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Title:

Sentence processing: How words generate syntactic structures in the brain

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Abstract:

Language comprehension relies on the fundamental ability to create meaningful syntactic structures from single words during on-line processing. Time-resolved neuroimaging techniques can be used to measure electrophysiological activity revealing the neural dynamics underpinning these combinatorial processes in the brain. In the present chapter, we review and critically evaluate studies that have specifically investigated the electrophysiological bases of sentence-level syntactic processing using different types of analyses and paradigms. Besides reviewing event-related potential (ERP) studies, we focus on recent investigations of neural oscillations, highlighting their relevance and implications for our understanding of syntactic processing. Furthermore, we discuss critical issues related to the interpretation of current electrophysiological findings, including open questions such as the relationship between syntax and semantics and the link between ERPs and oscillations.

Key words: syntactic processing, sentence processing, ERPs, neural oscillations

1. Introduction

A fundamental requirement for successful language comprehension is the ability to create syntactically structured sentential representations that allow for a coherent semantic interpretation. Because sentences manifest in external input as sequences of words without explicit structure, syntactic structures must be encoded internally in the brain. At the core of this ability is the cognitive capacity to generate syntactic structures from sequential input by actively grouping single words into unified multi-word structures (i.e., phrases and sentences) and identifying their abstract relations. Advancing our understanding of language comprehension therefore requires explaining how this combinatorial syntactic grouping process is implemented in the brain. The remarkable speed and accuracy with which the brain processes language suggests that such syntactic structures are most probably generated

incrementally (i.e., roughly on a word-by-word basis) in real time. Since syntactic processing is inherently incremental, investigating the dynamic flow of underlying neural activity requires tools with exquisite temporal precision (at the millisecond scale). Time-resolved neuroimaging techniques – Electroencephalography (EEG), Magnetoencephalography (MEG), or Electrocorticography (ECoG) – can provide this kind of detailed information about the electrophysiological time-course of different cognitive processes and are thus uniquely suited to research on syntactic processing (cf. Chapters 5-8). Importantly, the electrophysiological data obtained from these techniques is multidimensional (see Section 2) and specific types of analysis can be used to explore distinct aspects of neural activity. It is therefore not surprising that in the past decades there has been a large increase in the methodological tools used to study the electrophysiological dynamics that underlie syntactic processing (or, more generally, sentence processing) in the brain.

In the present chapter, we review and critically evaluate studies that have specifically investigated the electrophysiological bases of sentence-level syntactic processing. Our aim is to provide a comprehensive and updated review of the main findings obtained using different paradigms and types of analyses. We review evidence based on more traditional time-domain analyses such as event-related potentials (ERPs) as well as more recent results from frequency-domain analyses of neural oscillations. In Section 2, we briefly introduce various methodological aspects of time-domain and frequency-domain analyses of syntactic processing, presenting them in the context of the most commonly employed experimental paradigms. In Section 3, we provide a concise review of the main findings on syntactic processing in the time domain from ERP analyses, mostly from studies using incorrect sentence paradigms. In Section 4, we review recent work exploring syntactic processing in the frequency domain, examining various aspects of neural oscillations, studied using both correct (Section 4.1) and incorrect (Section 4.2) sentence paradigms. Finally, in Section 5, we critically discuss

the interpretation and implications of current evidence on syntactic processing at the electrophysiological level – focusing particularly on neural oscillations – and consider some open questions to be explored in future research.

2. Methodological aspects of electrophysiological studies on sentence processing

The electrophysiological signal recorded from time-resolved techniques such as EEG, MEG, and ECoG is multidimensional: it encompasses multiple properties independently related to neural activity such as time, space, amplitude and frequency. These distinct aspects of the same underlying signal can be captured using various time-resolved analytical approaches such as time-domain and frequency-domain analyses.

Time-domain analyses, such as Event-Related Potential (ERP) analyses, have been the main focus of studies exploring the electrophysiological correlates of syntactic processing. They are based on the analysis of *evoked* responses, signals that are characterized by systematic patterns in time and amplitude (technically, time- and phase-locked signals) that occur after specified events. ERP responses are estimated by averaging neural responses and are often categorized into ERP components defined by certain properties (for further details, see Chapter 6). The main advantage of the ERP approach is that it offers high temporal resolution. In the context of syntactic processing, the most common paradigm using time-domain analyses is the violation paradigm. This paradigm compares ERP responses triggered by single words (embedded in sentences) containing different types of (morpho-)syntactic errors/violations with their syntactically correct word counterparts (e.g., the plural-inflected verb *were* in *Two girls were...* compared to **One girl were...*). Another productive paradigm in this literature focuses on the interpretation of structural ambiguities instead, for instance comparing words preceded by non-ambiguous (e.g., *The student saw that the teacher was...*) and ambiguous (e.g., *The student saw the teacher was...*) sentential contexts. By examining amplitude modulations at certain time windows following such single words, it can be inferred whether

and when various ERP components are sensitive to certain types of information. In Section 3, we review ERP components that are usually related to different (morpho-)syntactic violations.

Despite their high temporal detail, time-domain analyses have certain limitations. First, they adopt a univariate approach based on an averaged-response procedure, which reduces the complexity of the electrophysiological signal to a single variable (i.e., an ERP component). This means that if there were two ongoing processes occurring in parallel, both would be either reflected in the same ERP component or would cancel each other out. Second, they disregard an important part of the signal – oscillatory activity that is not phase-locked, assumed to be noise – which nevertheless might provide relevant information (see below). Third, given the univariate nature of ERPs, it might be difficult to capture neural activity associated with a sentence as a whole: rather than resulting in a sentence-level component, this information would be embedded in the evoked response to each of the words that composed the sentence.

Frequency-domain approaches are less rigid in relation to such considerations. Compared to time-domain analyses, they incorporate one additional dimension of electrophysiological evidence: oscillatory activity. Technically, they capture neural activity that is time-locked (like ERPs) but not necessarily phase-locked to a specific event. Instead of representing the electrophysiological signal as a single component, frequency-domain analyses decompose the signal into multiple and independent frequency-specific components or neural oscillations. Neural oscillations are usually categorized according to their frequency bands: delta (< 4 Hz), theta (4-8 Hz), alpha (9-12 Hz), beta (13-30 Hz) and gamma (> 30 Hz). Based on this frequency decomposition, different neural oscillations can be concurrently distinguished at distinct timescales, possibly displaying a hierarchical organization in which faster (higher) frequencies are nested within slower (lower) frequencies. The multivariate nature of oscillatory analyses makes it possible to account for parallel processes (e.g., mapped onto distinct but temporally overlapping oscillatory components). However, although they take the temporal dimension into

account, frequency-domain analyses result in a “smoothed” representation whose temporal detail is lower than that of time-domain, such as ERP, analyses. In this respect, frequency-domain approaches provide evidence that is complementary to time-domain approaches. In addition, oscillatory analyses allow for the study of fast frequency components (> 10 Hz) that are typically not visible (or have been filtered out) in ERP analyses. Furthermore, because of their analytical criteria, frequency-domain approaches are more suitable for exploring neural activity that goes beyond the single word, for instance, in whole sentences (see below for an example of experimental paradigm that takes advantage of this property). In Section 4, we review the main paradigms that have been used to exploit the potential of frequency-domain analyses of syntactic processing. Importantly, neural activity analysed in the frequency domain can be related to disparate aspects of the same electrophysiological signal. Given this heterogeneity, we provide some further distinctions regarding two frequency-domain components of the signal: power and phase (see Chapter 7 for further details).

One component of oscillatory activity is *power*, which refers to the squared amplitude of an oscillatory signal. The result of a power analysis is a power spectrum that reveals the frequencies that consistently show the highest amplitude values across the time window of interest. While providing a frequency-domain representation of the signal, this type of analysis does not reflect the temporal evolution of power. It is possible to overcome this limitation by applying *time-frequency* analyses, which provide an estimation of power variations across multiple frequencies over time. Another frequency-domain component is *phase*, which indicates the directionality of the angle of one or several cycles of the oscillation in a given time window. Because it focuses on inter-trial consistency in the phase parameter at a specific frequency, this type of analysis is particularly informative about the temporal structure of the neural signal. Note that oscillatory activity perfectly phase-aligned to a specific event across multiple trials would elicit a clear ERP component. While phase analyses can be represented

in the frequency domain independently from the temporal dimension (i.e., as a power spectrum), it is also possible to represent phase patterns by considering their temporal modulations over selected time windows. A related time-frequency measure that takes power into account is *power envelope*, which provides information about the temporal evolution of power, that is, the specific shape of its temporal structure (i.e., a proxy for phase angle). Finally, there are also several types of interactions between these frequency-domain components, for example, *phase-amplitude coupling* (PAC) (see [1–4]). PAC is based on the distinctive hierarchical organization of neural oscillations (see above) and refers to the cross-frequency coupling between the amplitude of higher-frequency oscillations and the phase of lower-frequency oscillations – a measure that is to some extent similar to power envelope.

While time-domain analyses have traditionally dominated the study of syntactic processing, frequency-domain methods have recently received considerable attention in this literature. As mentioned above, frequency-domain approaches enable the analysis of neural activity across a whole sentence, thus facilitating the use of experimental paradigms that examine how multi-word syntactic structures are represented at the neural level. A recently implemented paradigm exploiting such characteristics is the *frequency-tagging* paradigm, which evaluates whether specific oscillatory patterns repeat over time. In short, this paradigm is characterized by the presentation of continuous streams of sensory input consisting of certain types of stimuli that are repeated periodically (i.e., at a fixed frequency). In neural terms, it relies on the observation that electrophysiological activity typically aligns to the rhythmic properties of periodic stimuli (for a review of this paradigm in the context of musical perception, see [5]). This alignment between external events and internal oscillatory activity is commonly known as *entrainment* (see [6, 7], for recent reviews). Oscillatory entrainment to certain types of information occurs if the dominant frequency of the neural signal - as reflected in the power spectrum or in certain phase analyses of the frequency domain – corresponds to the frequency of presentation of such

stimuli. In the case of the frequency-tagging paradigm, frequency-domain measures are computed after ERP analyses. It has been shown that, apart from entrainment to external (bottom-up) cues present in the sensory input, entrainment can also emerge when dealing with abstract information that additionally requires internal (top-down) processes. For example, when two independently presented syllables are perceived as a single word, a response occurs at the frequency of these words in the power spectrum [8]. Given that the exact combination of sensory units is not evident from bottom-up cues, oscillatory entrainment to abstract properties (e.g., two-syllable words) can be considered evidence for the internal grouping of separated units. Building on these findings, recent applications of the frequency-tagging paradigm have focused on the neural representation of multi-word syntactic structures, particularly assessing oscillatory entrainment when grouping words into specific syntactic structures. In Section 4.1, we review studies that have implemented the frequency-tagging paradigm as well as other paradigms that use correct single sentences to explore the oscillatory dynamics of sentence-level syntactic processing.

3. Syntactic processing in ERP responses

A variety of experimental designs has been used to study syntactic processing from an electrophysiological perspective in the time domain (see Table 1). While only a few studies have manipulated syntactic structure to create potentially ambiguous continuations, a large body of literature has relied on the manipulation of word category and (morpho-)syntactic relations within so-called violation paradigms, i.e. experimental designs in which an anomalous stimulus is compared to its correct counterpart. As will be evident from the review below, several ERP components, and their modulation in terms of amplitude and topography, that relate to (morpho-)syntactic aspects of linguistic input as it unfolds over time have been identified: the P600, the (e)LAN, as well as the N400 effect (also see [9] for a comprehensive review).

--- please insert Table 1 around here ---

The P600 effect, a long-lasting positive voltage shift, typically distributed in centro-parietal areas of the scalp, that arises about 600 milliseconds post-stimulus onset is a common denominator across most experimental designs. Processing a sentence that is well formed but at some point contains at least two alternative structural interpretations (i.e. a garden-path sentence) results in a P600 effect compared to its unambiguous counterpart. This effect has been functionally interpreted as an index of syntactic reanalysis. Similarly, P600 effects have been found for well-formed sentences that are more complex or less preferred when compared to sentences that are easier to parse or more preferred, although there are (much debated) modulations in the distribution of this effect, namely broad/frontal P600s. A number of independent proposals have been advanced that link broad/frontal positive effects either to costs associated with overwriting preferred (more active structural representations of a sentence, as in the case of non-preferred continuations [10]), or to costs associated with increasing syntactic complexity where revision of previous sentence fragments may not be involved [11].

In the context of syntactic manipulations, the P600 has also been reported as part of biphasic patterns: an early left anterior negativity (e)LAN and the N400 as illustrated in Table 1. In the presence of a syntactic category violation, some authors reported that the P600 is preceded by an eLAN arising between 120 and 200 milliseconds after word onset [12]. This effect was functionally interpreted as reflecting the initial building of local phrase structure, which relies on the extraction and analysis of syntactic category information from the linguistic input, a process thought to be automatic, and independent from both attentional processes [13] and task requirements [12]. Recently, a number of methodological concerns have been raised that question the validity and reliability of eLAN effects and thus their functional interpretation (see [14]).

Besides word category violations, the presence of anomalous inflectional morphology that prevents the correct assignment of grammatical roles (subject and object) can also generate an early negative response. In several languages, incorrect agreement between a controller and a target (e.g. subject-verb, adverb-verb, determiner-noun and adjective-noun agreement), as well as incorrect case marking [15], have been found to elicit a left-lateralized negative effect (LAN) between 300 and 500 milliseconds relative to their correct counterparts. This has motivated a functional interpretation of the LAN as an effect that indexes the automatic detection of morpho-syntactic inconsistency between the controller and the target of a syntactic relation [16–18].

It should be noted that LAN effects are not consistent either across or within languages and syntactic configurations. They are found less systematically in morphologically poor languages with rigid word-order like English than in morphologically rich languages like Spanish and Italian with relatively free word-order. For example, in English, a LAN effect was found for number agreement violations between subject and verb [19], while verb finiteness violations between a modal auxiliary and a verb (e.g. the cat won't **eating*/eat the food) only elicited a P600 effect [20–22]. In contrast, subject-verb and determiner-noun agreement violations in Spanish and Italian have consistently shown a biphasic LAN-P600 pattern [23–28]. A possible explanation for this variability is that the presence/absence of the LAN is a continuum [29–31], with the likelihood of observing this effect varying as a function of a language's inflectional morphology richness and the weight that it gives to the assignment of grammatical roles. In other words, the greater the morphological richness of a language, and the more relevant the assignment of grammatical roles for comprehension, the higher the probability of finding a LAN effect.¹

¹ The validity of the LAN as an electrophysiological correlate of sentence processing has recently been questioned. Specifically, recent studies have advanced the claim that LAN effects are by-products of artefacts in

Variability in ERP responses associated with syntactic processing is not limited to the presence vs. absence of LAN effects. In Spanish, the presence of a person mismatch between subject and verb has been shown to elicit LAN or N400 effects depending on the type of subject (pronominal, as in [32], or lexical, as in [24, 33]) and the person specifications being manipulated (1st vs. 2nd, as in [32], or 3rd vs. 2nd, as in [24, 33]). In particular, while person agreement violations between 1st/2nd pronominal subject and 1st/2nd person verbs (as in *Yo*_{1sg} **abres*_{2sg}/*abro*_{1sg} *la puerta*, I open_{*2sg/1sg} the door) have been shown to elicit anterior negative effects, person mismatches between lexical subjects and verbs (as in *El cocinero*_{3sg} **cocinaste*_{2sg}/*cocinó*_{3sg} *un arroz muy rico*, The cook_{3sg} cooked_{3sg/*2sg} very tasty rice) appear to generate early negative effects with a centro-posterior maximum. As some authors point out [24], this difference in topographical distribution may be attributed to the distinct interpretive relevance that being a participant (the speaker and addressee indexed by 1st and 2nd person) or a non-participant (3rd person) in the speech event has.

One last aspect of agreement processing that deserves note is the effect generated by apparent morphosyntactic mismatches between subject and verb. A case in point is represented by the so-called unagreement pattern, i.e. agreement patterns in which a 3rd person plural subject can be followed by a 1st or 2nd person plural verb without ungrammaticality (*Los cocineros*_{3pl} *cocinamos*_{1pl}/*cocinasteis*_{2pl} /*cocinaron*_{3pl} *un arroz muy rico*, We/You/The cooks cooked very tasty rice). Mancini and colleagues [33] found that, as with outright person anomalies, processing unagreement yielded a posteriorly distributed negative effect, but unlike them, no P600 effect was found, suggesting that detection of morphosyntactic mismatch did not trigger

the grand-averaging process that obscure potential individual variability in the ERP response. As this issue appears to be tangential to the purpose of the current chapter, the reader is referred to [97, 112–114] for further readings.

any repair mechanisms, in line with its grammatical status (see also [34] for similar effects found in Basque).

In addition to agreement violations, other syntactic manipulations elicit early negative effects (Table 1). Fully grammatical sentences that contain long-distance dependencies, such as filler-gap constructions and verb gapping are a case in point. In filler-gap constructions, a constituent is moved leftward from its original position (*which cake* in the example provided in Table 1), leaving a gap that, during processing, must be “filled” with the fronted constituent to afford a proper interpretation. In verb gapping sentences, the verb is omitted from the second clause of a conjoined structure (the verb *read* in the example provided in Table 1, see [35]). In the context of these manipulations, LAN effects arising at the position of the gap have been interpreted as correlates of increased working memory costs [36–39].

4. Syntactic processing in the frequency domain

Research in sentence processing at the electrophysiological level is becoming increasingly focused on oscillatory-based analyses that explore the neural dynamics in the frequency domain. As explained above, frequency-domain approaches allow for the examination of neural activity from different perspectives. They have been used to study neural activity time-locked to specific events such as words, as in the ERP studies described above – but have also been employed to better understand the processing of multi-word events, such as phrases and sentences. Here we will review studies that investigate the neural basis of structure-based syntactic processing using these types of frequency-domain analyses by implementing two complementary experimental approaches. One approach examines the frequency-domain correlates of syntactic processing through the manipulation of a syntactic variable of interest within syntactically correct configurations, using both ERP-like single-word as well as multi-word contrasts. The second approach focuses on oscillatory responses elicited by the disruption

of specific (morpho)syntactic computations using various types of violations within single word, a methodology commonly used in the ERP literature.

4.1. Oscillatory dynamics of syntactically correct configurations

Recent research using the frequency-tagging paradigm has found a close link between low-frequency oscillations in the delta band (< 4 Hz) and the computation of basic syntactic structures. As explained in Section 2, the logic behind this frequency-domain paradigm is that neural activity typically fluctuates in response to the rhythmic properties of periodic stimuli (i.e., repeated at a fixed frequency), resulting in oscillatory entrainment to these external events. Oscillatory entrainment to syntactic structures was first shown in a pioneering MEG/ECOG study by Ding and colleagues [40]. They auditorily presented Chinese- and English-speaking participants with continuous sequences of mono-syllabic Chinese or English words, which could be grouped into two phrases (*[new plans] [dry fur]*) or into a sentence comprised by two phrases (*[[new plans] [gave hope]]*). Because words were presented periodically at 4 Hz (i.e., 250 ms per word), phrases repeatedly occurred at 2 Hz and sentences at 1 Hz (i.e., in the delta-band range). Their critical finding was that power spectrum peaks appeared bilaterally at the frequency of phrases and sentences only when participants listened to these sequences in their native language. Importantly, this delta-band entrainment emerged despite the lack of syntactically informative prosodic cues in the stimuli, as well as when controlling for word (lexical) predictability. This result suggests that delta-band oscillations support the structure-based processing of linguistic information by selectively grouping words into syntactic structures. Moreover, assuming that phrases and sentences constitute a hierarchical relationship with each other (i.e., phrases are nested into sentences), the entrainment effect observed at multiple nested levels seems to mirror the hierarchical organization of syntactic structures. Subsequent EEG and MEG studies using this paradigm have replicated this main finding [41–

43], also extending it to delta-band phase [41, 42], confirming the robustness and replicability of this effect.

Delta-band oscillations have also been related to structure-based processing in the time domain using more conventional single-sentence paradigms. The strongest evidence for such a link comes from a speech comprehension study carried out by Meyer and colleagues [44]. Their design used syntactically ambiguous German sentences such as *the client sued the murderer with the corrupt lawyer*, where the two critical phrases *the murderer* and *with the corrupt lawyer* could be grouped either into one or two phrases depending on their interpretation. Participants were presented with these ambiguous sentences, in which a prosodic boundary between critical phrases was either absent or present to acoustically favour the former or latter grouping. After each sentence, subjects were asked a comprehension question, whose answer indicated which interpretation they had favoured. The main finding was that, before the bias induced by the prosodic cue, the delta-band phase over left-anterior and left-posterior electrodes varied systematically with the actual syntactic grouping preferred by participants. Crucially, this delta-band phase effect was independent of the prosodic cue. This result shows that delta-band oscillations adjust their phase to the intended syntactic grouping, thus suggesting a critical role for delta-band oscillations in the incremental formation of specific syntactic structures (see also [45]). Besides this selective effect for syntactic grouping, another study in German provides evidence that delta-band modulations are more generally related to structure-based processing [46]. In this study, participants were presented with written stimuli consisting of sentence fragments with minimal semantic content (*they were yesterday evening at the*) and word lists lacking syntactic structure (*they the at evening yesterday were*) in German. Moreover, to control for the differential attentional demands of these sequences, after each trial, participants had to perform a task that was either related (serial retention) or not (lexical decision) to the stimuli. They found that the availability of syntactic structure in

sentence fragments, but not in unstructured word lists, lead to delta-band (4 Hz) power increases, mostly localized in central and bilateral posterior electrodes. Because this delta effect appeared regardless of the task, it was taken to reflect an automatic process associated with the combination of words into structured representations.

Oscillatory effects related to syntactic processing have also been reported at higher frequencies. Bastiaansen and colleagues [47] analysed spectral power changes while subjects were presented with written sentences and unstructured words lists. They found that beta-band (13-18 Hz) power linearly increased only for sentences, but not word lists, supporting its role in structure-based processing. However, note that this unique comparison between full sentences and word lists cannot exclude the involvement of non-syntactic, for instance, content-based semantic processing in such sentences. In a follow-up study, Bastiaansen and Hagoort [48] directly addressed this issue by also presenting participants with meaningless sentences with correct syntactic structure (e.g., *the dusty prison engraves the gender for the innocent throat*) and found analogous power increases in the alpha and beta ranges (10-20 Hz). This last finding seems to suggest that such alpha-beta effects may be directly implicated in structure-based operations required to deal with both meaningful and meaningless sentences. In partial contrast to these previous results, other authors found power decreases at the alpha and beta frequency bands (alpha: 8.75-11.25 Hz; beta: 14-18 Hz) during the processing of sentences compared to word lists [49]. These power modulations were localized mainly across different left-hemisphere regions (for further localization details, see also [50]). In this case, oscillatory activity was not analysed across the time window of the whole sequence but at the single-word level following the ERP approach, contrasting the same words appearing either in sentences or word lists. Despite discrepancies about the directionality of these effects (perhaps related to methodological differences between studies), there seems to be converging evidence relating alpha and beta oscillations to some aspect of processing relevant for sentences, but not word

lists. For example, it has been proposed that beta-band oscillations might index processes that are specifically syntactic such as the structural combination of words [48] or more general processes related to sentence-level compositional meaning, which require both structure- and content-based operations [51].

Finally, syntactic processing of sentences has also been associated with modulations in the high-gamma band (> 70 Hz) in two ECoG experiments conducted with epileptic patients. ECoG data from a frequency-tagging study by Ding and colleagues [40] showed that, in addition to delta-band power, high-gamma (70 – 200 Hz) power envelope entrained to phrases and sentences. While power itself is only sensitive to amplitude modulations, power envelope is a measure that does reflect how the amplitude of the signal dynamically unfolds over time, thus providing important information on the temporal structure of brain activity (see Section 2 for further details). Based on this, the finding by Ding and colleagues [40] would suggest that the temporal evolution of high-gamma power might reflect the fundamental properties of syntactic structures, and their incremental building over time. Second, during visual presentation of single sentences in French and English, Nelson and colleagues [52] observed temporal modulations in broadband high-gamma (70 – 150 Hz) power envelope depending on the specific syntactic properties of each word. For example, after the onset of each word, high-gamma power linearly increased (peaking at ~ 300 ms) in accordance with the number of words to be grouped into the corresponding phrase. In contrast to this apparent sensitivity to syntactic structure, a third ECoG study by Fedorenko and colleagues [53] observed that high-gamma effects were not driven by purely structural information. Aiming to isolate the contribution of structure-based from content-based processing, they created jabberwocky sentences (i.e., sentences formed by non-words, lacking lexical-semantic information, but with preserved syntactic structure; e.g., *the gar was swarbing the mume from atar*) and compared them to real-word sentences with both structure and meaning, as well as to unstructured lists of real- and

non-words. They found that high-gamma (70 – 170 Hz) power envelope increased linearly after the onset of each word only when epileptic patients were visually or auditorily processing real-word (but not jabberwocky) sentences, suggesting that structural processing in itself is not sufficient to trigger such effects. Specifically, they interpreted these high-gamma band power modulations as reflecting the incremental composition of sentence-level meaning – which requires the processing of both structural and lexical-semantic information. However, there is a methodological point to take into account: unlike the other two ECoG studies, the power envelope reported in Fedorenko and colleagues's experiment lacked a temporal dimension, as it was analysed as the mean power activity during the presentation window of each word. Based on this, the lack of sensitivity to syntactic structure that emerged in their data cannot be directly linked to temporal modulations in the high-gamma power envelope. Thus, their result might not necessarily contradict the findings by [40] and [52], as they focused on slightly different measures. Furthermore, Fedorenko and colleagues [53] also showed that real-word lists generally displayed the most similar pattern to real-word sentences eliciting increased high-gamma activity compared to both of the conditions without lexico-semantic information (jabberwocky sentences and non-word lists), which in turn revealed rather similar oscillatory profiles. Interestingly, power effects across the gamma spectrum (> 30 Hz) are typically associated with lexico-semantic processing [45, 51]. This might suggest that, in addition to a sentence-level compositional component, the lexico-semantic characteristics of single words might have an important influence on the high-gamma effects found by Fedorenko and colleagues [53], with real-word conditions (real-word lists and sentences) and non-word conditions (non-word lists and Jabberwocky sentences) showing more similar oscillatory patterns within than between them. Taken together, the current evidence suggests that high-gamma effects reflect some aspects of structure-based syntactic processing, although the involvement of content-based lexical factors still remains unclear.

4.2. Oscillatory dynamics of syntactic violations

There have also been a considerable number of frequency-domain studies that focus on understanding the electrophysiological dynamics underlying the disruption of syntactic processing. Following the common ERP approach, these studies (see below) manipulated the presence of words with different types of (morpho)syntactic violations, generally exploring the time-frequency effects (i.e., power changes over time) elicited by these grammatically incorrect words. Prystauka and Lewis [54] recently provided a thorough review of studies reporting time-frequency power analyses in the context of sentence processing, including those implementing (morpho)syntactic violation paradigms. Here we will just briefly review the most representative findings obtained from this paradigm (for further studies and a more extended discussion, see [54]).

One way to disrupt the computation of syntactic structures is to use syntactic-category violations, that is, words whose syntactic category is ungrammatical within that sentential context. For example, Davidson and Indefrey [55] presented participants with written sentences in Dutch containing violations of syntactic category (e.g., *The director [of the]/*[the of] bank...*). When comparing correct (e.g., *of*) and incorrect (e.g., *the*) critical words, they found that syntactically incorrect words resulted in power decreases in the alpha-beta bands (8-30 Hz) in a time window between 500-900 ms after word onset. Bastiaansen and colleagues [47] also looked at the oscillatory activity produced by syntactic-category violations in Dutch sentences (e.g., *Janneke kreeg de zegen_{noun}/*zegenen_{verb}...*). In this case, they found that syntactically incorrect words elicited earlier long-lasting (0-2500 ms) power decreases in the alpha band (8-12 Hz) and later short-lived (~ 500-1000 ms) power decreases in the gamma (60-80 Hz) band. Furthermore, when looking at power modulations across the whole sentence, they observed that linear increases in the beta-band (13-18 Hz) power that emerged as sentences unfolded ceased shortly after encountering such syntactic-category violations.

Another productive manipulation within the violation paradigm consists of using incorrect verb tenses. Kielar and colleagues have tested this tense violation manipulation in English (e.g., *She will go/*going...*) in a series of experiments [20, 56, 57]. Across all experiments, tense violations elicited power effects in the frequency band comprising alpha-beta oscillations (8-30 Hz) starting around 500 ms after word onset. Power increases in delta-theta (1-5 Hz) band were also observed in one study [20]. Using similar tense manipulations during auditory presentation of English sentences, other authors also found power decreases in the beta (13-20 Hz) band starting around 500 ms after incorrect verbs [21, 58].

Other studies have focused on morphosyntactic violations that result from different types of inconsistent agreement relations between subjects and verbs. Davidson and Indefrey [55] presented participants with sentences in Dutch containing subject-verb number agreement violations (e.g., *The spoiled little kid throws/*throw...*). In partial correspondence with the effects observed for syntactic-category violations (see above), they found alpha-band (8-13 Hz) power decreases between 600 and 800 ms after morphosyntactically incorrect words. Also manipulating number agreement in subject-verb relations in English, theta (4-8 Hz) band power decreases were reported between 350 – 450 ms after the critical incorrect verb [59]. This theta effect was followed by power decreases in the beta (13-30 Hz) band starting around 500 ms after word onset. Finally, the computation of morphosyntactic (person) information was further investigated by Pérez and colleagues [60] who implemented a design from a previous ERP study [33] in the context of frequency-domain analyses. As explained in Section 3, they compared correct sentences in Spanish to violations of subject-verb person agreement and to unagreement configurations, which exceptionally allow person mismatches. They reported that person violations were uniquely characterized by power increases in the theta-band (4-7 Hz) around 400 ms after word onset and later (~ 1000 ms) followed by power decreases in the alpha (8-12 Hz) band. Interestingly, both incorrect (person violations) and correct (unagreement)

verbs showed power decreases in the alpha (8-12 Hz) and beta (13-18 Hz) bands in an intermediate time window (~ 500 ms).

Given the current evidence, the most systematic effects of (morpho)syntactic violations seem to emerge as power decreases in the alpha and/or beta bands. Such violations notably encompass distinct (morpho)syntactic errors including syntactic category [47, 55], verb tense [20, 21, 56–58] and subject-verb agreement [55, 59, 60]. Conversely, modulations in other frequency bands – i.e., delta, theta or gamma – appear less consistently across studies. This is also the case for the directionality of the reported theta-band effects, which were found in two studies testing number [59] and person agreement violations [60] as power decreases and increases, respectively. There are several possible interpretations for these consistent effects in the alpha-beta frequency range (for further discussion, see [54]). On the one hand, they could either exclusively [48] or partially [51] reflect processes related to the interruption of syntactic processing. On the other hand, considering that (morpho)syntactic violations might also interfere with semantic content-based processing, they could alternatively index effects involved in semantic rather than syntactic computations (see [45]). Moreover, alpha-beta effects reported by Pérez and colleagues [60] corresponding to both incorrect and correct agreement configurations suggest that morphosyntactic incongruency – rather than incorrectness – could be the driving factor behind such power modulations in these two frequency bands. Finally, if violations attract the attention of participants, domain-general attentional processes due to task demands could also play a key role in triggering such oscillatory effects.

5. The emerging picture and future directions.

5.1. The link between delta-band oscillations and structure-based processing

Several studies using (time-)frequency analyses seem to converge on the key role of oscillations in the delta band (< 4 Hz) in structure-based processing of linguistic information.

This evidence is derived most notably from delta-band (power and phase) effects selectively modulated by grouping words into particular syntactic structures (frequency-tagging paradigm: [40–43]; single-sentence paradigm: [44, 46]). These recent findings from two different paradigms provide important and promising advancements in our understanding of the neural dynamics underlying syntactic processing. Nevertheless, given the novelty of the frequency-tagging paradigm and the existence of relatively few studies supporting this delta-syntax link, we also highlight some issues relevant for the interpretation of these findings.

The nature of the mapping between delta-band oscillations and syntactic structures is of fundamental concern: is it due to the physical properties of the stimuli or, rather, to some special feature of this specific frequency band? In the frequency-tagging paradigm, the main characteristic of this mapping is that stimulus frequency determines the frequency of the oscillatory activity. That is, if words were presented at another frequency range than delta (e.g., at a faster frequency within the theta-band range, > 4 Hz), oscillatory entrainment to syntactic structures would presumably also appear in this frequency band. Likewise, because Meyer and colleagues [44] presented their critical syntactic phrases at a normal speech rate within the delta-band time window, a similar stimulus-based explanation could in principle account for their findings (but see below). Under this view, delta-band oscillatory modulations would reflect the encoding of *delta-band* syntactic constituents, that is, the word groupings presented at this specific frequency band. Therefore, any neural frequency – even above the delta band – corresponding to the frequency in which the relevant stimuli are presented could in principle play a key role in structure-based processing. An alternative explanation for the apparent delta-band specificity of syntax would be that delta-band frequency provides the optimal time window in which syntactic information can be processed given domain-general processing constraints (see [45], for a discussion). From this perspective, the reported delta-syntax link would be a reflection of the typical duration of syntactic phrases as used in these previously

reviewed studies. Future frequency-tagging and single-sentence experiments could present critical syntactic information in shorter time windows – either applying faster presentation rates or using shorter words such as pronouns – to determine whether the oscillatory effects of syntactic structures are restricted to the delta band.

Furthermore, it is not clear whether all the reported delta-band effects associated with syntactic groupings reflect the same phenomenon (cf. [45]). Important task differences cast doubt on the validity of making direct comparisons between these delta-band findings. More specifically, the frequency-tagging paradigm requires the repetitive segmentation of continuous speech streams composed of multiple sentences without necessarily providing access to their structured sentence-level meaning. In contrast to this artificial task, Meyer and colleagues' paradigm consisted of single sentences and focused on assessing sentence interpretation [44]. This also points to a potential problem: that the contribution of interpretative semantic factors may differ considerably across paradigms (see below for a further discussion of the syntax-semantics relationship). In addition, as explained above, given the characteristics of the frequency-tagging paradigm, identical oscillatory patterns should theoretically appear at higher frequencies (e.g., theta band) if the presentation rate is increased. However, this might not necessarily be the case for paradigms in which speech is used in more naturalistic contexts as with single sentences, since delta-band oscillations seem to play a privileged role in speech-to-brain entrainment [61]. More research is needed to clarify to what extent these findings are comparable considering these important differences between paradigms.

Finally, an important point concerns the implications of the observed effects for theories of natural language. Results from the frequency-tagging paradigm have generally been taken as evidence in favour of hierarchical views of language syntax (e.g., [40]). However, these results could alternatively be compatible with a sequential model of language [62], which considers syntactic structure to be composed of sequences of words based on linear rather than nested,

that is, hierarchical, relations (for a discussion see [63, 64]). In particular, it has been shown that computational models based on either hierarchical [65] or sequential representations [62] can similarly reproduce human data using materials from Ding and colleagues [40]. Interestingly, the hierarchically-based model [65] also replicated human results using jabberwocky sentences, in which lexical contribution is minimized. Frequency-tagging experiments using jabberwocky sentences are non-existent in the current literature and would help us better understand the contribution of lexical factors.

5.2. Beyond delta-band oscillations and structure-based processing

Apart from delta-band oscillations, frequency effects in the alpha, beta and high-gamma band have been shown to be modulated during syntactic processing (see Section 4). Although these effects could be related to structure-based operations (e.g., [48]), they might alternatively be involved in additional components relevant for sentence processing [45, 51, 54]. For example, alpha-band oscillations could play a role in the storage of syntactic information in working memory [45, 66]. In what follows, we examine the important role of semantic processing in sentence comprehension, and explore how it could interact with syntactic processing in the context of neural oscillations.

The interplay between structure-based syntactic and content-based semantic factors is of critical concern. However, it has received scant attention in the studies reviewed so far (except for [53]), especially because of two problems that emerge when trying to experimentally distinguish the contributions of these two factors. First, it is difficult to make a logical dissociation, since any syntactic manipulation almost inevitably corresponds to some modification in terms of meaning. This is the case when using either correct configurations or violation paradigms. Moreover, although the involvement of lexico-semantic factors can be reduced by using non-words as in jabberwocky materials, semantic components cannot be

completely removed because certain sentence-level meaning information is still available even in such cases (e.g., argument relations indicating semantic roles such as agent, patient, etc.). Second, with respect to their distinction in time, it is conceivable that syntactic and semantic processes temporally operate to a certain extent in parallel, and thus overlap within the same time windows (see [67] for a discussion). Furthermore, predictive processing – especially the prediction of semantic content (see Box 1) – seems ubiquitous during sentence processing, and such predictive processes would also occur simultaneously with the integration of syntactic structures. Interestingly, this interdependence between syntax and semantics resembles the hierarchical organization of neural oscillations, in which faster (higher) frequencies are nested within slower (lower) frequencies. This distinctive organization enables neural oscillations to exhibit several types of cross-frequency interactions (see Section 2), resulting in different potential links between linguistic components and oscillatory frequencies.

--- please insert Box 1 around here ---

One way to conceptualize the syntax-semantics relationship at the oscillatory level is to assume a division of labour between lower and higher frequencies associating them with structure-based syntactic and content-based semantic processes, respectively. Based on the findings discussed above, delta-band oscillations could be implicated in syntactic structuring, while beta-band oscillations could instantiate either the top-down prediction of lexico-semantic information [68] or, more generally, sentence-level meaning representation involving both syntactic and semantic prediction [51]. There is considerable evidence showing that beta-band oscillations are sensitive to lexico-semantic prediction [51, 68, 69], although it is less clear how syntactic factors interact with these lexico-semantic predictive processes. For example, beta-band effects were found after the establishment of different types of distant syntactic dependencies (argument-verb relations [66]; relative clauses [70–72]; and filler-gap dependencies [73]), which can be associated with the lexico-semantic prediction of upcoming

words (e.g., certain lexico-semantic properties of the second element in the dependency) but also with changes in the meaning of the current representation (probably also involving the satisfaction of the predicted syntactic category ending the structural dependency). Furthermore, some post-stimulus beta-band modulations driven by structural components have been accompanied by pre-stimulus predictability effects in the alpha band. Specifically, alpha-band power increases have been found for predictable local subject-verb relations ([74], along with beta-band power increases) as well as for distant argument-verb relations [66] in a time window preceding the appearance of the predictable word ending the syntactic dependency (i.e., the verb). Moreover, corpora-derived computational measures of syntactic predictability are correlated with alpha-band power effects [75]. Although this might suggest that alpha- (rather than beta-)band oscillations are specifically involved in syntactic prediction (or the pre-activation of syntactic categories in general) there is also some evidence for semantic prediction effects prior to the critical word in the alpha band [76]. Likewise, studies using violation paradigms have reported modulations in the alpha and/or beta bands triggered by both (morpho-)syntactic and semantic errors (see [54]). Taken together, these oscillatory similarities between syntactic and semantic manipulations suggest that alpha-beta effects could reflect a more general mechanism related to sentence-level meaning [54], which could explain why they were observed in sentences but not in word lists lacking any structured meaning [47–50].

The link between syntax and semantics could also be conceived differently through a cross-frequency interaction such as phase-to-amplitude coupling (PAC), according to which the phase of lower frequencies modulates the amplitude of faster frequencies. In this scenario, structure-based syntactic processes might be instantiated in the phase of delta-band oscillations, which would constrain content-based semantic processes reflected in the power of faster frequencies – comprising alpha, beta and gamma ranges (cf. [77, 78]). While in the previous account, syntax and semantics were only associated with different frequency bands, in this case

they would also be distinguished in terms of oscillatory properties (phase vs. power), resulting in a direct (and consequently modulatory) relationship between structure and meaning. Partial support for this account comes from the effects reported by Meyer and colleagues [44] exhibiting delta-band phase adjustments depending on the specific syntactic structure to be interpreted in ambiguous sentences (no power analyses were reported). In addition, PAC could be involved in the ECoG results from the original frequency-tagging study by Ding and colleagues [40] showing that syntax-driven entrainment emerged in both the delta band (in power, but delta-band phase also appears to entrain to syntactic structures [41, 42]) and high-gamma oscillations (in power envelope). Although no PAC measure was reported, this pattern of results could be explained if the temporal fluctuations of high-gamma oscillations (i.e., its power envelope) followed the phase of delta-band oscillations. In addition, the fact that the syntax-sensitive temporal modulations in high-gamma power envelope observed by Nelson and colleagues [52] were comprised for most words within a delta-band time window (i.e., peaking after 300 ms, < 4 Hz) could also suggest a potential PAC between delta and high-gamma oscillations. Moreover, if high-gamma power modulated by delta-band phase – rather than high-gamma power itself – reflects this structure-meaning interdependence, then this gives further support to the possibility that the high-gamma effects lacking temporal modulations (i.e., obtained from the averaged power envelope) observed in real but not jabberwocky sentences [53] are strongly influenced by the distinct lexical contributions present in real-words relative to non-words. We underscore that the possibility of PAC remains speculative, since phase analyses were not reported in these ECoG studies showing high-gamma effects, and the same problem applies to the studies showing alpha-beta effects. However, a recent MEG study [79] observed supporting evidence for this type of cross-frequency interaction, reporting speech-to-brain PAC between delta-phase (speech) and beta-power (brain) for sentences that were correctly comprehended. This cross-frequency scenario would also allow us to approach

the issue of predictive processing differently, for example with certain types of prediction reflected in pre-stimulus phase modulations [44, 80] (see also [81]). Future studies assessing how neural oscillations interact across multiple dimensions such as PAC are needed to provide a more detailed explanation of their role in sentence processing.

5.3. On the relationship between neural oscillations and ERPs

Despite arising from the same underlying time-resolved electrophysiological activity, the exact relationship between neural oscillations and ERPs has not yet been determined (see [82–84]). In the particular context of syntactic processing, the oscillation-ERP connection has scarcely been addressed, and the few existing attempts have mostly focused on the link between time-frequency and ERP effects driven by (morpho)syntactic violations. More specifically, two studies [21, 59] found significant correlations between beta-band power and P600 effects, while another study [55] observed a correlation with alpha-band power effects instead (see Section 3 and 4.2 for details about these ERP and oscillatory findings, respectively). Moreover, despite not having statistically assessed this relationship, other studies testing (morpho)syntactic violations reported that oscillations and ERPs appeared to show distinct characteristics. First, power modulations in a broad oscillatory range (delta-theta: 1-5 Hz; alpha-beta: 8-30 Hz) and P600 effects differed in terms of cortical localization and sensitivity to presentation modality [20]. Second, within a similar time window (~ 500-800 ms), correct and incorrect person agreement relations showed comparable power effects in the alpha and beta bands [60], but P600 effects were only observed for incorrect stimuli [33]. Thus, despite not being extensive, the current evidence suggests that there is no clear one-to-one mapping showing that specific oscillatory frequencies and ERP components are concurrent phenomena reflecting identical processes. This preliminary conclusion might indeed be expected given that frequency- and time-domain analyses are based on different electrophysiological principles

regardless of their specific relationship, and thus potentially provide (non-redundant) complementary information.

We also highlight that, because most ERP studies follow violation paradigms, it is currently not possible to easily accommodate such violation-based ERP findings with the frequency-domain results obtained from correct sentence paradigms. Nevertheless, the latency of certain syntax-related components could speculatively be linked to specific frequency bands. For example, faster components like the LAN effect (lasting ~ 200-250 ms, i.e., > 4 Hz) might correspond to one cycle of a theta-band oscillation, while slower components such as the P600 effect (lasting ~ 300-350 ms, i.e., < 4 Hz) might correspond to one cycle of a delta-band oscillation (see [45] for a similar discussion regarding slow ERPs). Although ERPs were not reported, a recent auditory single-sentence study [85] provided interesting frequency-domain evidence along the lines of this sort of integrative approach, establishing a connection between correct and incorrect sentence paradigms. More concretely, it was found that delta-band phase modulations were aligned to the distribution of syntactic information in correct sentences (estimated from probabilistic measures derived from corpora) and that this notably influenced the detection of (morpho)syntactic violations. Further intricate experimental designs combining distinct analyses (e.g., in the time and frequency domains) and paradigms (e.g., correct and incorrect sentences) are clearly needed to understand the link between these two dimensions of the electrophysiological signal.

6. Conclusion

Current electrophysiological findings provide convergent evidence on the key role of certain ERP components as well as specific frequency bands in syntactic processing at the sentence level. However, as discussed especially with regard to the more recent oscillatory findings, definitive conclusions as to their interpretation are still premature. In particular, we emphasize the need for a better understanding of how semantic processing is integrated with syntactic

processing. We suggest this could best be pursued by examining cross-frequency interactions. In this context aimed at clarifying the link between syntax and semantics, an important characteristic of language that is likely to play a fundamental role is predictive processing (see Box 1). Most notably, a prediction-oriented account would allow to represent specific syntactic and/or semantic types of information in distinct predictive components (i.e., prediction generation and prediction error) at certain time- and frequency-domain dimensions of neural activity, thus resulting in additional flexibility to deal with the syntax-semantics connection. Furthermore, a critical issue that has not been explored here is the neural implementation of electrophysiological effects in specific brain regions. These and other unresolved questions (see Box 2) need to be addressed in future studies. By combining evidence from different techniques, paradigms, and analyses we will develop a better understanding of the neural dynamics that support sentence processing in the brain.

--- please insert Box 2 around here ---

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Table 1. Overview of the main experimental designs and ERP correlates of syntactic processing (legend: sg=singular, pl=plural; 2=2nd person, 3= 3rd person).

Manipulation	ERP response(s)	
Syntactic ambiguity and complexity [11, 86–88]	<p>The workers saw (that) the employer was sincere [88]</p> <p><u>Ambiguous continuation:</u> The man painted the house and the garage was already finished</p> <p><u>Less preferred continuation:</u> The man painted the house but the garage was already finished [86]</p> <p><u>Minor complexity:</u> Den/*Dem Vater trug/*trugen er den Mantel He carried the coat for the father</p> <p><u>Major complexity:</u> Dem Vater getragen *(hat) er den Mantel The father carried has the coat [11]</p>	P600
Syntactic category violation <i>German</i> : [12, 89]; <i>French</i> : [90]; <i>Dutch</i> : [55]; <i>English</i> : [91–93]; see [31] for a review	<p>Die pizza wurde *im gegessen The pizza was *in-the eaten <i>German</i>: [12]</p> <p>The broker hoped to sell the stock *The broker persuaded to sell the stock [92]</p>	<p>(e)LAN + P600</p> <p>P600</p>
Agreement violation <i>German</i> : [94, 95] <i>Italian</i> : [23, 26]; <i>Spanish</i> : [24, 25, 28, 32, 33, 96, 97]; <i>English</i> : [19]; <i>Hebrew</i> : [98]; <i>Basque</i> : [34, 99, 100]; <i>Dutch</i> : [55, 101]	<p>Most cats like/*likes to play outside [19]</p> <p><u>Number agreement violation:</u> *El turista_{3sg} visitaron_{3pl} un parque muy grande</p> <p><u>Person agreement violation:</u> *El turista_{3sg} visitaste_{2sg} un parque muy grande The tourist_{3sg} visited_{3sg} a very big park <i>Spanish</i>: [24]</p>	<p>LAN + P600 N400 + P600</p>
Filler-gap dependencies [35–39]	<p>Which cake_i did you choose_i? [36]</p> <p>John read a book and Helen a newspaper [35]</p>	LAN

Box 1: Predictive processing

The role of predictive processing in language has been extensively investigated [102–104] and plays a prominent role in ERP-based [105, 106] as well as oscillatory-based [69, 81, 107] approaches. Predictive processing theories, such as predictive coding [108], assume that the brain uses prior experience to make predictions about upcoming events, comparing these top-down predictions to the bottom-up integration of perceptual information and adapting its cognitive state according to prediction-integration discrepancies (i.e., prediction error). With respect to sentence comprehension, speakers would use their prior knowledge, that is, expectations for upcoming words with certain lexical characteristics, to incrementally combine words as the current input unfolds over time. Prediction appears to be intrinsically related to content-based semantic processing (e.g., sentential contexts strongly constrain the set of potential word continuations in terms of meaning), although it may also take place on other linguistic levels such as syntax (see [109], for references) or phonology, or even sensory levels such as orthography (cf. [105]). Also note that, from a predictive perspective, violation paradigms focus on the manifestation of prediction error, since the detection of (morpho-)syntactic or semantic violations necessarily involves the integration of word continuations that are highly unexpected given preceding context.

Box 2: Outstanding questions

- Which specific regions of the brain support the time- and frequency-domain activity reported in the studies reviewed here? What is the specific contribution of cortical and subcortical regions to syntactic processing? How do cortical and subcortical regions interact during language comprehension (see [77, 78] for proposals)?
- What are the implications of the electrophysiological studies presented here for existing neurobiological models of language processing [30, 106, 110, 111]?
- What do the current data on the oscillatory basis of syntax tell us about theories of natural language processing? Are they better explained by a rule-based hierarchical vs. sequential word-level model of syntactic processing? (see Section 5)
- What is the exact role of delta-band oscillations in supporting syntactic processing? Are the reported mappings between delta oscillations and syntactic structures due to the frequency at which stimuli were presented or instead to some cognitive constraint that makes delta frequency an ideal rhythm to process syntactic structures? (see Section 5)
- What is the exact relationship between lexico-semantic and syntactic processing? Can content-based semantic and structure-based syntactic processes be completely disentangled at the neural level? Are they part of the same or different mechanism(s)? Can cross-frequency interactions (e.g. phase-to-amplitude coupling) provide a neurophysiologically plausible mechanism for linking lexico-semantic and syntactic processing? (see Section 5)
- Most of the current studies on the electrophysiological basis of syntactic processing were carried out on healthy adults. Are the neural underpinnings of syntactic processing the same in younger and older individuals? How do they change in populations with language damage (e.g., aphasia)?

- What is the exact relationship between ERP components and oscillatory effects found in the context of language processing? (see Section 5)
- How generalizable are the effects found in the frequency domain? To what extent are they driven by stimuli and task characteristics? Do they differ across distinct perceptual domains (e.g., auditory and visual)? Do they still arise under more naturalistic paradigms?