Bilingualism: Language and Cognition

cambridge.org/bil

Research Article

Cite this article: Rossi E, Prystauka Y (2020). Oscillatory brain dynamics of pronoun processing in native Spanish speakers and in late second language learners of Spanish. *Bilingualism: Language and Cognition* **23**, 964–977. https://doi.org/10.1017/S1366728919000798

Received: 11 July 2018
Revised: 1 November 2019
Accepted: 9 November 2019
First published online: 29 January 2020

Keywords:
time-frequency representation; grammatical processing; bilingualism; neural oscillations; second language learning; clitic pronouns

Address for correspondence:
Eleonora Rossi, E-mail: eleonora.rossi@ufl.edu

Oscillatory brain dynamics of pronoun processing in native Spanish speakers and in late second language learners of Spanish

Eleonora Rossi[1,2] and Yanina Prystauka[3]

[1]Department of Linguistics, University of Florida; [2]Department of Psychology, University of Florida and [3]Department of Psychological Sciences, University of Connecticut

Abstract

A longstanding question in the second language acquisition literature is whether late second language (L2) learners process grammatical structures in a native-like manner. Here, we use Time Frequency Representation (TFR) analysis to test morpho-syntactic processing of clitic pronouns in native and late L2 learners of Spanish. The TFR results show overall similar power decreases in theta, alpha, and beta frequencies in both groups. Critically, the observed oscillatory effects persisted in time for native Spanish speakers, but declined earlier for L2 learners. We discuss the results using cell-assembly theory models for language processing (e.g., Pulvermüller, 1999) that posit a biphasic time-course for neural assemblies consisting of an early ignition (recognition) and a later reverberation (re-processing) phase. We propose a working hypothesis for L2 processing in tune with a cell-assembly theory suggesting that the length of the reverberation phase could be a distinguishing feature between native and L2 processing.

Introduction

A longstanding question in the second language (L2) literature is whether individuals who acquire an L2 after childhood process grammatical structures in a native-like manner (e.g., Birdsong, 1999; Long, 1990). Evidence from past behavioral studies is mixed, revealing that late L2 learners are often less sensitive than native speakers in identifying grammatical violations, particularly when processing structures that are unique to the L2 and not readily transferable from the L1 (e.g., Clahsen & Felser, 2006a; MacWhinney, 2005; Weber-Fox & Neville, 1996). On this account, native-like processing of the L2 grammar is hypothesized to be difficult to achieve (Clahsen & Felser, 2006b; Herschensohn, 2001). An alternative view proposes that native-like processing in late L2 learners is possible even for L2 unique structures, especially when speakers achieve high proficiency (e.g., Birdsong & Molis, 2001; Coughlin & Tremblay, 2012; McDonald, 2000), or when their working memory capacities are matched to native speakers' (Hopp, 2013).

Whereas much of the previous literature is based on behavioral results, electrophysiological measures such as Event Related Potentials (ERPs) have added foundational data to understand the neural underpinnings of L2 processing, providing temporally sensitive signatures of linguistic processing without an overt meta-linguistic judgment task (Tokowicz & MacWhinney, 2005), and even in the absence of behavioral significance (McLaughlin et al., 2010). The extant ERP literature on L2 processing has also yielded mixed results, highlighting that L2 processing is highly variable. For example, ERPs have been found to be quantitatively and qualitatively different than the ones observed in native speakers (Ivanova & Costa, 2008 for lexical processing; Sabourin & Stowe, 2008; Tolentino & Tokowicz, 2011 for a review; Guo et al., 2012; Kotz, 2009; Proverbio et al., 2002; Weber & Lavric, 2008; Weber-Fox & Neville, 1996 for no P600; Caffarra et al., 2015 for a review), leaving an open debate as to whether late L2 learners face hard constraints for syntactic processing (e.g., Clahsen & Felser, 2006a; Díaz et al., 2016; Sabourin & Stowe, 2008; Sabourin, Stowe & de Haan, 2006) or whether native-like processing is feasible (Sabourin & Stowe, 2008; Tokowicz & MacWhinney, 2005; Foucart & Frenck-Mestre, 2012; Rossi et al., 2014; van Hell & Tokowicz, 2010; Dowens, Vergara, Barber & Carreiras, 2010).

For example, the P600 component is a positive ongoing wave typically observed between 400-900 ms that is generally linked to morpho-syntactic reanalysis and repair (Osterhout & Holcomb, 1992; Osterhout, McKinnon, Bersick & Corey, 1996; Osterhout & Nicol, 1999; Kaan & Swaab, 2003). For L2 speakers, a number of studies have reported a lack of a P600, or a decreased/delayed P600 (Rossi et al., 2014), suggesting that the P600 might represent a continuum of L2 proficiency. An N400 has also been often observed in L2 learners in response to grammatical violations, suggesting that they might relay on lexico-semantic processing (for a review: Tolentino & Tokowicz, 2011). Other studies demonstrate instead native-like processing for grammatical structures that are shared between the two languages (Sabourin & Stowe, 2008; Tokowicz & MacWhinney, 2005), and also for constructs that are not shared between the two languages (McLaughlin et al., 2010; Tokowicz & MacWhinney, 2005).

Notably, factors that have been reported to influence L2 processing include; linguistic similarity between the two languages (Tokowicz & MacWhinney, 2005), age of acquisition, L2 proficiency (Foucart & Frenck-Mestre, 2012; Rossi et al., 2014; van Hell & Tokowicz, 2010; but see Díaz et al., 2016 and for different conclusions), and extensive immersion in the L2 environment (e.g., Dowens, Vergara, Barber & Carreiras, 2010). Taken together, the extant ERP evidence points toward the idea that the native-like L2 processing in late learners is possible, and there might be fewer hard constraints than originally proposed.

The analysis of the electrophysiological (EEG) activity of the brain during complex cognitive functions provides a rich source of data that can be analyzed in a number of ways. Most of the extant EEG research on language has analyzed the signal locked to specific cognitive and linguistic events (i.e., ERPs). This research has provided invaluable information about what brain responses occur when time-locked to a specific linguistic stimulus. However, information about the induced activity associated with the critical manipulation, but not necessarily time-locked to it, is lost after averaging.

More recently, researchers have started to analyze the EEG signal decomposing it into different frequencies, and have investigated the local synchrony (the amount of power in each frequency band), and the long-range synchrony (oscillatory phase relation measures between different sources/channels) using Time Frequency Representation (TFR) analysis. While traditional ERP analysis reflects specific ongoing language processes locked to a specific event, they do not fully capture the multidimensionality of language processing, which happens in synchrony with a number of domain general cognitive processes that enable it to unfold in a fluid and timely manner (e.g., working memory maintenance, memory encoding and retrieval, attention, prediction, maintenance of the current cognitive set; Bastiaansen, Mazaheri & Jensen, 2012; Buzsaki, 2006; Lewis & Bastiaansen, 2015; Lewis et al., 2015).

Language-related ERP components likely represent the integration of language specific and domain general cognitive processes that allow for language to unfold in a fluid and timely manner, such as working memory, memory encoding and retrieval, attention, prediction, maintenance of the current cognitive set (Bastiaansen et al., 2012; Lewis & Bastiaansen, 2015; Lewis et al., 2015). Decomposing the EEG signal into different frequencies, investigating local synchrony (the amount of power in each frequency band), and long-range synchrony of the signal (oscillatory phase relation measures between different sources/channels) allows to capture the dynamics of language-specific as well as domain-general processes that are involved in language processing that might otherwise not be distinguishable (Bastiaansen et al., 2012; Buzsáki, 2006). Time-Frequency representation analysis (TFR), i.e., analyzing the properties of the spectral signal in time, is emerging as a powerful analysis that enables to capture different subcomponents of complex cognitive processes that originate from the synchronization/desychronization of neuronal activity at certain frequencies, times, and neural locations. Crucially, TFR can highlight how distinct brain oscillations contribute to the formation of neuronal assemblies, which are thought to reflect different aspects of linguistic processing (Bastiaansen et al., 2012). More specifically, the Hebbian cell assembly framework (Hebb, 1949) proposes that groups of cortical neurons (i.e., neural assembly) strengthen their connections when they are frequently activated at the same time. In turn, the frequent coactivation of neural assemblies leads to synaptic strengthening, resulting in a generalized activation of the cell assembly even when a sub-portion of that assembly is activated. The theory of neural assembly has been recently extended to language processing (Pulvermüller, 1999) proposing that there are specific neural assemblies that respond selectively to lexical and grammatical processing (among other cognitive functions). Crucially, neural assemblies have been proposed to have two temporally distinct time-courses which subserve different cognitive and linguistic processes. A first fast IGNITION activation phase of the whole assembly has been linked to "target identification" (Dehaene et al., 2006; Strijkers, 2016), which is then followed by a slower sequential REVERBERATION phase of the neural assembly posited to signal second-order processes such as reprocessing, decision-making and metacognitive awareness (Dehaene et al., 2006). For language processing more specifically, the activation phase signals a first processing/recognition step of lexical or grammatical information, while the reverberation phase has been linked to grammatical reprocessing and verbal working memory processes (Buszaki, 2010; Pulvermüller, 2002; Pulvermüller et al., 2014). Crucially, classic ERP components such as the N400 and the P600 have been proposed to be the surfacing instantiation of the slow-oscillating reverberation phase.

The study of the oscillatory signal related to language processing is still a relatively new field of research. The extant literature has overall revealed that the (de)synchronization of neural activity at four different frequency bands relates to a number of language processes. Low-frequency oscillations (delta, 1-3 Hz, and theta 4-7 Hz) are active in response to speech rhythm phase entrainment, providing evidence for oscillatory changes in relation to auditory comprehension, in lexical retrieval (particularly in the theta frequency range; Peelle & Davis, 2012; Gross, Hoogenboom, Thut, Schyns, Panzeri, Belin & Garrod, 2013), and in paradigms that elicit syntactic reanalysis within a sentence context. For example, Bastiaansen, van Berkum and Hagoort (2002b) found that adjective-noun gender and number violations elicited increases in theta-power (4-7 Hz) relative to a correct condition, in an interval of 300-500 ms after word onset. In contrast, decrease in theta power has been associated with suppression of memory traces (Waldhauser et al., 2015). Detection of grammatical violations and language reprocessing also elicit power decrease in higher frequency bands, such as alpha (8-12 Hz) and beta (13-30 Hz) (Davidson & Indefrey, 2007), an effect often associated with the P600. These oscillatory signals have been replicated in response to both semantic and syntactic violations during sentence comprehension (for EEG: Kielar, Meltzer, Moreno, Alain & Bialystok, 2014; for MEG: Kielar, Panamsky, Links & Meltzer, 2015). Finally, gamma activity (>30 Hz) has been linked to morphological unification processes (Fonteneau, Bozic & Marslen-Wilson, 2011; Levy, Hagoort & Démonet, 2014), and prediction during sentence processing (Lam, Schoffelen, Uddén, Hultén & Hagoort 2016, Lewis & Bastiaansen, 2015 for a review). For example, Bastiaansen, Magyari and Hagoort (2010) report power decreases in alpha and gamma bands upon detection of word category violations in syntactically well-structured sentences, and increase in beta power across correct sentences, which can be disrupted upon occurrence of word category violations. The authors relate these effects to the building of a working memory trace, and to syntactic unification processes. In sum, even though some data and their interpretation are still unclear, the current literature suggests that oscillatory activity in alpha, beta and gamma frequencies is related to different aspects of grammatical processing. Relatedly, increase in theta frequencies have been suggested to signal increase in memory processing, while a decrease in theta might suggest suppression of memory traces.

The majority of the existing TFR literature on grammatical processing is based on native speakers (Prystauka & Lewis, 2019). Very few studies have investigated the oscillatory dynamics of language processing in speakers of a second language (L2). Crucially, TFR analysis can be particularly useful in populations for which language processing performance is particularly variable, such as in pathological populations (Kielar et al., 2012; Swaab et al., 1997) and for L2 learners, whose processing performance in the L2 might vary greatly, both quantitatively and qualitatively. In particular, given that TFR analysis is sensitive to non-phase locked activity, analyzing the EEG signal in the TFR domain minimizes the changes in signal strength related to differences in timing, making it more sensitive to aspects of the signal that are missed in a time-domain analysis. For example, provided a similar EEG-time locked component between native and L2 speakers (i.e., P600), analyzing the signal in the frequency domain might highlight that the underlying mechanisms might be qualitatively different. As such, TFR analysis represents a particularly appealing method to be applied to the investigation of L2 processing (Kielar et al., 2014).

To date however, only a handful of studies have looked at the oscillatory signatures of L2 language processing. Kielar et al. (2014) tested monolingual and bilingual participants reading in the L2 while they performed acceptability and grammaticality judgment tasks when presented with syntactically or semantically correct or incorrect items. In the acceptability judgment task, participants were instructed to rate sentences as unacceptable if they had semantic or syntactic anomalies. In the grammaticality judgment task instead, participants were asked to ignore meaning and only judge sentences as incorrect if they contained syntactic anomalies. The authors reasoned that grammaticality judgments would be more cognitively demanding because they require to focus only on grammar (for experimental evidence, see Bialystok & Majumder, 1998). The combined results for monolinguals and bilinguals showed a decrease in alpha-beta frequencies (8-30 Hz) for both semantic and syntactic violations as well as delta-theta (1-5 Hz) increase to semantic violations around 500-1500 ms. The direct comparison between monolinguals and bilinguals demonstrated that bilinguals, but not monolinguals, showed a reduction in alpha-beta frequencies for syntactic violations (e.g., *A new computer will lasting for many years*). Based on previous data suggesting that grammaticality judgments represent a more complex task that requires more attentional control (see Bialystok & Majumder, 1998) and since bilinguals have been found to perform better than monolinguals on cognitively taxing tasks (see Moreno, Rodrigues-Fornells & Laine, 2008; Bialystok, Craik & Ryan, 2006; Bialystok, Klein, Craik & Viswanathan, 2004), the authors interpreted the results as demonstrating that bilinguals need to use fewer neural resources (as indexed by reduced alpha-beta response to violations) and are more efficient processers under taxing behavioral conditions.

Lewis et al. (2016) used TFR analysis to study how processing of grammatical determiner-noun gender and number agreement modulate beta oscillatory dynamics. In a series of studies, they tested native speakers of German who were all late L2 learners of Dutch. Their results showed that determiner-noun grammatical gender violations in Dutch (e.g.,: "*Ze gebruijkte de$_{\text{com gender}}$ hout$_{\text{neu gender}}$…"; she used the wood) elicited changes in beta (12-18 Hz) and theta (3-7 Hz) in native speakers of Dutch, while changes in beta power in L2 speakers were only observed when L2 learners were required to make an explicit grammaticality judgment, suggesting that sensitivity to L2 grammar might be driven by top-down attentional control processes. In the same study, determiner-noun violations in Dutch (e.g.,: "Ze gebruijkte het$_{\text{singular}}$ hotels$_{\text{plural}}$…"; she used the hotel) were indexed only by a theta power increase in monolinguals and no significant results for the bilingual group. The authors reasoned that a decrease in beta power is a marker of syntactic processing (Davidson & Indefrey, 2007), while changes (typically an increase) in theta frequencies that are connected to syntactic processing are yet to be determined. Theta band modulations have also been found in connection to working memory (e.g., Jensen & Tesche, 2002; Luu & Tucker, 2001), lexico-semantic processing (Davidson & Indefrey, 2007), and the build up of memory traces during on-line sentence comprehension (Bastiaansen et al., 2002a). Power decrease in theta has signaled suppression of memory traces (Waldhauser at al., 2015). Lewis et al. provide a very important validation for utilizing ERPs and TFR analysis to investigate L2 processing. Critically, their work focused on syntactic features (grammatical gender and number) that are shared between the native language (German) and the second language (Dutch) in their bilingual group. Importantly, the processing of shared or similar grammatical structures between the L1 and the L2 is typically easier to achieve and has been reported to have a more native-like neural signature than grammatical structures that are not shared between the two languages.

The goal of the present work is to provide novel neurophysiological evidence on L2 morpho-syntactic processing by investigating the neural oscillatory activity related to the processing of pronominal reference (i.e., direct-object clitic pronouns) in native Spanish speakers, and in English speakers who are late, intermediate L2 learners of Spanish. This study will follow from Rossi et al.'s ERPs study (2014), which analyzed clitic pronoun processing using ERPs, by relating these findings to the EEG signal in the frequency domain. As noted above, very little research has asked to what extent differential oscillatory signals can inform theories of L2 language processing. This work will therefore contribute to the current literature by analyzing the oscillatory signal while L2 speakers process direct-clitic pronouns embedded in a sentence context. Critically, clitic pronouns represent a strong testing ground for studying the neurophysiological underpinnings of L2 attainment in late L2 learners. In contrast to the grammatical structures and features that have been previously investigated using TFR in bilingual speakers (i.e., grammatical gender and number, Lewis et al., 2016; verb tense violations, Kielar et al., 2014), which were shared between the bilinguals' two languages, clitic pronouns are a grammatical structure that is UNIQUE to Spanish (the L2 for our bilingual group) and is not encoded in English (the native language for our bilingual group). As such, this study will provide a unique contribution to the understanding of the neurophysiological underpinnings of L2 morpho-syntactic processing, and how induced oscillatory activity during syntactic processing might vary as a function of syntactic complexity and cross-language overlap.

Based on previous TFR literature for morpho-syntactic processing, we can formulate a number of predictions, both for native Spanish speakers and for L2 learners of Spanish. For native

Spanish speakers, we predict a decrease in alpha/beta power frequency ranges for the experimental conditions in which grammatical gender and number will be violated at the clitic pronoun (see details in the Method section). An effect in the alpha/beta frequency ranges for the incorrect conditions would support previous literature that has reported modulations of the signal in those frequencies in response to grammatical violations (e.g., Davidson & Indefrey, 2007; Bastiaansen et al., 2010; Kielar et al., 2014; Lewis et al., 2016).

Under the assumption that late L2 learners cannot access and process grammatical structures that are unique to the L2 (e.g., Clahsen & Felser, 2006b; Sabourin, Stowe & de Haan, 2006; Tokowicz & MacWhinney, 2005), late English–Spanish bilinguals should not reveal any sensitivity to the clitic structure, and no modulations of alpha/beta responses should be expected. Conversely, if late bilinguals can process grammatical structures unique to the L2 (i.e., clitic pronouns), but are only sensitive to the features of the L2 that are shared with the L1 (as number agreement is present both in English and Spanish), we then predict that L2 speakers should show sensitivity to number, but not to gender violations while processing the clitic pronoun. We should then observe power decrease in the alpha/beta frequency bands for number violations, but not for gender violations. Moreover, if late L2 speakers are able to fully acquire sensitivity to the clitic pronoun, which is a unique L2 structure, we expect to find modulations of the alpha/beta frequency band in response to both gender and number violations. Regarding the role of theta frequencies during language processing, the evidence is more mixed. Incremental increase in theta has been observed over the course of processing an entire sentence (Bastiaansen et al., 2002a), or in more localized response to open-class versus closed-class words, while a power decrease in theta frequencies has corresponded to retrieval-related control processes (Khader & Rösler, 2011) and suppression of memory traces (Waldhauser at al., 2015). As we are investigating a closed-class word (clitic pronoun), we might observe no theta power increase. However, it could also be hypothesized that a decrease in theta frequencies could signal retrieval control processes and suppression of memory traces of competing grammatical interpretations.

Finally, differences in the oscillatory response between native and second language processing could also emerge, not only in terms of the presence and modulations of specific frequency bands, but also in their relative duration. More specifically, under a cell assembly view of language processing, (Hebb, 1949; Pulvermüller, 1999; Strijkers, 2016) it is hypothesized that differences in the length of the reverberation phase (i.e., the length of the oscillatory signal post stimulus onset) could signal differences in cell assembly functioning between native and L2 processing. If differences in the length of the reverberation phase between the two groups were to be observed, it could be argued that those differences could be influenced by external factors, such as the overall complexity of the syntactic construct, or by internal factors such as individual variation in availability in cognitive resources that are central to the ability to process linguistic information in real time (such as verbal working memory and attention).

Method

Participants

26 native speakers of Spanish (11 female, 15 male; mean age: 29.5 yrs.; SD = 6.3), and 21 native English L2 learners of Spanish (17 female, 4 male; mean age: 22.8 yrs.; SD = 4.76) were recruited and paid for participation from the student population at Pennsylvania State University in accordance to IRB approval. Data from several participants had to be discarded due to technical problems and excessive EEG artifact. The data presented hereafter come from 19 native (6 female, 13 male; mean age: 29.7 yrs.; SD = 4.6) and 14 L2 (12 female, 2 male; mean age: 24 yrs.; SD = 5.7) speakers. Participants were all right-handed (as assessed by a handedness questionnaire), had normal or corrected-to-normal vision, and no history of neurological disorder. All participants completed a language history questionnaire to assess their language history and skills in both Spanish and English. Participants rated their Spanish language knowledge using a scale from 1 to 10 (1 being the lowest and 10 being the highest score) for oral comprehension, oral production, reading and writing. Scores from the self-ratings revealed that participants recruited for the native Spanish speakers' group were dominant in Spanish (M = 9.9; SD = 0.3), even though they also reported to be proficient in English (M = 8.2; SD = 1.2). L2 learners of Spanish, instead, reported being dominant in English, with an intermediate-high L2 proficiency (mean self-reported proficiency: 8.4; SD = 0.7). All participants started learning Spanish after age 14. Participants' demographics and language characteristics are fully reported in Rossi et al., 2014.

Materials and design

The original materials can be found in Rossi et al. (2014). Here, we summarize the characteristics of the materials and the design. There were 384 experimental sentences (192 experimental stimuli and 192 fillers). Each experimental item began with a preamble, which contained an antecedent (a determiner and a noun) followed by a clitic pronoun. For example: "Después de lavar *los cuchillos*, Andrea *los* colocó en la mesa del comedor" (After washing the knives, Andrea placed them on the dinner table). There were four experimental conditions. In one condition gender and number marked on the clitic correctly matched the antecedent. We will refer to this correct condition as + Gender + Number. In a second condition, gender was uniquely violated, i.e., the gender marked on the clitic mismatched the gender of the antecedent while number was kept correct (-Gender + Number). In the third condition, only the number marked on the clitic was violated while gender was kept correct (+Gender-Number). Finally, in the fourth condition, both gender and number were violated (-Gender-Number). Examples for each condition are provided in Table 1. There were a total of 48 sentences per condition. Gender (feminine, masculine) and number (singular and plural) marked on the antecedent were equally represented within each condition. For example, out of the 48 sentences for each condition, 12 experimental items contained a masculine plural antecedent (i.e., "los mangos", the mango), 12 a feminine plural antecedent (i.e., "las manzanas", the apple), 12 a singular masculine antecedent (i.e., "el libro", the book), and finally 12 a singular feminine antecedent (i.e., "la pera", the pear). A more detailed description of the experimental items, fillers, and design can be found in Rossi et al. (2014).

Procedure

Participants sat in a soundproof chamber optimized for EEG recordings. Experimental stimuli were presented through a Faraday-caged mirror monitor connected with a stimulus

Table 1. Examples of the experimental sentences for each condition.

	Correct clitic position
+Gender + Number	Antes de leer el libro, Ana lo sacó de la envoltura de plástico
-Gender + Number	*Antes de comer la manzana, Ana lo peló con un cuchillo
+Gender-Number	*Antes de leer el libro, Ana los sacó de la envoltura de plástico
-Gender-Number	*Antes de comer la manzana, Ana los peló con un cuchillo

Legend: * signifies a violation

presentation computer located in the EEG control room. Stimuli were presented using E-Prime 2.0 (Psychological Software Tools, Inc., Pittsburgh, PA). Each trial started with a fixation cross for 2500 ms to allow participants to blink freely. Sentences were then presented word by word in the center of the screen at a fixed rate. Each word was presented for 300 ms, followed by an interstimulus interval (ISI) of 350 ms. Participants were instructed to read each sentence and to perform an acceptability judgment at the end of each sentence as quickly and as accurately as possible. When prompted with a fixation cross, they pressed a red response key to signal that they considered the previous sentence unacceptable or a green key to signal that they considered it acceptable. They were explicitly instructed to try to minimize movements while pressing the response keys. They were also instructed to read each sentence carefully, as they would be asked to answer periodic comprehension questions, using the same response keys. Response times (RTs) and accuracy for the acceptability judgments were collected for analysis.

EEG data acquisition

EEG activity was recorded from 28 Ag/AgCl - sintered electrodes mounted in a Quik-Cap (Neuroscan Inc.). EEG activity was recorded at the following International 10–20 locations: O1/OZ/O2, P3/PZ/P4, P7/P8, CP3/CP4, TP7/TP8, C3/CZ/C4, T7/T8, FC3/FC4, FT7/FT8, F3/FZ/F4, F7/F8, FP1/FP2. All electrodes were referenced to the right mastoid during recording and re-referenced offline to average mastoids. Bipolar horizontal and vertical electro-oculographic (EOG) activity was recorded for artifact rejection purposes. Vertical EOG was recorded from two electrodes placed above and below the left eye (VEOU, VEOL), while horizontal EOG was recorded from electrodes lateral to the right (HEOR) and left eyes (HEOL). All electrode impedances were kept below 5 kilo-Ohms (kΩ) throughout recording. The EEG signals were continuously recorded with a band-pass filter from 0.05 to 100 Hertz (Hz) and a Notch filter, with a sampling rate of 500 Hz.

Preprocessing and Time-frequency analysis

Time-frequency data preprocessing and analysis were performed in the Fieldtrip toolbox for Matlab (Oostenveld, Fries, Maris & Schoffelen, 2010). Only correct behavioral items were used for further preprocessing and analysis. Data were demeaned and high-pass filtered at 0.1 Hz, segmented and re-referenced off-line to the averaged mastoids. An independent component analysis was performed to identify and remove eye blinks. For the final preprocessing step and time-frequency analysis we redefined the trials to include 300 ms before and 1300 ms after the clitic onset to look at the power spectrum associated with the clitic and the subsequent verb (given that each word appeared on the screen for 300 ms and was followed by a 350 ms long ISI), additional 450 ms padding areas were included on each side of the trial to allow for the time-frequency analysis (for details, see below). We then ran automatic artifact rejection to eliminate trials exceeding the +/-100 mV threshold. To allow for adequate statistical power, and for an optimal signal- to-noise ratio, the minimum percentage of trials per participant per condition to enter the analysis was 50% (24 trials). For the native Spanish speakers group, a total of 13.5% of trials were eliminated due to artifacts and incorrect behavioral responses (14% for the correct condition, 15% for the gender violation condition, 12.5% for the number violation condition and 12.5% for the double violation condition). For the L2 learners' group, a total of 15% of trials were eliminated due to artifact and incorrect behavioral responses (14% for correct condition, 19% for the gender violation condition, 13% for the number violation condition and 12.5% for the double violation condition).

To calculate power spectrum in the 4-30 Hz frequency range, a 500 ms long moving window and a Hanning taper were used. Power changes were computed in steps of 10 ms and 2 Hz. Then, TFRs were averaged for each subject, separately for each of the four conditions. To compare between conditions, baseline normalization was not performed.

Statistical analysis

A cluster-based random permutation approach with 1000 randomizations (for more details see Maris & Oostenveld, 2007) was used to compare the neural response between conditions in three time windows (450-750ms; 750-1050ms, and 1050-1300ms). Frequencies from 4 to 30 Hz were included in the analysis to capture theta (4-7 Hz), alpha (8-12 Hz) and beta (13-30 Hz) ranges. We used a statistical threshold of $p < .025$ per tail to compute t-values for every electrode-time-frequency point and for corrected cluster-level significance.

Since this approach only allows for pairwise comparisons, the following pairwise contrasts were computed for each of the three time-windows within each language group: 1) number agreement violation (+Gender-Number) versus correct sentences (+Gender + Number), 2) gender agreement violation (-Gender + Number) versus correct sentences (+Gender + Number), and 3) gender and number agreement violations (-Gender-Number) versus correct (+Gender + Number) sentences. We also examined the condition by group interaction by directly comparing the violation to the control difference responses between the native and L2 speakers.

Results

Behavioral results

The full behavioral results (accuracy and RTs) are reported in Rossi et al. (2014). For the purpose of the present study, we summarize them here. For the native Spanish group, there was a main effect of Gender, $F1(1, 17) = 5.4$, $p < .05$, with native Spanish speakers being more accurate for the conditions in which gender was correct, and less accurate when number was violated (i.e., +Gender-Number). The RT analysis revealed a gender by number interaction $F1(1, 17) = 6.06$, $p < .05$, with pure gender violations (-Gender + Number) leading to faster responses than the double violation condition (-Gender-Number) or the pure number violation condition (+Gender-Number).

For the L2 learners group, the results revealed that L2 learners of Spanish are less accurate in determining pure gender violations, and more accurate in determining number violations, as revealed by a significant main effect of gender and a gender by number interaction ($F1(1, 20) = 10.258$, $p < 0.05$; $F1(1, 20) = 13.028$, $p < 0.05$), supporting the hypothesis that L2 learners are better able to process a linguistic feature that is similar to their native language, such as number, while they fail to process features of the L2 that are not encoded in their L1. However, behavioral off-line performance represents an aggregate of linguistic and cognitive processes, making it difficult to disentangle the various mechanisms that guide real-time language processing. The analysis of the neural processes engaged while language processing unfolds can reveal patterns of sensitivity to L2 syntax that might otherwise not be captured (Tokowicz & MacWhinney, 2005). Moreover, as mentioned above, TFR analysis allows us to analyze the EEG signal while minimizing the variability related to differences in timing, making it a particularly appealing method to be applied to the investigation of L2 processing (Kielar et al., 2014).

Time-frequency results

In what follows we present the time-frequency results for the three contrasts of interest: 1) number agreement violation (+Gender-Number) versus correct sentences (+Gender + Number), 2) gender agreement violation (-Gender + Number) versus correct sentences (+Gender + Number), and 3) gender and number agreement violations (-Gender-Number) versus correct sentences (+Gender + Number), in the three time windows (450-750 ms; 750-1050 ms; 1050-1300 ms). Table 2 summarizes the effects for the frequencies at which there were significant differences in these contrasts (alpha-threshold of 0.025 (two-tailed).

Contrast 1: Number Agreement Violations compared to the Correct Condition.

Figure 1 shows the effects for the number agreement violation for native Spanish speakers, L2 learners, and the direct comparison between the two groups respectively.

Native Spanish speakers

No significant effect was observed in the first time window. In the second time-window there was a marginally significant power decrease in the 10-12 Hz frequency range, corresponding to alpha frequencies ($p= 0.059$). Decrease in alpha power protracted into the third window ($p= 0.014$).

L2 Spanish learners

For this contrast, results reveal only a marginally significant decrease in beta frequencies (14-18 Hz) at the second time window ($p = 0.061$).

Comparison between native Spanish and L2 learners

A direct group comparison of the number agreement violation, compared to the correct condition, revealed no significant differences between the two groups.

Contrast 2: Gender Agreement Violations compared to the Correct Condition.

Figure 2 shows the effects for the gender agreement violation for native Spanish speakers, L2 learners, and the direct comparison between the two groups respectively.

Native Spanish speakers

Gender agreement violations generated a significant power decrease compared to the correct condition in the 10-18 Hz range, corresponding to alpha and lower beta ranges in the first time window ($p= 0.006$). In the second and the third windows there was a significant decrease in alpha power ($p= 0.021$; $p= 0.004$).

L2 Spanish learners

Results revealed a significant power decrease in the beta range (14-18Hz) in the first time window (450-750ms; $p= 0.013$). A significant power decrease in alpha and lower beta frequencies (8-14 Hz) was also observed in the second time-window (750-1050ms; $p= 0.043$). No significant effect was observed in the third time-window.

Comparison between native Spanish and L2 learners

A direct group comparison of the gender agreement violation compared to the correct condition, revealed no differences in the first or second time window, but a significant difference in the third time window (1050-1300ms) for frequencies between 10 and 14 Hz, such that native Spanish speakers showed a significant power decrease but the effect was not present in L2 learners.

Contrast 3: Gender/Number Agreement Violations compared to the Correct Condition.

Figure 3 shows the effects for the double agreement violation for native Spanish speakers, L2 learners, and the direct comparison between the two groups respectively.

Native Spanish speakers

Presentation of sentences with combined gender and number agreement violations marked on the clitic pronoun yielded a significant decrease in power as compared to correct sentences in the upper theta, alpha-and beta frequencies (12-14 Hz) in the second time windows (750-1050ms window: $p= 0.0039$). In the third time window there was a significant power decrease encompassing upper theta, and alpha frequencies (6-12 Hz) (1050-1300ms; $p= 0.0039$). No significant effect was revealed for the first time window.

L2 Spanish learners

A significant power alpha power decrease (8-10Hz) was observed in the second time window (750-1050ms; $p= 0.032$). The effect continued into the third time-window (1050-1300ms; $p= 0.019$) ranging in theta and alpha frequencies (4-10 Hz). No significant effect was observed in the first time-window.

Comparison between native Spanish and L2 learners

A direct group comparison of the double agreement violation compared to the correct condition, revealed no differences between the groups.

Table 2. The table reports a summary of results for both groups. We present the output of the cluster-based random permutation test for the three time windows, and the reported frequencies are the most likely contributors to the effect. Only frequencies that were significant at $p < 0.05$ or below are presented.

	Time window (in s)					
	0.45-0.75		0.75-1.05		1.05-1.3	
	Significant frequencies (in Hz)					
Condition	L1	L2	L1	L2	L1	L2
Number violation	*n.s.*	*n.s.*	*10-12*$^{+}$	*14-18*$^{+}$	10-12**	*n.s.*
Gender violation	*10-18***	*14-18***	*10-12***	*8-14**	8-12**	*n.s.*
Double violation	*n.s.*	*n.s.*	*12-14***	*8-10***	*6-12***	*4-10***

Legend: $^{+}$ $p = 0.059$; $^{*}p < 0.05$; $^{**}p < 0.01$; n.s. not significant

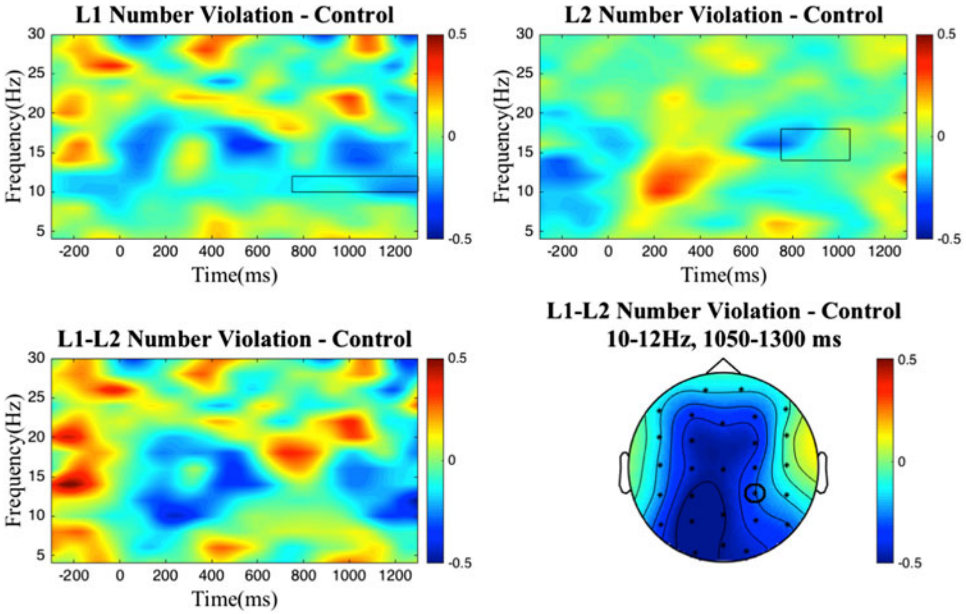

Fig. 1. Number violation. Top left: between-conditions difference at electrode CP4 in the L1 group. Top right: L2 between-conditions difference at electrode CP4 in the L2 group. Color scale indicates power change in the number violation condition relative to the correct condition. Bottom left: L1-L2 difference between condition differences at electrode CP4. Bottom right: scalp topography of the L1-L2 difference between condition differences (averaged for the frequencies which were the most likely contributors to the significant effect observed in the L1 group in the third time-window). Color scale indicates change in the difference power spectrum in the L1 group relative to the L2 group (while visual analysis suggests a difference in the L1-L2 comparison of between condition differences, this difference wasn't significant according to the cluster-based permutation analysis).

General discussion

Previous ERP research on L2 processing in late learners has suggested that there may be hard constraints for morpho-syntactic processing, especially for grammatical structures that are not shared between the L1 and the L2 (e.g., Nichols & Joanisse, 2017; Sabourin & Stowe, 2008; Sabourin, Stowe & de Haan, 2006). However, despite the difficulty of acquiring L2 grammatical structures, a number of recent ERP studies have revealed that at least a subset of late L2 speakers with extensive immersion experience (e.g., Dowens et al., 2010) or with high proficiency levels (e.g., Rossi et al., 2014; Foucart & Frenck-Mestre, 2012; Tokowicz & MacWhinney, 2005) show a similar neural signature to native speakers (for evidence using an artificial language, see Morgan-Short, Sanz, Steinhauer & Ullman, 2010), even for unique grammatical structures of the L2 that are not encoded in the L1 (Foucart & Frenck-Mestre, 2012). Differential signatures of L2 processing have also been driven by an interaction of linguistic factors (i.e., similarity across grammatical structures between the L1 and the L2), and speakers' factors such as age of acquisition and proficiency. For instance, Nichols and Joanisse (2017) propose a graded model for L2 processing according to which proficiency and age of acquisition might play partly independent roles in shaping the ERP signatures to different types of violations. For example, proficiency levels seem to be important for early stage markers of grammatical processing such as the Left Anterior Negativity in response to grammatical violations for syntactic structures that overlap between the two languages, while age of acquisition seems to play an independent role in shaping the neural response for grammatical structures that are not shared between the two languages.

In this study we used Time Frequency Representation to analyze the oscillatory signal generated in response to clitic pronoun

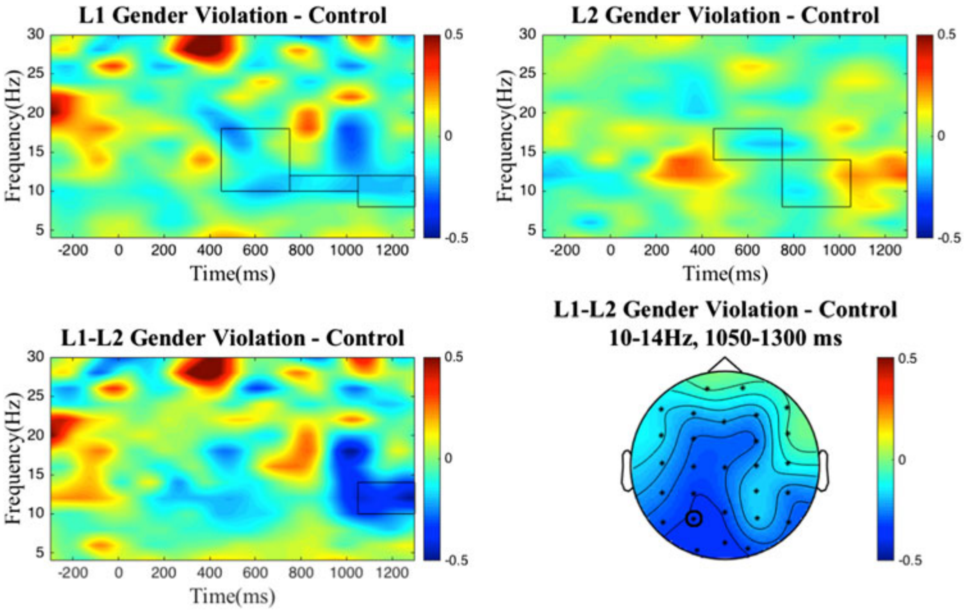

Fig. 2. Gender violation. Top left: between-conditions difference at electrode P3 in the L1 group. Top right: L2 between-conditions difference at electrode P3 in the L2 group. Color scale indicates power change in the gender violation condition relative to the correct condition. Bottom left: L1-L2 difference between condition differences at electrode P3. Bottom right: scalp topography of the L1-L2 difference between condition differences (averaged for the frequencies which were the most likely contributors to the significant effect observed in the third time-window in the between-groups comparison). Color scale indicates change in the difference power spectrum in the L1 group relative to the L2 group.

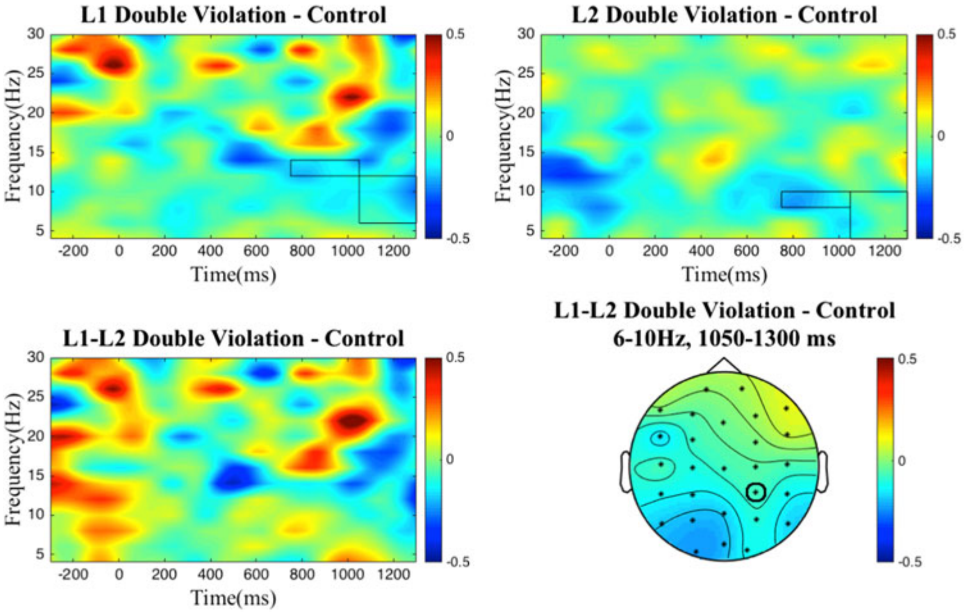

Fig. 3. Double violation. Top left: between-conditions difference at electrode CP4 in the L1 group. Top right: L2 between-conditions difference at electrode CP4 in the L2 group. Color scale indicates power change in the double violation condition relative to the correct condition. Bottom left: L1-L2 difference between condition differences at electrode CP4. Bottom right: scalp topography of the L1-L2 difference between condition differences (averaged for the frequencies which were the most likely contributors to the significant effects observed in both groups in the third time-window). Color scale indicates change in the difference power spectrum in the L1 group relative to the L2 group.

processing in native Spanish speakers and late L2 learners of Spanish to further investigate the neurophysiological bases of L2 processing for a grammatical structure that is unique to the L2. To our knowledge this is the first study to analyze the oscillatory brain dynamics of clitic pronouns, both in native speakers and L2 learners. Importantly, while averaging the EEG signal time-locked to specific events (ERPs) that are highly variable in timing across items and participants can result in an underestimation of the real effect (Kielar et al., 2014; Luck, 2014; Mouraux & Iannetti, 2008), TFR minimizes changes in the signal related to differences in timing, making it a particularly sensitive method for studying L2 processing (Kielar et al., 2014).

For native speakers the results revealed sensitivity to all three violations. Power decrease in the alpha (8-12 Hz), and beta

(13-30 Hz) frequencies was observed for gender violations, decrease in beta frequencies was observed for number violations, and decrease in alpha, beta, and upper theta (4-7 Hz) emerged in response to the double violation. The results also demonstrate that the TFR modulation across the three conditions spanned across the three time windows, starting at around 450 ms after stimulus presentation and lasting till 1300 ms. L2 speakers also showed sensitivity to the three violation conditions. Pure gender violations elicited power decrease in alpha and beta frequencies starting around 450 ms and extending up to 1000 ms. Number violations at the clitic pronoun revealed a marginal effect in beta frequencies between 750-1000 ms, while the double violation elicited power decrease encompassing upper theta, and beta frequencies starting at 750ms and extending till 1300ms. Even though the direct comparison of the TFR signal between the two groups showed overall a qualitatively similar oscillatory pattern, some qualitative differences in TFR emerged between native and L2 speakers. For example, decrease in beta oscillations in native speakers was only observed in the first window, while it was sustained in the first and second window of interest for L2 speakers. In Lewis et al., 2016 beta modulations were observed in L2 speakers only when they were required to make an explicit grammaticality judgment, suggesting that sensitivity to L2 grammar might be driven by top-down attentional control processes. Similarly to that interpretation, it is possible also for our data that sustained L2 speakers engage sustained attentional control while processing in the L2.

The current TFR results allow us to draw some important general conclusions. First, in line with a growing body of literature, we provide evidence that the TFR analysis is a very sensitive methodology for studying language processing in highly variable populations, such as L2 learners whose language performance might vary greatly both quantitatively and qualitatively (e.g., Ivanova & Costa, 2008; Sabourin & Stowe, 2008; Tolentino & Tokowicz, 2011; Kielar et al., 2014; Lewis et al., 2016). Most importantly, the current results support previous behavioral and neurophysiological evidence showing that late L2 speakers can process unique L2 syntax in a native-like manner (e.g., Foucart & Frenck-Mestre, 2012; Rossi et al., 2014), confirming that speakers who acquire an L2 later in life can be sensitive to syntactic structures that are not shared between the two languages, even in the absence of behavioral sensitivity. Our results are therefore in line with processing theories of L2 performance (Hopp, 2007; Hopp, 2010; White et al., 2004) which argue against a critical period, and a representational "deficit" (Clahsen & Felser, 2006a; 2006b; 2006c) for morphosyntax in L2 acquisition, and suggest that differences between native and L2 processing might be due to less efficient L2 computation due to variations in proficiency and availability of working memory while processing in the L2 (Sagarra & Herschenshon, 2010).

Critically, our data demonstrate that, despite the large qualitative similarity in the TFR signature between native speakers and L2 learners, the time-course of the observed effects in the three violation conditions differed between the two groups. More specifically, the data revealed that the TFR signal is longer lived in native speakers than in L2 learners. Significant modulations of the TFR signal in native speakers were observed up to the third window of interest (1000-1300 ms) while longer TFR modulations in L2 learners were observed only for the double violation. Importantly, direct comparisons between the two groups revealed that for pure gender violations, only native speakers' TFR continued to oscillate into the third window of interest.

In what follows, we will first discuss our results in the light of the current literature, focusing on the significance of the different frequency components that have been observed for language processing. Given the relative scarcity of TFR studies on language processing and specifically for L2 processing, it is important to situate the current results with the previous reported literature. We will then discuss the differences in oscillatory duration observed between the groups, linking our findings to two-stage cell assemblies models (Hebb, 1949; Pulvermüller, 1999). We will consider this new proposal and its implications for future research in L2 processing.

The present results show a decrease in alpha power (8-12 Hz) in response to all violation conditions (number, gender, and double violation) for native speakers. L2 learners also show alpha power decrease for the three violation conditions. Alpha and upper alpha power decrease have been suggested to signal attentional and semantic memory processes (Klimesch, Schimke & Schwaiger, 1994; Klimesch, 1999; Klimesch, 1997; Weiss & Mueller, 2003; Weiss & Mueller, 2012), storage of syntactic information in shown term memory (Meyer, 2017), and explicit grammatical processing (Bastiaansen & Hagoort, 2006; Lewis et al., 2016). Power decrease in alpha also reflects lexico-semantic integration during sentential processing (Bastiaansen et al., 2002a; Grabner et al., 2007; Strauß et al., 2014), unification of semantic and syntactic information during sentence comprehension (Lam et al., 2016), and detection of syntactic anomalies (Bastiaansen, Magyari & Hagoort, 2010; Davidson & Indefrey, 2007). Moreover, Kielar et al. (2014) demonstrate that alpha power is modulated in response to cognitive and task demands, such that changes in alpha frequencies were observed in bilinguals when an explicit grammaticality judgment task was required. In line with these findings, our results support the interpretation that power decrease in alpha frequencies signals syntactic re-analysis during native and L2 processing, and is observed also for L2 speakers when processing grammatical structures that are unique to the L2.

With regards to beta frequencies (13-30 Hz), decrease in beta power in response to all violation conditions was observed for native Spanish speakers, while L2 learners show a decrease in beta frequencies for gender violation and the double violation starting at 750ms. These findings are compatible with previous literature investigating the relationship between oscillatory dynamics and morpho-syntactic processing that reveal decrease in beta frequency power for sentences containing morpho-syntactic violations both in native speakers (Davidson and Indefrey, 2007; Bastiaansen, 2010) and also for the few studies that investigated language comprehension in L2 learners (Kielar et al., 2015; Lewis et al., 2016). For example, Lewis et al. (2016) tested determiner-noun grammatical gender agreement in native speakers of Dutch and in German late L2 learners of Dutch. Their findings revealed that modulations of beta frequencies were observed in the learners group only when they were required to explicitly attend to grammatical information. In our design, participants were not explicitly asked to make a grammaticality judgment, but were nevertheless instructed to make an acceptability judgment. The intent was for them to pay attention to the task, and to provide their judgment about whether they considered the sentences acceptable or not, with the goal of collecting a measure of explicit performance. It is therefore possible that this less focused task requirement explicitly cued participants to focus on grammatical information, thus eliciting beta activity.

Our results can also be discussed in the context of the Memory, Unification and Control (MUC) framework

(Bastiaansen & Hagoort, 2006; Hagoort, 2013), which posits that language comprehension relies on two main processes: retrieval of language building blocks from memory (phonological, semantic, and syntactic) and their combination into meaningful representations (unification). Importantly, MUC proposes that syntactic unification operations are associated with activity in the beta frequency band. As such, the observed power decrease in beta frequencies supports the MUC model and indicates potential commonalities between syntactic unification processes across native speakers and L2 learners of Spanish.

Finally, according to the proposed predictive coding framework (Lewis & Bastiaansen, 2015; Lewis, Wang & Bastiaansen, 2015), beta activity supports the active maintenance of the Neuro Cognitive Network -NCN- (Bressler & Richter, 2015) which emerges as a result of building the representation of meaning at a sentence level and as a consequence of top-down propagation of predictions to lower processing levels based on this representation. Under this proposal, high beta reflects active maintenance of the current NCN and decrease in beta signals that the currently active NCN has changed as a function of incoming cues during sentence processing (Engel & Fries, 2010; Lewis & Bastiaansen, 2015). In the context of this study, when the clitic pronoun does not match in number with the antecedent, the predictive coding framework predicts that the speaker needs to construct representations of objects introduced in the sentence such as "inanimate, singular, masculine object" (*mango*), as well as other lexical items. In a syntactically legal sentence, when participants encounter the clitic pronoun 'lo', they start looking for a plausible antecedent among the representations that have been built before. However, upon encountering 'los' (plural and masculine), the predicted representation fails to be built, triggering a decrease in beta frequencies. In sum, the reported results confirm that a decrease in beta frequencies is a marker of syntactic re-analysis during native processing, and is likely observed for L2 speakers when processing a grammatical structure unique to the L2.

Results in the theta frequencies (4-7 Hz) show a decrease in upper theta (6-7 Hz) for the double violation between 1000-1300ms for native speakers. Similar effects were observed for L2 speakers. Our results deviate from previous studies that report increase in theta (not decrease) for incorrect sentences in native speakers when grammatical number and gender are violated (Bastiaansen et al., 2002a; Bastiaansen et al., 2002b; Lewis et al., 2016). Theta increase was also found in Lewis et al. (2016) for L2 speakers for grammatical violations, but only when the data was analyzed according to when participants subjectively deemed that there was a violation. Increase in theta activity has been connected to building a working memory trace during sentence comprehension (Bastiaansen et al., 2002a; Bastiaansen et al., 2002b), and more generally to increase in working memory load (Khader et al., 2010; Jensen & Tesche, 2002). Importantly, theta power decrease has been reported in retrieval-related control processes (Khader & Rösler, 2011), and suppression of memory traces (Waldhauser at al., 2015). Therefore, a possible interpretation for our results is that the decrease in theta power in the double violation condition in native Spanish speakers and L2 learners and theta decrease for gender and number violations in native Spanish speakers could be interpreted as the suppression of potentially alternative interpretations that arise in the context of an otherwise grammatical violation. For example, in the double violation condition, it is possible that speakers build temporary alternative interpretations at the discourse, for example analyzing the incorrect clitic pronoun as potentially referring to an antecedent that was not previously introduced in the discourse. Power decrease in theta was also observed in the gender and number violation conditions but only for native Spanish speakers. Again, it is plausible that native speakers maintain an alternative interpretation active for the incorrect sentence, which then might need to be suppressed once that alternative interpretation becomes unviable. However, there was no power decrease in theta for number violation in native Spanish speakers, which might undermine the hypothesis that links theta decrease with maintenance of an alternative interpretation. However, it is possible that pure number violations on the clitic pronoun might be interpreted as a true grammatical error, and might not engage higher discourse processing reanalysis. In sum, we propose that decrease in theta frequencies might be implicated in the suppression of memory traces (Waldhauser et al., 2015), suggesting a role of theta modulation for predictive processing. Future research will be needed to further test this proposal.

Beyond sensitivity to the L2 grammar: a Hebbian perspective on quantitative differences the oscillatory signal

These results demonstrate that the TFR signal in response to grammatical processing is overall similar between native speakers and L2 learners. However, we observed that the time-course of the observed effect differed between the two groups. Native speakers' TFR signal lasted up to the third window of interest (i.e. 1300 ms), while the TFR signal of L2 learners ceased earlier in time. Here we propose that a possible distinguishing feature between native and L2 processing might be captured by differences in the duration of the oscillatory signal.

To discuss this proposal, we assume a Hebbian cell assemblies model framework for neural information processing (Hebb, 1949; Buzsáki, 2010; Pulvermüller, 1996). This framework has also recently been discussed in the context of (bi)language processing (Hagoort, 2013; Hickok & Poeppel, 2007; Strijkers, 2016). Hebb's cell assembly framework (Hebb, 1949) relies on a number of important assumptions for our proposal. Cell assemblies have been recognized to have shown two temporally distinct activation time-courses (Pulvermüller, 1996); a first fast ignition activation phase of the whole neural assembly followed by a slower reverberation of the whole cell assembly (or at least a specific sub-part of the assembly). The first ignition phase has been linked to "target identification" (Pulvermüller, 2013; Dehaene et al., 2006; Strijkers, 2016), while the reverberation phase has been posited to signal second-order processes such as reprocessing, decision-making and metacognitive awareness (Dehaene et al., 2006). For language processing more specifically, the reverberation phase has been linked to grammatical reprocessing and verbal working memory (Buszaki, 2010; Pulvermüller et al., 2014). Crucially, classic ERP components such as the N400 and the P600 have been proposed to be the surfacing instantiation of the slow-oscillating reverberation phase.

Critically, our data show that for native speakers the beginning of the observed reverberation phase overlaps with the onset of a typical P600/LPC component (around 500 ms), but continues beyond its typical duration. If the observed reverberation signals grammatical re-processing and/or verbal working memory processes (Buszaki, 2010; Pulvermüller et al., 2014), changes in the length of the reverberation phase could be then modulated by processing difficulties. Longer oscillatory phases could signal higher processing difficulty. Importantly, both external and internal factors should be considered. On the one hand, external factors, such as the overall complexity of the syntactic construal (in terms of both linear and syntactic complexity, including increasing levels of ambiguity), could play a role in modulating the duration of the reverberation phase. According to this hypothesis, we can predict that the processing of more complex grammatical structures should lead to a longer reverberation phase. On the other hand, internal factors, such as individual variation in availability in cognitive resources that are central to the ability to process linguistic information in real time (such as verbal working memory and attention), could also impact the overall duration of the reverberation phase. The idea that neural processes are shaped by availability in cognitive resources is not novel. For example, it has been shown that ERP effects can change as a function of individuals' working memory capacity (Vos, Gunter, Kolk & Mulder, 2001), but also as a function of individual differences in proficiency, even in the native language (e.g., Tanner & van Hell, 2014), and in response to task demands (Tokowicz & MacWhinney, 2005). As such, it could be predicted that differences in the reverberation phase should be observed as a function of individual differences in cognitive functions, such as verbal working memory and attention. A number of EEG studies that are aimed at adjudicating between these possible alternatives are underway in our laboratories.

For L2 speakers instead, a decrease in the duration of the reverberation phase could be interpreted as indicating incomplete/shallow grammatical processing for L2 speakers (Clahsen & Felser, 2006c). Besides the difference in the length of the reverberation phase, our data show that native Spanish speakers and L2 learners have comparable TFR activity, suggesting that they are both successful at processing the clitic pronoun and its gender and number features. Also, the reverberation signal observed in the 500-1000 ms time-window coincides with the typical time-course of the P600/LPC components that signal successful syntactic processing. Importantly for the present data, Rossi et al. (2014) demonstrated that a subset of L2 learners showed a comparable P600 effect to native speakers, thus ruling out the possibility that the reduction in duration of the observed reverberation phase for L2 learners signals a shallower processing state than that for native speakers.

One plausible account, to explain the differences in the reverberation phase duration between native and L2 speakers, could rely on the idea that L2 speakers might face limited cognitive resources availability when processing in the L2. It is widely accepted in the bilingual literature that a bilingual's two languages are always coactivated, at the lexical (Blumenfeld & Marian, 2007; Kroll, Bobb & Wodniecka, 2006; Kroll, Gullifer & Rossi, 2013), and grammatical levels (Dussias & Sagarra, 2007), even at beginning stages of L2 learning (Bice & Kroll, 2015). As such, given that bilinguals have to control and monitor two languages that are competing for selection, L2 processing has been shown to be cognitively demanding. Recently, a growing body of research has highlighted how bilingual speakers engage a number of language-independent executive functions necessary for successful language processing (Abutalebi & Green, 2007; Green & Abutalebi, 2013), the recruitment of which also changes as a function of proficiency in the L2 (Abutalebi, Della Rosa, Ding, Weekes, Costa & Green, 2013). Working memory (WM), for example, has been indicated to be a core component of those cognitive functions that is under high demand in L2/bilingual language processing. It is therefore not surprising that previous results revealed that availability of WM resources is positively correlated with sensitivity to complex grammatical structures in the L2 (e.g., Coughlin & Tremblay, 2011; MacDonald & Christiansen, 2002), supporting the view that WM is a central cognitive substrate for L2 language processing. A recent meta-analysis by Linck and colleagues (2014) further confirms that WM is positively correlated with both L2 processing and proficiency outcomes. As such, it could be hypothesized that the observed difference in the duration of the reverberation phase in L2 speakers could reflect overall diminished availability of WM resources while processing in the L2. Because WM resources are necessary during on-line language processing and are central for the detection, maintenance, re-analysis and repair processes of morpho-syntax (Causse, Peysakhovich & Fabre, 2016), diminished WM availability during L2 processing has the potential to impact the duration of the observed sustained reverberation phase which has been linked to consolidation, syntactic reprocessing, and crucially also to WM itself (Buszáki, 2010; Pulvermüller, 2002; Pulvermüller et al., 2014).

It is also possible that the cognitive demands of L2 processing diminish when a shift from declarative to more procedural/automatic memory-based processing emerges as a function of improved L2 proficiency (Ullman, 2001). Future research will need to address this possibility and test whether the length of the reverberation phase changes as a function of increasing L2 proficiency levels. It is also possible that the difference in the duration of the reverberation phase might have been driven by the fact that L2 speakers were processing a grammatical structure that is specific to the L2 and is also an example of a long-distance dependency. Long distance dependencies have been shown to be particularly hard for late L2 learners to process (Clahsen & Felser, 2006a). One additional possibility is that the length of the oscillatory phase may be modulated by the type of grammatical structure under investigation, especially as more complex structures could themselves lead to increases in WM demands. We are currently testing this hypothesis by analyzing the neural oscillatory underpinnings of subject-verb agreement in native Spanish speakers and in late, intermediately-proficient English L2 learners of Spanish (Rossi, Krass & Prystauka, 2020). Different from clitic pronouns, subject verb agreement is a grammatical construal that is shared between English and Spanish, allowing us to ask whether processing linguistic structures that are shared between a learner's two languages modulates the observed length of the reverberation oscillatory phase.

Finally, an alternative interpretation for the observed differences in the duration of the TFR signal between native speakers and L2 learners is that the difference reflects general violation detection/repair strategies. Under this hypothesis, it is predicted that no group differences should be observed while processing correct sentences. Instead, differences while processing correct sentences would suggest a reliance on partly different linguistic/cognitive processes during language comprehension. In order to test this prediction, we performed a post-hoc analysis directly comparing the TFR signal in the correct condition between native speakers and L2 learners. The results show a significant difference between the two groups in all the three windows of interest spanning across alpha, beta, and theta frequencies (using a 300 ms pre-stimulus baseline). Time window: 0.45-0.75 (8-16 Hz; $p = 0.014$); time window: 0.75-1.05 (4-16 Hz; $p = 0.004$); time window: 1.05-1.3 (4-20 Hz; $p = 0.002$). Once again, native speakers show more power across the three frequencies in all the three time windows. Importantly, higher alpha and theta have been demonstrated to be connected to better memory retrieval, retrieval of lexico-semantic information (Bastiaansen et al., 2008), and even as a predictor of the speed at which information can be retrieved from memory (Klimesch, 1997; Klimesch, 1999), and is increasingly been demonstrated to play a role in supporting verbal working memory during on-line sentence comprehension (e.g., Meyer, 2017). The data we report suggest then that sentence processing in the L2, even when processing correct sentences, might need to happen on relatively decreased verbal working memory capacities. However, as mentioned earlier, because bilinguals' two languages are constantly coactivated, it is not surprising to observe that L2 on-line processing is cognitively relatively demanding. Similarly, stronger activity in beta oscillations has been associated with building and maintenance of sentence-level meaning representation (e.g., Lewis et al., 2015) as discourse unfolds, and possibly prediction processes during sentence comprehension (Meyer, 2017), suggesting that processing in the L2 might be less efficient in these linguistic processes.

Conclusions

In this study, we used TFR to analyze morphosyntactic processing in native Spanish speakers and in L2 late learners of Spanish, while gender, and number agreement marked on clitic pronouns during sentence processing. Overall, the TFR results confirm qualitatively for the most part similar oscillatory signatures between the two groups, in line with processing theories of L2 acquisition. However, our data reveal that the TFRs differed between the two groups in their time-course. We discussed this result in the context of Hebbian cell assembly framework. We propose a novel working hypothesis for L2 processing; mainly, that the length of the reverberation phase of the cell assembly might be a distinguishing feature between native and L2 processing, and also for individual differences in language processing more generally. Further research will need to test this proposal with more direct experimental manipulations to assess specific predictions of this proposal.

Acknowledgements. Data collection for this research was supported by the NIH Grant HD053146 to Judith F. Kroll, NSF Grants BCS-0955090 and OISE-0968369 to Judith F. Kroll and Paola E. Dussias, and NSF Grant BCS-0821924 to Paola E. Dussias. The authors would like to thank Megan Zirnstein and Gerry Altmann for important suggestions on this work.

References

Abutalebi, J, Della Rosa, PA, Ding, G, Weekes, B, Costa, A and Green, DW (2013) Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex* **49**, 905–911.

Abutalebi, J and Green, D (2007) Bilingual language production: The neurocognition of language representation and control. *Journal of neurolinguistics* **20**, 242–275.

Bastiaansen, MCM and Hagoort, P (2006) Oscillatory neuronal dynamics during language comprehension. *Progress in brain research* **159**, 179–196.

Bastiaansen, MC, Oostenveld, R, Jensen, O and Hagoort, P (2008) I see what you mean: theta power increases are involved in the retrieval of lexical semantic information. *Brain and language* **106**, 15–28.

Bastiaansen, MCM, Magyari, L and Hagoort, P (2010) Syntactic unification operations are reflected in oscillatory dynamics during on-line sentence comprehension. *Journal of cognitive neuroscience* **22**, 1333–1347.

Bastiaansen, MCM, Mazaheri, A and Jensen, O (2012) Beyond ERPs: oscillatory neuronal dynamics. In *The Oxford handbook of event-related potential components*. Oxford University Press, pp. 31–50.

Bastiaansen, MCM, van Berkum, JJA and Hagoort, P (2002b) Event-related theta power increases in the human EEG during online sentence processing. *Neuroscience Letters* **323**, 13–16.

Bastiaansen, MCM, van Berkum, JJA and Hagoort, P (2002a) Syntactic processing modulates the theta rhythm of the human EEG. *NeuroImage* **17**, 1479–1492.

Bialystok, E, Craik, FIM and Ryan, J (2006) Executive control in a modified antisaccade task: Effects of aging and bilingualism. *Journal of Experimental Psychology: Learning Memory and Cognition* **32**, 1341–1354.

Bialystok, E, Klein, R, Craik, FIM and Viswanathan, M (2004) Bilingualism, aging and cognitive control: Evidence from the Simon task. *Psychology and Aging* **19**, 290–303.

Bialystok, E and Majumder, S (1998) The relationship between bilingualism and the development of cognitive processes in problem solving. *Applied Psycholinguistics* **19**, 69–85.

Bice, K and Kroll, JF (2015) Native language change during early stages of second language learning. *NeuroReport* **26**, 966–971.

Birdsong, D (1999) *Second language acquisition and the critical period hypothesis*. Mahwah, NJ: Erlbaum.

Birdsong, D and Molis, M (2001) On the evidence for maturational constraints in second-language acquisition. *Journal of memory and language* **44**, 235–249.

Blumenfeld, HK and Marian, V (2007) Constraints on parallel activation in bilingual spoken language processing: Examining proficiency and lexical status using eye-tracking. *Language and Cognitive Processes* **22**, 633–660.

Bressler, SL and Richter, CG (2015) Interareal oscillatory synchronization in top-down neocortical processing. *Current Opinion in Neurobiology* **31C**, 62–66.

Buzsáki, G (2006) *Rhythms of the brain*. New York: Oxford University Press.

Buzsáki, G (2010) Neural Syntax: Cell Assemblies, Synapsembles, and Readers. *Neuron* **68**, 362–385.

Caffarra, S, Molinaro, N, Davidson, D and Carreiras, M (2015) Second language syntactic processing revealed through event-related potentials: an empirical review. *Neuroscience & Biobehavioral Reviews* **51**, 31–47.

Causse, M, Peysakhovich, V and Fabre, EF (2016) High Working Memory Load Impairs Language Processing during a Simulated Piloting Task: An ERP and Pupillometry Study. *Frontiers in Human Neuroscience* **10**, 1–14.

Clahsen, H and Felser, C (2006a) Grammatical processing in language learners. *Applied Psycholinguistics* **27**, 3–42.

Clahsen, H and Felser, C (2006b) How native-like is non-native language processing?. *Trends in cognitive sciences* **10**, 564–570.

Clahsen, H and Felser, C (2006c) Continuity and shallow structures in language processing. *Applied Psycholinguistics* **27**, 107–126.

Coughlin, CE and Tremblay, A (2012) Proficiency and working memory based explanations for nonnative speakers' sensitivity to agreement in sentence processing. *Applied Psycholinguistics* **34**, 615–646.

Davidson, DJ and Indefrey, P (2007) An inverse relation between event-related and time–frequency violation responses in sentence processing. *Brain Research* **1158**, 81–92.

Dehaene, S, Changeux, JP, Naccache, L, Sackur, J and Sergent, C (2006) Conscious, preconscious, and subliminal processing: a testable taxonomy. *Trends in Cognitive Sciences* **10**, 204–211.

Díaz, B, Erdocia, K, de Menezes, RF, Mueller, JL, Sebastián-Gallés, N and Laka, I (2016) Electrophysiological Correlates of Second-Language Syntactic Processes Are Related to Native and Second Language Distance Regardless of Age of Acquisition. *Frontiers in Psychology* **7**, 1–13.

Dowens, MG, Vergara, M, Barber, HA and Carreiras, M (2010) Morphosyntactic processing in late second-language learners. *Journal of Cognitive Neuroscience* **22**, 1870–1887.

Dussias, PE and Sagarra, N (2007) The effect of exposure on syntactic parsing in Spanish–English bilinguals. *Bilingualism: Language and Cognition* **10**, 101.

Engel, AK and Fries, P (2010) Beta-band oscillations—signalling the status quo?. *Current opinion in neurobiology* **20**, 156–165.

Fonteneau, E, Bozic, M and Marslen-Wilson, W (2011) Cortical oscillations underlying morphological processing: an MEG/EEG study. In *Front. Hum. Neurosci. Conference Abstract: XI International Conference on Cognitive Neuroscience* (*ICON XI*).

Foucart, A and Frenck-Mestre, C (2012) Can late L2 learners acquire new grammatical features? Evidence from ERPs and eye-tracking. *Journal of Memory and Language* **66**, 226–248.

Grabner, RH, Brunner, C, Leeb, R, Neuper, C and Pfurtscheller, G (2007) Event-related EEG theta and alpha band oscillatory responses during language translation. *Brain Research Bulletin* **72**, 57–65.

Green, DW and Abutalebi, J (2013) Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology* **25**, 515–530.

Gross, J, Hoogenboom, N, Thut, G, Schyns, P, Panzeri, S, Belin, P and Garrod, S (2013) Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS Biol* **11**, e1001752.

Guo, T, Misra, M, Tam, JW and Kroll, JF (2012) On the time course of accessing meaning in a second language: An electrophysiological and behavioral investigation of translation recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition* **38**, 1165.

Hagoort, P (2013) MUC (memory, unification, control) and beyond. *Frontiers in Psychology* **4**, 416.

Hebb, D.O (1949) *The organization of behavior. A neuropsychological theory.* New York: Wiley.

Herschensohn, J (2001) Missing inflection in second language French: accidental infinitives and other verbal deficits. *Second Language Research* **17**, 273–305.

Hickok, G and Poeppel, D (2007) The cortical organization of speech processing. *Nature Reviews Neuroscience* **8**, 393–402.

Hopp, H (2007) *Ultimate Attainment at the Interfaces in Second Language Acquisition: Grammar and Processing.* PhD Dissertation, Rijksuniversiteit Groningen.

Hopp, H (2010) Ultimate attainment in L2 inflection: Performance similarities between non-native and native speakers. *Lingua* **120**, 901–931.

Hopp, H (2013) Grammatical gender in adult L2 acquisition: Relations between lexical and syntactic variability. *Second Language Research* **29**, 33–56.

Ivanova, I and Costa, A (2008) Does bilingualism hamper lexical access in speech production? *Acta Psychologica* **127**, 277–288.

Jensen, O and Tesche, CD (2002) Frontal theta activity in humans increases with memory load in a working memory task. *European journal of Neuroscience* **15**, 1395–1399.

Kaan, E and Swaab, TY (2003) Repair, revision, and complexity in syntactic analysis: An electrophysiological differentiation. *Journal of cognitive neuroscience* **15**, 98–110.

Khader, PH, Jots, K, Ranganath, C and Rösler, F (2010) Theta and alpha oscillations during working-memory maintenance predict successful long-term memory encoding. *Neuroscience Letters* **468**, 339–343.

Khader, PH and Rösler, F (2011) EEG power changes reflect distinct mechanisms during long-term memory retrieval. *Psychophysiology* **48**, 362–369.

Kielar, A, Meltzer, JA, Moreno, S, Alain, C and Bialystok, E (2014) Oscillatory responses to semantic and syntactic violations. *Journal of Cognitive Neuroscience* **26**, 2840–2862.

Kielar, A, Meltzer-Asscher, A and Thompson, CK (2012) Electrophysiological responses to argument structure violations in healthy adults and individuals with agrammatic aphasia. *Neuropsychologia* **50**, 3320–3337.

Kielar, A, Panamsky, L, Links, KA and Meltzer, JA (2015) Localization of electrophysiological responses to semantic and syntactic anomalies in language comprehension with MEG. *Neuroimage* **105**, 507–524.

Klimesch, W (1997) EEG-alpha rhythms and memory processes. *International Journal of Psychophysiology* **26**, 319–340.

Klimesch, W (1999) EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain research reviews* **29**, 169–195.

Klimesch, W, Schimke, H and Schwaiger, J (1994) Episodic and semantic memory: an analysis in the EEG theta and alpha band. *Electroencephalography and Clinical Neurophysiology* **91**, 428–441.

Kotz, SA (2009) A critical review of ERP and fMRI evidence on L2 syntactic processing. *Brain and Language* **109**, 68–74.

Kroll, JF, Bobb, SC and Wodniecka, Z (2006) Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. *Bilingualism: Language and Cognition* **9**, 119–135.

Kroll, J.F, Gullifer, J and Rossi, E (2013) The multilingual lexicon: The cognitive and neural basis of lexical comprehension and production in two languages. *Annual Review of Applied Linguistics* **33**, 102–127.

Linck, JA, Osthus, P, Koeth, JT and Bunting, MF (2014) Working memory and second language comprehension and production: A meta-analysis. *Psychonomic Bulletin & Review* **21**, 861–83.

Lam, NHL, Schoffelen, J-M, Uddén, J, Hultén, A and Hagoort, P (2016) Neural activity during sentence processing as reflected in theta, alpha, beta and gamma oscillations. *NeuroImage* 1–12.

Levy, J, Hagoort, P and Démonet, JF (2014) A neuronal gamma oscillatory signature during morphological unification in the left occipitotemporal junction. *Human brain mapping* **35**, 5847–5860.

Lewis, AG and Bastiaansen, M (2015) A predictive coding framework for rapid neural dynamics during sentence-level language comprehension. *Cortex* **68**, 155–168.

Lewis, AG, Wang, L and Bastiaansen, M (2015) Fast oscillatory dynamics during language comprehension: Unification versus maintenance and prediction? *Brain and language* **148**, 51–63.

Lewis, AG, Lemhöfer, K, Schoffelen, JM and Schriefers, H (2016) Gender agreement violations modulate beta oscillatory dynamics during sentence comprehension: A comparison of second language learners and native speakers. *Neuropsychologia* **89**, 254–272.

Long, MH (1990) Maturational constraints on language development. *Studies in second language acquisition* **12**, 251–285.

Luck, SJ (2014) *An introduction to the event-related potential technique.* MIT press.

Luu, P and Tucker, DM (2001) Regulating action: Alternating activation of midline frontal and motor cortical networks. *Clinical Neurophysiology* **112**, 1295–1306.

MacDonald, MC and Christiansen, MH (2002) Reassessing working memory: comment on Just and Carpenter (1992) and Waters and Caplan (1996). *Psychological Review* **109**, 35–54.

MacWhinney B (2005) *A unified model of language acquisition.* In Kroll JF, de Groot AMB (eds), *Handbook of bilingualism: Psycholinguistic approaches.* Oxford: Oxford University Press; 2005. pp. 49–67.

Maris, E and Oostenveld, R (2007) Nonparametric statistical testing of EEG-and MEG-data. *Journal of neuroscience methods* **164**, 177–190.

McDonald, JL (2000) Grammaticality judgments in a second language: Influences of age of acquisition and native language. *Applied psycholinguistics* **21**, 395–423.

McLaughlin, J, Tanner, D, Pitkänen, I, Frenck-Mestre, C, Inoue, K, Valentine, G and Osterhout, L (2010) Brain potentials reveal discrete stages of L2 grammatical learning. *Language Learning* **60**, 123–150.

Meyer, L (2017) The neural oscillations of speech processing and language comprehension: state of the art and emerging mechanisms. *European Journal of Neuroscience* 1–13. https://doi.org/10.1111/ejn.13748

Moreno, EM, Rodrigues-Fornells, A and Laine, M (2008) Event-related potentials (ERPs) in the study of bilingual language processing. *Journal of Neurolinguistics* **21**, 477–508.

Morgan-Short, K, Sanz, C, Steinhauer, K and Ullman, MT (2010) Second language acquisition of gender agreement in explicit and implicit training conditions: An event-related potential study. *Language learning* **60**, 154–193.

Mouraux, A and Iannetti, GD (2008) Across-trial averaging of event-related EEG responses and beyond. *Magnetic resonance imaging* **26**, 1041–1054.

Strauß, A, Kotz, SA, Scharinger, M and Obleser, J (2014) Alpha and theta brain oscillations index dissociable processes in spoken word recognition. *NeuroImage* **97**, 387–395.

Nichols, ES and Joanisse, MF (2017) Individual differences predict ERP signatures of second language learning of novel grammatical rules. *Bilingualism: Language and Cognition* 1–15.

Oostenveld, R, Fries, P, Maris, E and Schoffelen, JM (2010) FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational intelligence and neuroscience* **2011**.

Osterhout, L and Holcomb, PJ (1992) Event-related brain potentials elicited by syntactic anomaly. *Journal of memory and language* **31**, 785–806.

Osterhout, L and Nicol, J (1999) On the distinctiveness, independence, and time course of the brain responses to syntactic and semantic anomalies. *Language and cognitive processes* **14**, 283–317.

Osterhout, L, McKinnon, R, Bersick, M and Corey, V (1996) On the language specificity of the brain response to syntactic anomalies: Is the syntactic positive shift a member of the P300 family? *Journal of Cognitive Neuroscience* **8**, 507–526.

Peelle, JE and Davis, MH (2012) Neural oscillations carry speech rhythm through to comprehension. *Frontiers in psychology* **3**, 320.

Proverbio, AM, Čok, B and Zani, A (2002) Electrophysiological measures of language processing in bilinguals. *Journal of Cognitive Neuroscience* **14**, 994–1017.

Prystauka, Y and Lewis, AG (2019) The power of neural oscillations to inform sentence comprehension: A linguistic perspective. *Language and Linguistics Compass* **13**, e12347.

Pulvermüller, F (1996) Hebb's concept of cell assemblies and the psychophysiology of word processing. *Psychophysiology* **33**, 317–333.

Pulvermüller, F (1999) Words in the brain's language. *Behavioral and Brain Sciences* **22**, 253–336.

Pulvermüller, F (2013) How neurons make meaning: brain mechanisms for embodied and abstract-symbolic semantics. *Trends in cognitive sciences* **17**, 458–470.

Pulvermüller, F, Garagnani, M and Wennekers, T (2014) Thinking in circuits: toward neurobiological explanation in cognitive neuroscience. *Biological Cybernetics* **108**, 573–593.

Rossi, E, Kroll, JF and Dussias, PE (2014) Clitic pronouns reveal the time course of processing gender and number in a second language. *Neuropsychologia* **62**, 11–25.

Rossi, E, Krass, K and Prystauka, Y (2020) *Neural underpinnings of grammatical processing for less proficient L2 learners*. Unpublished manuscript in preparation.

Sabourin, L and Stowe, LA (2008) Second language processing: when are first and second languages processed similarly? *Second Language Research* **24**, 397–430.

Sabourin, L, Stowe, LA and De Haan, GJ (2006) Transfer effects in learning a second language grammatical gender system. *Second Language Research* **22**, 1–29.

Sagarra, N and Herschensohn, J (2010) The role of proficiency and working memory in gender and number agreement processing in L1 and L2 Spanish. *Lingua* **120**, 2022–2039.

Strijkers, K (2016) A neural assembly based view on word production : The bilingual test case. *Language Learning* **66**, 92–131.

Swaab, T, Brown, C and Hagoort, P (1997) Spoken sentence comprehension in aphasia: Event-related potential evidence for a lexical integration deficit. *Journal of Cognitive Neuroscience* **9**, 39–66.

Tanner, D and Van Hell, JG (2014) ERPs reveal individual differences in morphosyntactic processing. *Neuropsychologia* **56**, 289–301.

Tokowicz, N and MacWhinney, B (2005) Implicit and explicit measures of sensitivity to violations in second language grammar: An event-related potential investigation. *Studies in second language acquisition* **27**, 173.

Tolentino, LC and Tokowicz, N (2011) Across languages, space, and time. *Studies in Second Language Acquisition* **33**, 91–125.

Ullman, MT (2001) The neural basis of lexicon and grammar in first and second language: the declarative/procedural model. *Bilingualism: Language and Cognition* **4**, 105–122.

Van Hell, JG and Tokowicz, N (2010) Event-related brain potentials and second language learning: Syntactic processing in late L2 learners at different L2 proficiency levels. *Second Language Research* **26**, 43–74.

Vos, SH, Gunter, TC, Kolk, HH and Mulder, G (2001) Working memory constraints on syntactic processing: An electrophysiological investigation. *Psychophysiology* **38**, 41–63.

Weber-Fox, CM and Neville, HJ (1996) Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of cognitive neuroscience* **8**, 231–256.

Weber, K and Lavric, A (2008) Syntactic anomaly elicits a lexico-semantic (N400) ERP effect in the second language but not the first. *Psychophysiology* **45**, 920–925.

Weiss, S and Mueller, HM (2012) "Too many betas do not spoil the broth": the role of beta brain oscillations in language processing. *Frontiers in psychology* **3**, 201.

Weiss, S and Mueller, HM (2003) The contribution of EEG coherence to the investigation of language. *Brain and language* **85**, 325–343.

White, L, Valenzuela, E, Kozlowska-Macgregor, M, Leung, YK (2004) Gender and number agreement in nonnative Spanish. *Applied Psycholinguistics* **25**, 105–133.