cortex, 18*(4), 846–867. <https://doi.org/10.1093/cercor/bhm116>
- 21 Segaert, K., Mazaheri, A., & Hagoort, P. (2018). Binding language: structuring sentences through  
22 precisely timed oscillatory mechanisms. *European Journal of Neuroscience, 48*(7), 2651–  
23 2662. <https://doi.org/10.1111/ejn.13816>
- 24 Sekiguchi, H., Takeuchi, S., Kadota, H., Kohno, Y., & Nakajima, Y. (2011). TMS-induced artifacts

- 1 on EEG can be reduced by rearrangement of the electrode's lead wire before recording.  
2 *Clinical Neurophysiology*, 122(5), 984–990. <https://doi.org/10.1016/j.clinph.2010.09.004>
- 3 Shain, C., Blank, I. A., van Schijndel, M., Schuler, W., & Fedorenko, E. (2020). fMRI reveals  
4 language-specific predictive coding during naturalistic sentence comprehension.  
5 *Neuropsychologia*, 138(December 2019), 107307.  
6 <https://doi.org/10.1016/j.neuropsychologia.2019.107307>
- 7 Siebner, H. R., Hartwigsen, G., Kassuba, T., & Rothwell, J. C. (2009). How does transcranial  
8 magnetic stimulation modify neuronal activity in the brain? Implications for studies of  
9 cognition. *Cortex*, 45(9), 1035–1042. <https://doi.org/10.1016/j.cortex.2009.02.007>
- 10 Snijders, T. M., Vosse, T., Kempen, G., Van Berkum, J. J. A., Petersson, K. M., & Hagoort, P.  
11 (2009). Retrieval and unification of syntactic structure in sentence comprehension: An fMRI  
12 study using word-category ambiguity. *Cerebral Cortex*, 19(7), 1493–1503.  
13 <https://doi.org/10.1093/cercor/bhn187>
- 14 Steinhauer, K., & Drury, J. E. (2012). On the early left-anterior negativity (ELAN) in syntax  
15 studies. *Brain and Language*, 120(2), 135–162. <https://doi.org/10.1016/j.bandl.2011.07.001>
- 16 Stokes, M. G., Chambers, C. D., Gould, I. C., Henderson, T. R., Janko, N. E., Allen, N. B., &  
17 Mattingley, J. B. (2005). Simple metric for scaling motor threshold based on scalp-cortex  
18 distance: Application to studies using transcranial magnetic stimulation. *Journal of*  
19 *Neurophysiology*, 94(6), 4520–4527. <https://doi.org/10.1152/jn.00067.2005>
- 20 Suzuki, K., & Sakai, K. L. (2003). An event-related fMRI study of explicit syntactic processing of  
21 normal/anomalous sentences in contrast to implicit syntactic processing. *Cerebral Cortex*,  
22 13(5), 517–526. <https://doi.org/10.1093/cercor/13.5.517>
- 23 Thielscher, A., Opitz, A., & Windhoff, M. (2011). NeuroImage Impact of the gyral geometry on the  
24 electric field induced by transcranial magnetic stimulation. *NeuroImage*, 54(1), 234–243.

- 1 <https://doi.org/10.1016/j.neuroimage.2010.07.061>
- 2 Trettenbrein, P. C., Papitto, G., Friederici, A. D., & Zaccarella, E. (2020). The functional  
3 neuroanatomy of sign language without speech. *Human Brain Mapping, October*, 1–14.  
4 <https://doi.org/10.1002/hbm.25254>
- 5 Tyler, L. K., Shafto, M. A., Randall, B., Wright, P., Marslen-Wilson, W. D., & Stamatakis, E. A.  
6 (2010). Preserving syntactic processing across the adult life span: The modulation of the  
7 frontotemporal language system in the context of age-related atrophy. *Cerebral Cortex, 20*(2),  
8 352–364. <https://doi.org/10.1093/cercor/bhp105>
- 9 van den Bergh, D., van Doorn, J., Marsman, M., Draws, T., van Kesteren, E.-J., Derks, K.,  
10 Dablander, F., Gronau, Q. F., Kucharský, S., Gupta, A. R. K. N., Sarafoglou, A., Voelkel, J.  
11 G., Stefan, A., Ly, A., Hinne, M., Matzke, D., & Wagenmakers, E.-J. (2020). A Tutorial on  
12 Conducting and Interpreting a Bayesian ANOVA in JASP. *L'Année Psychologique, 120*(1),  
13 73. <https://doi.org/10.3917/anpsy1.201.0073>
- 14 van der Burght, C. L., Goucha, T., Friederici, A. D., Kreitewolf, J., & Hartwigsen, G. (2019).  
15 Intonation guides sentence processing in the left inferior frontal gyrus. *Cortex, 117*, 122–134.  
16 <https://doi.org/10.1016/j.cortex.2019.02.011>
- 17 Vandenberghe, R., Nobre, A. C., & Price, C. J. (2002). The response of left temporal cortex to  
18 sentences. *Journal of Cognitive Neuroscience, 14*(4), 550–560.  
19 <https://doi.org/10.1162/08989290260045800>
- 20 Veniero, D., Bortoletto, M., & Miniussi, C. (2009). TMS-EEG co-registration: On TMS-induced  
21 artifact. *Clinical Neurophysiology, 120*(7), 1392–1399.  
22 <https://doi.org/10.1016/j.clinph.2009.04.023>
- 23 Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q.  
24 F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van Kesteren, E. J., van

- 1 Doorn, J., Šmíra, M., Epskamp, S., Etz, A., Matzke, D., ... Morey, R. D. (2018). Bayesian  
2 inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin and*  
3 *Review*, 25(1), 58–76. <https://doi.org/10.3758/s13423-017-1323-7>
- 4 Wagenmakers, E. J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Love, J., Selker, R., Gronau, Q.  
5 F., Šmíra, M., Epskamp, S., Matzke, D., Rouder, J. N., & Morey, R. D. (2018). Bayesian  
6 inference for psychology. Part I: Theoretical advantages and practical ramifications.  
7 *Psychonomic Bulletin and Review*, 25(1), 35–57. <https://doi.org/10.3758/s13423-017-1343-3>
- 8 Walsh, V., & Cowey, A. (2000). Transcranial magnetic stimulation and cognitive neuroscience.  
9 *Nature Reviews Neuroscience*, 1(1), 73–79. <https://doi.org/10.1038/35036239>
- 10 Weise, K., Numssen, O., Thielscher, A., Hartwigsen, G., & Knösche, T. R. (2020). A novel  
11 approach to localize cortical TMS effects. *NeuroImage*, 209(December 2019).  
12 <https://doi.org/10.1016/j.neuroimage.2019.116486>
- 13 Widmann, A., Schröger, E., & Maess, B. (2015). Digital filter design for electrophysiological data -  
14 a practical approach. *Journal of Neuroscience Methods*, 250, 34–46.  
15 <https://doi.org/10.1016/j.jneumeth.2014.08.002>
- 16 Windhoff, M., Opitz, A., & Thielscher, A. (2013). *Electric Field Calculations in Brain Stimulation*  
17 *Based on Finite Elements : An Optimized Processing Pipeline for the Generation and Usage of*  
18 *Accurate Individual Head Models*. 935(March 2011), 923–935.  
19 <https://doi.org/10.1002/hbm.21479>
- 20 Wu, C. Y., Zaccarella, E., & Friederici, A. D. (2019). Universal neural basis of structure building  
21 evidenced by network modulations emerging from Broca's area: The case of Chinese. *Human*  
22 *Brain Mapping*, 40(6), 1705–1717. <https://doi.org/10.1002/hbm.24482>
- 23 Zaccarella, E., & Friederici, A. D. (2015a). Merge in the human brain: A sub-region based  
24 functional investigation in the left pars opercularis. *Frontiers in Psychology*, 6(NOV), 1–9.

1 <https://doi.org/10.3389/fpsyg.2015.01818>

2 Zaccarella, E., & Friederici, A. D. (2015b). Reflections of word processing in the insular cortex : A  
3 sub-regional parcellation based functional assessment. *Brain and Language*, *142*, 1–7.

4 <https://doi.org/10.1016/j.bandl.2014.12.006>

5 Zaccarella, E., Meyer, L., Makuuchi, M., & Friederici, A. D. (2017). Building by Syntax: The  
6 Neural Basis of Minimal Linguistic Structures. *Cerebral Cortex*, *27*(1), 411–421.

7 <https://doi.org/10.1093/cercor/bhv234>

8 Zaccarella, E., Papitto, G., & Friederici, A. D. (2021). Language and action in Broca’s area:

9 Computational differentiation and cortical segregation. *Brain and Cognition*, *147*, 105651.

10 <https://doi.org/10.1016/j.bandc.2020.105651>

11 Zaccarella, E., Schell, M., & Friederici, A. D. (2017). Reviewing the functional basis of the

12 syntactic Merge mechanism for language: A coordinate-based activation likelihood estimation  
13 meta-analysis. *Neuroscience and Biobehavioral Reviews*, *80*(July), 646–656.

14 <https://doi.org/10.1016/j.neubiorev.2017.06.011>

15