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Oscillatory brain responses to processing code-switches in the presence of others

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ABSTRACT

Code-switching, i.e. the alternation between languages in a conversation, is a typical, yet socially-constrained practice in bilingual communities. For instance, code-switching is permissible only when other conversation partners are fluent in both languages. Studying code-switching provides insight in the cognitive and neural mechanisms underlying language control, and their modulation by linguistic and non-linguistic factors. Using time–frequency representations, we analyzed brain oscillation changes in EEG data recorded in a prior study (Kaan et al., 2020). In this study, Spanish-English bilinguals read sentences with and without switches in the presence of a bilingual or monolingual partner. Consistent with prior studies, code-switches were associated with a power decrease in the lower beta band (15–18 Hz). In addition, code-switches were associated with a power decrease in the upper gamma band (40–50 Hz), but only when a bilingual partner was present, suggesting the semantic/pragmatic processing of code-switches differs depending on who is present.

1. Introduction

1.1. Code-switching

In many bilingual communities it is common to code-switch, that is, to change languages while speaking or writing, even mid-sentence. Code-switching is constrained both in terms of its structure and function: it cannot occur at random points in the sentence (Myers-Scotton, 1993; Myers-Scotton & Jake, 2017; Poplack, 1980), often serves a pragmatic function, and its use is socially constrained (e.g. Gumperz, 1982). Code-switching therefore requires a relatively high degree of proficiency in both languages, and an intricate regulation of linguistic and social monitoring and control. Studying code-switching from a cognitive neuroscience perspective therefore provides a window into mechanisms underlying (bilingual) language control and its relation to general cognitive and socio-cognitive processes.

Psycholinguistic and cognitive neuroscience studies on code-switching have typically found that the comprehension and production of code-switches is costly (Costa & Santesteban, 2004; Meuter & Allport, 1999), but that this cost is modulated by participant characteristics, such as proficiency and language dominance (Bultena et al., 2015; Kheder & Kaan, 2019; Litcofsky & Van Hell, 2017), code-switching habits (Beatty-Martínez & Dussias, 2017; Kheder & Kaan, 2016; Valdés Kroff et al., 2020), frequency of switching patterns in the language (Guzzardo Tamargo et al., 2016), and social cues (Blanco-Elorrieta & Pylkkänen, 2017; Kaan et al., 2020; Martin et al., 2016). This suggests that code-switching is not necessarily costly, yet that its processing depends on how felicitous it is in a given context.

Studies using EEG have provided further insight as to the subprocesses involved in processing code-switches, and how these can be modulated by factors such as the ones mentioned above. EEG can be analyzed in terms of event-related potentials (ERP). In these analyses, the EEG is time-locked to the onset of the switch word or its non-switch control. Several ERP components have been observed for switch versus non-switch control positions in sentences (see for overview Van Hell et al., 2015). One component that has been consistently found for switches versus non-switches is a late posterior positivity, often labeled LPC (Late Positive Complex). This component is larger for switches into the weaker than into the more dominant language (Litcofsky & Van Hell, 2017), larger for less proficient bilinguals (Ruigendijk et al., 2016), and larger when a monolingual is present in the context compared to a bilingual (Kaan et al., 2020). This component has been interpreted as reflecting either the unexpectedness of a language change or sentence level restructuring processes (Litcofsky & Van Hell, 2017). Other components found for code-switching are the N400

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(Fernandez et al., 2019; Moreno et al., 2002) reflecting lexical access or semantic integration difficulties, and an early positivity especially in those who are not habitual switchers (Beatty-Martínez & Dussias, 2017; Valdés Kroff et al., 2020) or in situations in which code-switching is not socially permitted (Kaan et al., 2020). This early positivity has been attributed to pro-active attention shifting to a previously inhibited language (Kaan et al., 2020).

1.2. Oscillations and language processing

ERP research thus far suggests that code-switching involves the interplay of lexical access, sentence-level restructuring and inhibition/attention shifting, all of which can be affected by linguistic and extra-linguistic factors. Nevertheless, ERPs are used to capture phase-locked or evoked activity (oscillations of the same frequency with aligned peaks and troughs, which "survive" across-trial EEG averaging), while some brain activity associated with code-switch processing may not be phase-locked. This non-phase-locked activity may not be visible in the (time-locked) ERPs (Tallon-Baudry & Bertrand, 1999) since oscillations of the same frequency with unaligned peaks and troughs are cancelled out or dampened by averaging across individual trials. Time-frequency analysis is a way to reveal both phase-locked and non-phase-locked oscillatory activity, and its results do not necessarily correspond to findings in the ERP analysis. To illustrate, Regel and colleagues (2014) found a P600 ERP effect for both syntactic and pragmatic (irony) violations. However, these types of violations were associated with different extents of power change in the theta band. Investigating time–frequency representations (TFR) can therefore further our understanding of processes involved in language comprehension.

Changes in oscillatory activity can be expressed in terms of changes of power in certain frequency bands. Power modulation, i.e. an increase or decrease in power, is assumed to reflect the extent of synchronization of neural activation in the underlying networks (Bastiaansen & Hagoort, 2006). Different frequency bands are hypothesized to be associated with different domain-general processes and different language processes (Başar et al., 2001; Bastiaansen & Hagoort, 2006; Meyer, 2018; Prystauka & Lewis, 2019).

In the realm of sentence-level processing, linguistic factors have been shown to affect power across frequency bands (see for reviews Meyer, 2018; Prystauka & Lewis, 2019). Nevertheless, many of the interpretations for linguistic effects rely on findings from nonlinguistic paradigms. Linking changes in TFR to linguistic processes is still tentative, and there is contradictory evidence as to which language processes are associated with synchronization at specific frequency bands (Lewis et al., 2015). Additionally, extralinguistic modulations related to attention and inhibition might be particularly relevant for the interpretation of our study results. Therefore, we provide an overview of oscillation studies focusing on linguistic processes, yet add non-linguistic processes where relevant.

Increases in theta band power (4–7 Hz) have been reported for words that are semantically anomalous or unexpected in context (Bastiaansen & Hagoort, 2015; Hagoort et al., 2004; Hald et al., 2006; Rommers et al., 2017). Theta band activation has therefore been associated with (effortful) lexical-semantic information retrieval (Bastiaansen et al., 2005; Hagoort et al., 2004; Hald et al., 2006) and/or with disconfirmation of strong semantic predictions (Rommers et al., 2017).

Increases in beta band power (often divided into lower beta, 15–18 Hz, and upper beta, 20–30 Hz, e.g. Litcofsky & Van Hell, 2017) have been strongly associated with the building and maintaining of sentence-level syntactic representation (Bastiaansen & Hagoort, 2015; Weiss & Mueller, 2012). Disruptions in sentence-level syntactic representation building by morpho-syntactic violations lead to a relative decrease in beta band power (Bastiaansen et al., 2010; Bastiaansen & Hagoort, 2015; Davidson & Indefrey, 2007; Pérez et al., 2012). Nevertheless, there is evidence for beta decreases with semantic violations in sentence and discourse context (Wang et al., 2012a, Lewis et al., 2017, Rommers et al., 2017) and recent proposals suggest that the beta band reflects more domain-general processes in maintaining emerging sentence-level meaning representations (Lewis & Bastiaansen, 2015, Lewis et al., 2015).

Alpha band power (8–12 Hz) has been generally associated with attentional state: alpha band power increases accompany inward attentional shift as opposed to attention turned to external stimuli (Boudewyn & Carter, 2018; Cooper et al., 2003). Alpha activity has also been linked to inhibition of task-irrelevant regions (Jensen & Mazaheri, 2010) or of irrelevant information or processes to improve task performance (Klimesch, 1999; Klimesch et al., 2007). Alpha band power increases have been observed with (verbal) working memory load and task-demand increases (Cooper et al., 2003; Jensen et al., 2002; Meyer, 2018). Alpha band power decreases may also reflect effortful semantic retrieval (Klimesch, 1999; Rommers et al., 2017), possibly using inhibition mechanisms to suppress more accessible semantic items. Alpha band decreases have also been found in connection to processing morpho-syntactic violations (Bastiaansen et al., 2010; Davidson & Indefrey, 2007). Alpha band power could thus reflect inhibition and attentional and working memory processes required for language processing.

In language processing paradigms, gamma band (30–100 Hz) synchronization or power increase has been related to regular, violation-free semantic unification of (highly expected) words (35–45 Hz, Hald et al., 2006; Lewis et al., 2015; 40–50 Hz, Wang, et al., 2012b). Relative gamma decreases, on the other hand, have been found to accompany semantic violations during sentence processing (~40 Hz, 70–80 Hz, Bastiaansen & Hagoort, 2015; Hald et al., 2006; Lewis et al., 2015), as well as syntactic violations (60–80 Hz, Bastiaansen et al., 2010; 40–60 Hz, Bastiaansen & Hagoort, 2015), possibly reflecting unexpectancy or the mismatch between the top-down predictions and the incoming linguistic input (Lewis & Bastiaansen, 2015).

In sum, oscillation studies on language processing suggest that theta and gamma bands are related to semantic processing. The beta band may be related to sentence-level syntactic unification, whereas the alpha band is likely reflecting attention and executive control processes recruited for language processing.

1.3. Prior studies on TFR and code-switching

Time-frequency analysis can help fine-tune our understanding of the processes underlying the comprehension of code-switching and the effects of linguistic and extralinguistic factors. To our knowledge, only two studies have reported TFR analyses related to intrasentential code-switching. Litcofsky and Van Hell (2017) presented Spanish-English bilinguals with sentences that were in English, Spanish, or contained a switch from Spanish to English or from English to Spanish. Based on the participant's individual language dominance, switches were classified as switches into the weaker language or switches into the dominant language. When comparing the effect of switching (switch minus non-switch) into the weaker versus the dominant language, the authors found a decrease in alpha band (8–12 Hz) power between 350 and 950 ms and a power decrease in the lower beta band (15–18 Hz) between 250 and 950 ms. The authors do not provide an explicit interpretation of the effects for the switch effect comparison. These could be connected to the switches into the weaker language being relatively less frequent and likely to cause more effortful semantic retrieval and sentence-level unification issues. When analyzing switches into the weaker and dominant languages separately, Litcofsky and Van Hell (2017) report an increase in theta band power (4–7 Hz) between 300 and 650 ms over right frontal and central sites for switches into the dominant language. They interpret this effect as reflecting difficulties with lexical semantic processing (Bastiaansen et al., 2005; Bastiaansen & Hagoort, 2015) and word-level inhibition (Liu et al., 2017) as the inhibition of the dominant language needs to be released. For switches into the weaker language, a decrease in lower beta band power (15–18 Hz) was found between 300 and 600 ms, over posterior and frontal sites. Litcofsky and Van Hell (2017) interpret this effect as reflecting more effortful sentence-level restructuring. In the ERPs, only switches into the weaker language elicited an LPC, suggesting a relation between lower beta band power and the LPC. No N400 component was observed for either switch direction.

Fernandez et al. (2019) used the same materials and participant population as Litcofsky and Van Hell (2017) except that the sentences were presented auditorily. The ERPs showed an N400 for switches regardless of whether the switch was into the weaker or into the dominant language. An LPC was found only for switches into the weaker language. TFR analysis yielded a decrease in upper beta band power (20–30 Hz, 600 to 800 ms, left frontal sites) for switches into the weaker language (in which both N400 and LPC were seen). Fernandez et al. (2019) relate this finding to the lower beta decrease found in their previous study and associate the decrease in the upper beta band power with a shift in the construction of sentence-level representations or with difficulties in syntactic unification. The TFR analysis for switches into the dominant language yielded an increase in alpha band power (8–12 Hz, 450 to 900 ms, central sites). The authors interpreted this as reflecting the additional cognitive effort required to lift the inhibition of the dominant language when a switch is heard.

In sum, the two TFR studies on code-switching yielded a decrease in beta band power, mostly for switches into the weaker language, suggesting a disruption of, or a change in, the building of a sentence-level representation, especially when the direction of the switch (dominant to weak) is not what is typically encountered in the bilingual's experience. In addition, increases in theta band power and alpha band power have been observed for switches from the weaker into the dominant language, possibly reflecting more effortful lexical semantic processing and increased cognitive effort to lift inhibition.

1.4. *The present study*

1.4.1. *Goals*

The present study aimed to further our insight into the cognitive mechanisms underlying code-switching by investigating brain oscillations using TFR. In particular, the goals of the present study were (1) to see if prior TFR findings to code-switches would generalize to other experimental contexts, using different materials, participants and analysis methods; (2) to see if social factors, in particular the presence of a bilingual or monolingual partner, have an effect on the changes in oscillatory activity to code-switches, as observed in the ERPs (Kaan et al. 2020). To this aim, we conducted a time–frequency analysis on the data obtained by Kaan et al. (2020).

1.4.2. *Kaan et al. (2020)*

In Kaan et al. (2020), habitually switching Spanish-English bilinguals read sentences that were either in English only (no switch) or switched from English to Spanish. In Experiment 1, participants read the sentences while being alone in the experiment booth; in Experiment 2, participants read the sentences with a person sitting next to them whom they knew was either an English monolingual or a Spanish-English bilingual.

Experiment 1 of Kaan et al. (2020) collected data from sixteen healthy early Spanish-English bilinguals (2 male, mean age 20.4 yrs [range 18–28], mean age of acquisition for English: 0.6 yrs [range 0–6]). Participants reported to be regular code-switchers (3.63 average frequency of code-switching use with 5 meaning "always" and 1 "never", [SD = 1.15]). Participants were recruited in Florida from a population of mostly heritage speakers of Spanish, meaning that they were predominantly English-dominant and likely spoke a Caribbean Spanish variety. Participants read 80 sentences that were English only, and 80 that contained code-switches from English to Spanish (materials were Latin-Squared). An example of a non-switch item is *The soccer player scored the winning goal in the last minute of the game.* An example of a switch item is *The soccer player scored the winning goal <u>en el último minuto del partido</u>* (same meaning). Switch items always continued in Spanish after the switch.[1] Given that most of the participants were English dominant, the switches were from the dominant to the weaker language. The switch was always at a frequent function word, to avoid potential differences in lexical and semantic characteristics across languages and different switch sites. The switch could occur between the 5th to 13th word in the sentence, making the code-switches unpredictable. Sentences were presented in pseudorandom order. Participants were instructed to read the sentences for comprehension. Comprehension questions followed 28% of the sentences. Sentences were presented word-by-word at a rate of 500 ms/ word (words presented for 300 ms separated by a 200 ms blank screen).

In Experiment 2, a separate group of participants from the same population read the same set of materials as in Experiment 1, but in the presence of a bilingual or monolingual partner. Kaan et al. (2020) collected data from 39 healthy young adult Spanish-English bilinguals and included 33 data sets in the main analysis (8 male, mean age 19.6 [18–28 range]; mean age of acquisition for Spanish 0.4 years [0–8 range]; mean age of acquisition for English 3.4 years [0–9 range], average frequency of code-switching use: 3.58 [SD = 0.94]).

The 160 items were Latin-squared in 4 lists to include 40 experimental sentences per condition for the 2 crossed variables: Switch status (Switch versus Non-switch) × Partner (Bilingual versus Monolingual). Participants read the sentences in two blocks. Half of the participants included in the analysis read the switch and non-switch sentences with a monolingual partner in the first block and bilingual partner in the second block, whereas the other half had the opposite order of partners. Monolingual and bilingual partners were trained confederates, recruited from the same population as the participants. Participants were acquainted with the confederates' language background through chatting before the beginning of the experiment and through a map task (see Kaan et al., 2020, for details). Monolingual confederates were instructed to mention they only speak English, whereas bilingual confederates were instructed to code-switch while talking to the participant during the map task and to mention they speak Spanish as well. Sentence presentation was similar to Experiment 1, except that each sentence was followed by a *meta*-probe question, asking both the participant and confederate whether they believed their partner understood the sentence, to measure participants' sensitivity to their partners' language background. Participants aware of their partners' background would respond "no" to this *meta*-probe if the sentence was switched and the partner was monolingual. As in Experiment 1, 28% of the sentences were followed by a comprehension question. The comprehension question was followed by another *meta*-probe, asking the participant and confederate whether they believed their partner gave the correct response to the comprehension question. The procedure also included a post-experiment debriefing session, during which participants were asked whether they believed each of their partners was a monolingual or a bilingual.

In both studies, EEG was recorded from 64 Ag/AgCl electrodes mounted on an elastic cap (ANT-Neuro Waveguard™), at a sampling rate of 512 Hz, relative to an average reference using an ANT Refa 78 amplifier (ANT-Neuro, Hengelo, Netherlands). Eye movements were recorded from electrodes placed on the outer canthi, and above and below the right eye. EEG data were analyzed for the first switch word and its non-switch control (*en /in* in the example above), for the following ERP components: early frontal positivity (200–300 ms after word onset, central-frontal electrodes), N400 (300–500 ms after word onset, central-medial electrodes), LAN (300–500 ms, left frontal

[1] We did not include Spanish-to-English switches out of practical considerations. Such a condition would have required a Spanish monolingual peer as a partner. Finding such peers would have been logistically difficult in a US college context, and it would have been hard to make our participants believe that their partner did not understand English.

electrodes), and LPC (500–900 ms, central-parietal electrodes). ERP results for Experiment 1 as reported in Kaan et al. (2020) showed an LPC for the onset of the code-switches versus non-switch control positions. No N400 or LAN switch effects were found. Additionally, there was an early frontal positivity for switches vs. non-switches. Experiment 2 involved assessing the effect of partner language background on the two components found to be connected to switches in Experiment 1. The analysis also accounted for the order of partners with a specific language background. The switch LPC was larger when the participant was paired with a monolingual compared to a bilingual partner, especially for those participants who were aware of their partner's language abilities (as indicated by them responding "no" most of the time as to whether their monolingual partner understood the sentences with code-switches). The LPC interaction effects were ascribed to revision and updating processes being more extensive in the monolingual partner condition as the switch effects were socially less expected. In addition, an early positive switch effect was found for those who started the task with a monolingual partner, suggesting that they proactively inhibited Spanish and needed to shift attention when encountering a shift from English to Spanish.

1.4.3. Expected TFR results

Based on Litcofsky and Van Hell (2017), Fernandez et al. (2019), and the hypothesis that beta band activation reflects the building or maintenance of sentence-level representations, we expected a decrease in the lower and/or upper beta band for switches versus no switches in both Experiments, especially since the switch was into the weaker language in both experiments. In Experiment 2 (with a partner), we expected participants to inhibit Spanish, and to expect code-switches to a lesser extent when they did the task with a monolingual than with a bilingual partner; the sentence-level restructuring after a code switch would be more difficult in the former case. Accordingly, we expected a larger decrease in lower-beta band power (sentence-level restructuring) for switches versus non-switches when the participant performed the task with a monolingual versus a bilingual. In addition, we expected a larger decrease in power in the alpha band and an increase in theta for switches when participants were paired with a monolingual partner, due to more effortful lexical-semantic processing and cognitive control necessary to lift inhibition when encountering the inhibited Spanish.

2. Experiment 1

2.1. Methods

2.1.1. Participants, materials and procedure

Please see section 1.4.2 and Kaan et al. (2020) for more details regarding participants, materials and procedure.

2.1.2. EEG preprocessing

We used EEGLab (Delorme & Makeig, 2004) in Matlab to conduct signal preprocessing. We referenced the signal off-line to the mean of the left and right mastoids and applied a band-pass filter between 0.01 and 55 Hz (IIR Butterworth filter, 12 dB/octave rolloff). We extracted epochs of 1000 ms prior to and 2000 ms after the onset of the critical word (onset of the switch or non-switch control position), with the −1000 ms to 0 ms pre-target time window as baseline.

After applying the band-pass filter and re-referencing, we used visual inspection to manually remove segments with particularly strong noise, e.g. due to sweat or muscle contractions. We conducted Independent Component Analysis (Bell & Sejnowski, 1995; Makeig et al., 1996) on epoched data and corrected eye-movement artifacts by removing components associated with vertical and horizontal eye-movements. Particularly noisy channels were subsequently interpolated using the spherical method in the pop_interp function in EEGLab (Delorme & Makeig, 2004). After interpolation, we rejected trials with the Fp1, Fpz, and Fp2 frontal electrodes containing peak to peak activity greater than 100 μV (within a moving window of 200 ms with a 100 ms step) and trials where electrodes other than EOG electrodes had an amplitude smaller than −100 μV or larger than 100 μV. This was to remove remaining artifacts due to body or eye movement, or channel noise. The preprocessing procedure resulted in an average of 72.1 non-switch trials (9.88% trial loss for the non-switch condition) and 71.8 switch trials (10.25% trial loss for the switch condition) per subject being included in the time–frequency analysis.

2.1.3. TFR analysis

The time–frequency analysis was conducted using the FieldTrip toolbox in Matlab (Oostenveld et al., 2011). We used the multitaper time–frequency transformation based on multiplication in the frequency domain with discrete prolate spheroidal sequences (DPSS) as tapers for calculating time–frequency representations. The frequency representations were calculated for 4 to 55 Hz in steps of 1 Hz, for the time points encompassing 1000 ms before to 1200 ms after the target onset, in steps of 10 ms. The time–frequency analysis was conducted in windows of 5 cycles per frequency on all channels except for the mastoid and electro-oculography channels. The ± 0.4 Hz frequency smoothing width was applied, such that the smoothing increased with frequency. TFR representations were computed for each trial and then averaged within each condition for each participant. The resulting TFR data was baselined using the decibel baselining method to control for the loss of power with increasing frequency (decibel $= 10*\log_{10}$(activity/baseline), i.e. logarithmic conversion of the activity and baseline ratio; Cohen, 2014) and the −350 to −100 ms window prior to the target onset as the baseline window. The baseline was chosen as a trade-off between the length of the baseline, closeness to the critical word onset, and the previous word onset.

We conducted the Monte Carlo permutation analysis using the clustering method to control for multiple comparisons (Maris & Oostenveld, 2007) on separate frequency bands: 4–7 Hz (theta); 8–12 Hz (alpha); 15–18 Hz (lower beta); 20–30 Hz (upper beta); 30–40 Hz (lower gamma); 40–50 Hz (upper gamma), following Litcofsky & Van Hell (2017). The frequencies within each band were averaged to increase the power of the statistical tests, rendering them to a single central frequency point in the band. The statistical analysis was done on the 100 ms to 1200 ms time window after the target word onset. Channel neighborhood was determined via triangulation. The clusters in the channel dimension were made up of at least 3 electrodes. The cluster statistic was the maximum cluster t-value using the two-tailed, dependent samples T-test with alpha set to 0.05. One thousand permutations were performed to obtain a distribution of cluster t-values in a random distribution. We then tested actual obtained maximum cluster t-values against this distribution with a two-tailed T-test with alpha $= 0.025$ as we were interested in both positive and negative clusters. Using these parameters, we tested whether there was a significant main effect of Switch (Switch versus Non-switch). The TFR data, scripts, and plots can be found in the associated Open Science Framework repository (https://osf.io/u5qc9).

2.2. Results

We found no switch effects in the theta, alpha, or gamma bands. We found a significant negative cluster in the lower beta band (15–18 Hz, $p = 0.02$), such that the switch caused a decrease in power compared to the non-switch. The cluster spanned the time-period from 398 ms to 639 ms and covered the frontal regions, mostly bilaterally, see Fig. 1A. We also found a significant negative cluster in the upper beta band (20–30 Hz, $p = 0.004$), such that there was a decrease in power associated with processing switches versus non-switches. The cluster spanned the time-period of 469 ms to 719 ms from the target word onset and started over the bilateral frontal area, before spreading medially and retracting to the right parieto-occipital region, see Fig. 1B.

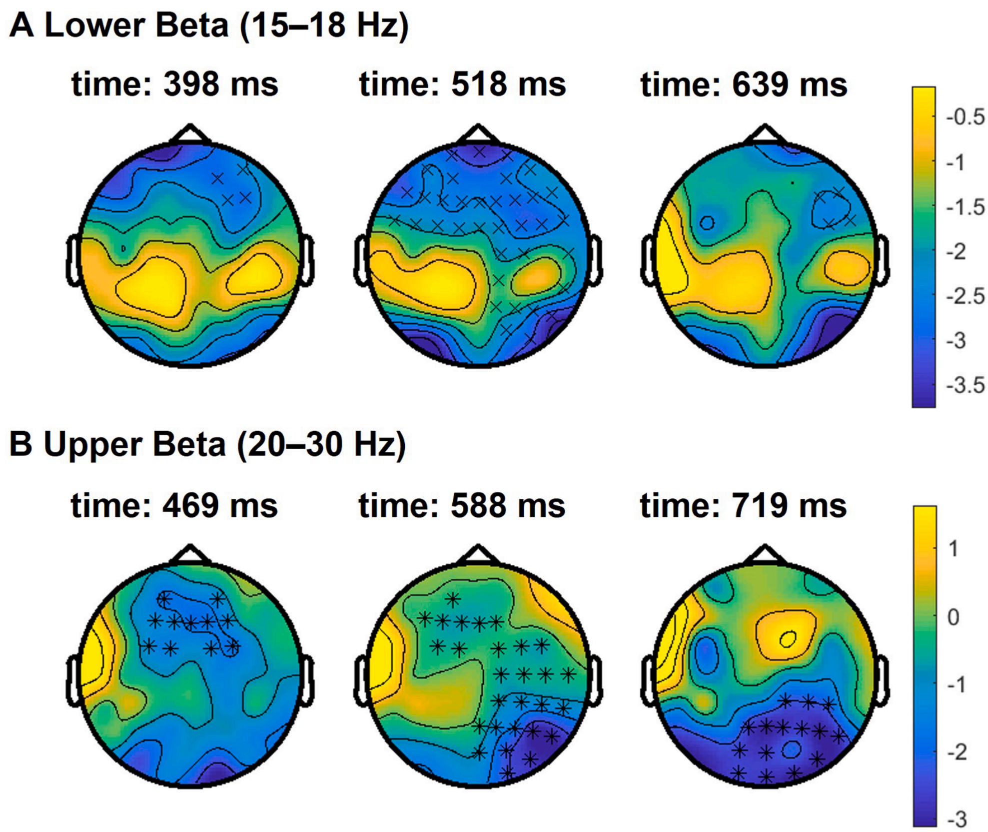

Fig. 1. A. First, middle, and last cluster subplot for the lower beta band (15–18 Hz), Experiment 1. B. First, mid, and last cluster subplot for the upper beta band (20–30 Hz), Experiment 1. The color bar represents channel-frequency-time sample t-values for the condition comparison in this and subsequent plots (here reflecting the *t*-test for the switch vs. non-switch condition). The × symbol marks the samples contributing to the clusters with cluster p-value < 0.025; the * symbol marks the clusters with cluster p-value < 0.01 in this and subsequent plots.

2.3. Discussion

Our results for the Switch effect in Experiment 1 replicate the TFR findings of previous auditory and visual studies on code-switching (Fernandez et al., 2019; Litcofsky & Van Hell, 2017). Our results include negative clusters in the lower and upper beta band comparable to clusters obtained in previous studies in association with the processing of dominant to weaker language code-switches and have been interpreted as indexing sentence-level reanalysis. We are careful not to attach significance to the spatial and temporal distribution of clusters (Maris & Oostenveld, 2007), yet the spatial and temporal distribution for the beta band clusters are remarkably similar despite many differences between our study and prior studies: lower beta band cluster with fronto-parietal distribution at ~ 300–600 ms in the present study and Litcofsky & Van Hell (2017); upper beta band cluster with fronto-parietal distribution at ~ 500–700 ms in the present study and with frontal distribution at ~ 600–800 ms in Fernandez et al. (2019). A decrease in beta band power is therefore a robust finding for code-switches, at least for the ones to the weaker language.

3. Experiment 2

3.1. Methods

3.1.1. Participants, materials and procedure

The study design depended on the participants' awareness of the partner background and the largest effect of partner type was obtained in Kaan et al. (2020) for those participants who were aware of their partner's language abilities (as indicated by them responding "no" most of the time as to whether their monolingual partner understood the sentences with code-switches). For the purpose of the TFR analysis, we therefore restricted the data to 24 participants (12 starting with a bilingual partner; 12 starting with a monolingual partner) who responded "no" to more than 40% of the questions of whether their monolingual partner understood the sentences with code-switches.[2] The data from 9 participants, who indicated they did not believe the monolingual partner understood code-switched sentences <30% of the time, was excluded. All participants included in the TFR analysis had the correct perception of their partners' respective language backgrounds, as confirmed by the debriefing session.

3.1.2. EEG preprocessing

The same procedure as in Experiment 1 was used to preprocess the EEG data from Experiment 2, yet with stricter artifact rejection criteria. After interpolation, the trials with Fp1, Fpz, and Fp2 frontal electrodes containing peak to peak activity greater than 60 μV (within a moving window of 200 ms with a 100 ms step) were rejected, as well as the trials where electrodes other than EOG electrodes had an amplitude smaller than −75 μV or larger than 75 μV. The preprocessing procedure resulted in an average of 63 non-switch trials (31 with a monolingual partner and 32 with a bilingual partner, 22.5% and 20% trial loss per condition, respectively) and 64.5 switch trials (32 with a monolingual partner and 32.5 with a bilingual partner, 20% and 18.75% trial loss per condition, respectively) being included in the Time-frequency analysis.

3.1.3. TFR analysis

Using the same analysis procedures and parameter settings as in the TFR analysis of Experiment 1, we tested whether there was a main effect

[2] ERP analyses for the 24 participants included in the TFR analysis are given in the supplementary materials to Kaan et al. (2020). In their main text, Kaan et al. (2020) reported the analysis on 21 participants who responded with "no" more than 50% of the time to the question of whether their monolingual partner understood the sentences with code-switches. ERP results for the analysis on 24 datasets did not differ from the analysis on the smaller data set. We selected the dataset of 24 for the TFR analysis so as to have an equal number in each of the two orders (monolingual or bilingual partner first).

of Partner (Bilingual versus Monolingual) and a main effect of Switch (Switch versus Non-switch). Additionally, we tested for a Switch × Partner interaction by comparing the switch minus non-switch differences in the monolingual vs. bilingual partner condition, to ascertain whether the processing of the code-switches differed depending on the type of Partner present.

3.2. Results

3.2.1. Switch main effect

The Switch main effect analysis yielded significant clusters in theta, alpha, upper beta and lower gamma bands. The theta band (4–7 Hz) showed a significant positive cluster ($p = 0.019$), such that the TFR in the switch condition showed an increase in power compared to the non-switches (see Fig. 2A). The cluster spanned the time period of 100 ms to 447 ms after the target onset and spread over the right hemisphere, to retreat to the right temporal region.

There was a broad significant negative cluster in the alpha band (8–12 Hz, $p = 0.002$), such that the TFR in the switch condition showed a decrease in power in this band relative to the non-switch condition. The cluster spanned all analyzed time points (~100 ms to 1200 ms). It started in the left fronto-temporal region, before spreading to left and right parieto-occipital regions, to ultimately spread to all but central electrodes (see Fig. 2B).

There was also a significant negative cluster in the upper beta band (20–30 Hz, $p = 0.003$), such that switches were accompanied by a decrease in power compared to non-switches. It spanned 787 ms to 1177 ms in the temporal dimension (Fig. 2C). Spatially, it started in the right parieto-occipital region, spread to medial and frontal electrodes, avoiding the temporal regions bilaterally, before retreating back to the right parieto-occipital region.

Finally, there was a significant negative cluster in the lower gamma band (30–40 Hz, $p = 0.006$), such that there was a decrease in power for switches compared to non-switches. The cluster started on central-medial electrodes spreading medially in both directions. It encompassed the time points from 799 ms to 979 ms (see Fig. 2D).

3.2.2. Partner main effect

The Partner main effect analysis yielded a positive cluster in the alpha band ($p = 0.012$), such that processing with a bilingual partner was associated with a relative increase in power compared to processing with a monolingual partner. The cluster started towards the mid point of analyzed time points and continued to the end (590–1200 ms). It started in the left fronto-temporal area, spreading to central and right fronto-temporal areas, then to left centro-parietal areas, before retreating to the left fronto-temporal area (see Fig. 3).

3.2.3. Switch × Partner interaction

The Switch × Partner interaction analysis yielded a significant positive cluster in the upper gamma frequency band (40–50 Hz, $p = 0.019$). The cluster occurred late in the analyzed time period (947–1049 ms). It started centrally to spread to medial electrodes towards the frontal and parietal areas and the left occipital area, before retreating to central electrodes (see Fig. 4A). Note that this positive cluster can be interpreted as a relative increase in power (for Switch versus Non-switch) for the monolingual partner conditions, and/or a relative decrease in power for the bilingual partner conditions. To resolve the interaction, we conducted a post-hoc analysis of the switch effect in the 40–50 Hz band for the monolingual partner and bilingual partner conditions separately. The analysis revealed no switch effect for the monolingual partner condition in the analyzed time and frequency span, but a significant negative cluster for the switch effect in the bilingual partner condition ($p = 0.007$, Fig. 4B) in the 908–1008 ms time period, over central sites, spreading to medial parietal and occipital areas. The Switch by Partner interaction was therefore driven by the negative switch effect (decrease in power for switch versus non-switch) for bilingual partners in the upper gamma frequency band.

3.3. Discussion

3.3.1. Summary of results

Experiment 2 tested whether code-switches would be processed differently in the presence of a bilingual or a monolingual. We expected participants to inhibit Spanish, and to expect code-switches to a lesser extent when they did the task with a monolingual than with a bilingual partner. We expected this to lead to a power decrease particularly in the beta band (sentence-level restructuring, unexpected continuations) for switches versus no switches when the participant performed the task with a monolingual rather than a bilingual. We also expected a decrease in power in the alpha band and increase in theta band power for switches when participants were paired with a monolingual partner, due to more effortful lexical-semantic unification when Spanish was not expected. To summarize our results, first, we observed switch effects. As in Experiment 1, TFR to switches showed a decrease in beta band power compared to non-switch control words, with similar spatial distribution as in Experiment 1 and in previous studies (fronto-parietal), albeit in a later time frame (~800–1200 ms) compared to Experiment 1 (~500–700) and previous studies (~600–800 ms in Fernandez et al., 2019) and only in higher beta frequencies, unlike Experiment 1. In addition, and unlike Experiment 1, TFRs to code-switches showed an increase in power in the theta band and decreases in power in the alpha and lower gamma bands. Second, we found a main effect of partner type: performing the task with a bilingual partner was associated with a relative increase in alpha band power regardless of whether there was a code-switch. Finally, we found an effect of the type of partner on the switch effect, but, unexpectedly, only in the upper gamma band: TFRs to code-switches showed a decrease of power in the upper gamma band only when a bilingual partner was present. We discuss these effects below.

3.3.2. Switch effects

Recall that in our study, code-switches were from the dominant language (English) into the weaker language (Spanish). In both Experiment 1 and 2 we found switches to be associated with a decrease in beta band power. Although there are some differences in the timing and location of the effects, our findings match those from Litcofsky & Van Hell (2017) and Fernandez et al. (2019), who also report decreases in lower and upper beta band power, respectively, for switches from the dominant to the weaker language. A relative decrease in beta band power has been associated with effortful semantic and syntactic unification when semantic and syntactic anomalies are encountered during sentence representation building (Bastiaansen & Hagoort, 2015; Rommers et al., 2017; Weiss & Mueller, 2012). The Switch effect results could thus be explained by the switch being more unexpected to participants, as well as representing more effort involved with unifying the switched words into the overall syntactic and semantic representation of the sentence.

In Experiment 2, TFRs to code-switches also showed a decrease in power in the alpha and gamma band, and an increase in theta band power. That we did not observe these effects in Experiment 1 may be due to differences in power (16 participants in Experiment 1, 24 in Experiment 2). In addition, participants may have been more engaged in Experiment 2 as somebody was sitting next to them in this study and they were probed about the other person's understanding.

Prior studies on code-switching have reported decreases in alpha and increases in theta band power as well (Litcofsky & Van Hell, 2017; Liu et al., 2017). Alpha band power decrease may reflect difficulties with semantic retrieval (Klimesch, 1999; Röhm et al., 2001). Alpha band power decreases have also been found along beta band power decreases in response to phrase structure syntactic violations (Davidson & Indefrey, 2007). Increases in theta band power have been associated with difficulties in lexical-semantic integration (Bastiaansen & Hagoort, 2015; Davidson & Indefrey, 2007; Rommers et al., 2017) and have been connected to the semantic N400 component (Davidson & Indefrey,

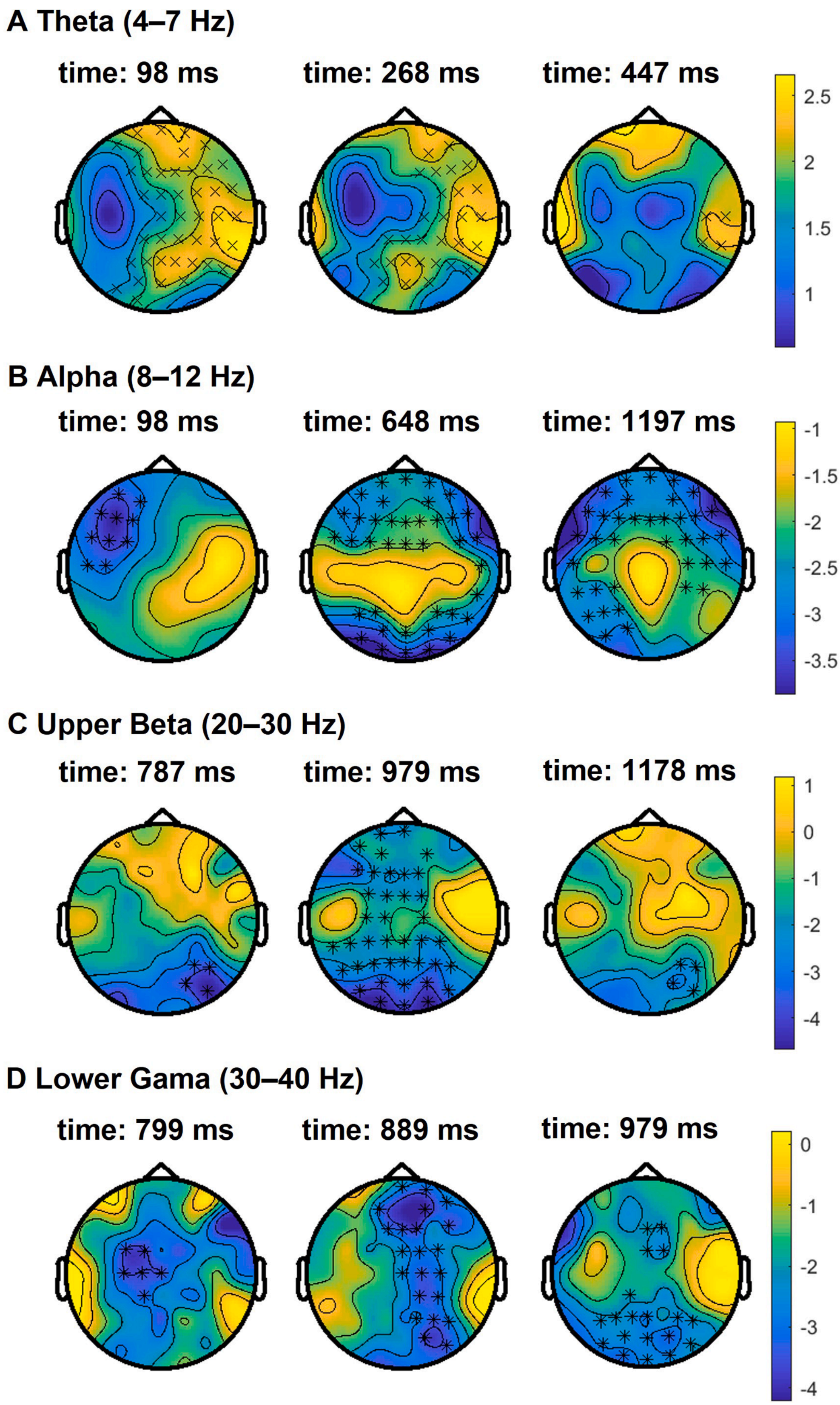

Fig. 2. A. First, middle, and last cluster subplot for the main switch effect in the theta band (4–7 Hz), Experiment 2. B. First, middle, and last cluster subplot for the main switch effect in the alpha band (8–12 Hz). C. First, middle, and last cluster subplot for the main switch effect in the upper beta band (20–30 Hz). D. First, middle, and last cluster subplot for the main switch effect in the lower gamma band (30–40 Hz).

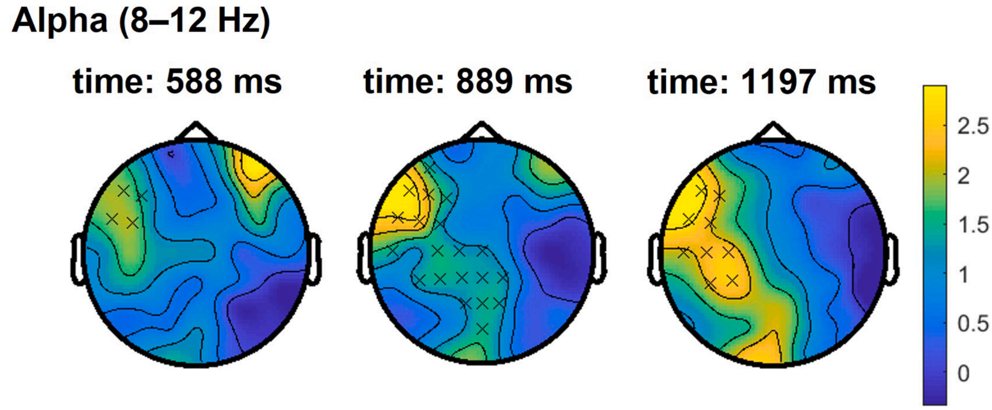

Fig. 3. First, middle, and last cluster subplot for the main partner effect in the alpha band (8–12 Hz), Experiment 2.

2007; Litcofsky & Van Hell, 2017), as well as inhibition of the dominant language when switching to the weaker language (Liu et al., 2017). Relative gamma band power decreases have been found in response to less predictable or semantically incongruent words as opposed to highly predictable words, as well (Wang et al., 2012b). Therefore, the decrease in alpha band and gamma band power and increase in theta band power can be interpreted as reflecting initial dominant language inhibition (Liu et al., 2017) and subsequent difficulty associated with lexical-semantic retrieval and integration after a switch to the non-dominant language (Litcofsky & Van Hell, 2017), even though code-switches were not observed to modulate the N400 component, related to semantic processing difficulties, in our study (Kaan et al., 2020) or in Litcofsky and Van Hell (2017).

The gamma band power decrease and theta band power increase are likely related to semantic integration difficulties despite the code-switch site always being a function word, due to several reasons. First, the last 700 ms of the analyzed time window pertain to the presentation of the second word in the code-switched segment, which was usually a content word. Additionally, TFRs are computed on the basis of a wide time window: TFR at a particular time point is based on what happens before and *after* this time point. Thus, despite the code-switched word being a function word with limited semantic content, effects found in the analyzed time window may also reflect semantic integration processes elicited by the following content word.

Taken together, the Switch main effect findings suggest that switches in our study (from the dominant into the weaker language) were unexpected and led to difficulty in unification at lexical-semantic and syntactic levels. We should note that for the Spanish-English bilinguals tested in our study, intra-sentential switching into English is more common than switching into Spanish (e.g. Blokzijl et al., 2017). In addition, switches occurred on a function word, which is less common than switches on nouns or verbs. These factors may have exacerbated

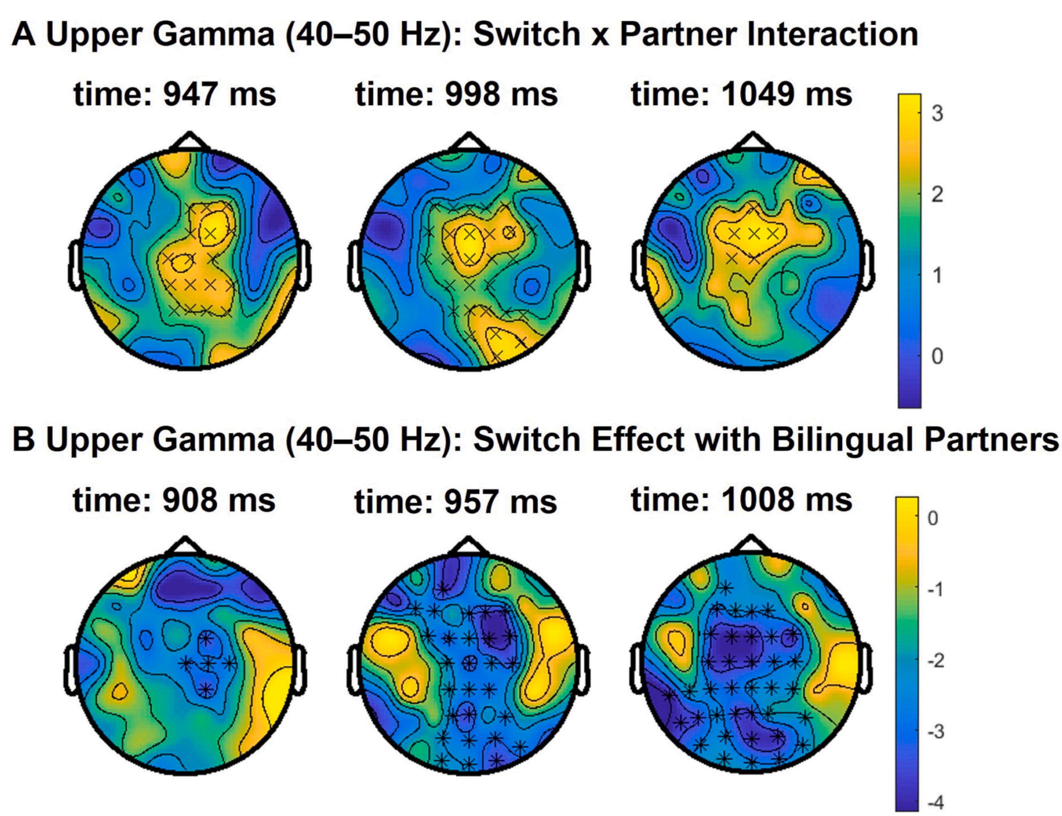

Fig. 4. A. First, middle, and last cluster subplot for the switch × partner interaction in the upper gamma band (40–50 Hz), Experiment 2. B. First, middle, and last cluster subplot for the main switch effect in the upper gamma band (40–50 Hz), Experiment 2, for bilingual partners only.

the syntactic and semantic unexpectancy of the switch and the resulting unification processes. Future studies should include both switch directions and participants of both dominance directions, while also manipulating the word class of the first code-switched word, to further specify the origin of these effects.

3.3.3. Partner effect

The bilinguals in our study showed an overall relative increase in alpha band power when performing the task with a bilingual compared to a monolingual partner, regardless of the occurrence of a switch. This effect was long lasting (roughly, 500–1200 ms after critical word onset) and was widely distributed over the scalp. Since we calculated power relative to a period preceding the critical word, we could interpret this effect as part of a general increase in alpha band power over the course of the sentence, with this increase being steeper when the task is performed with a bilingual than with a monolingual partner.

One interpretation of the increase in alpha band power for the bilingual partner condition is in terms of language control. Task-related alpha band power increases in certain brain regions, associated with inhibition in regions not necessary to perform the task (Klimesch et al., 2007), can lead to control of interfering processes or information and result in better task performance. Bilingual language use is believed to make use of the domain-general inhibition mechanisms more than monolingual language use, to dynamically inhibit and activate components of the two languages, maintain language goals, and resolve competition, causing an alpha increase in bilingual resting state EEG compared to monolinguals (Bice et al., 2020). Within bilingual language use, there are different bilingual contexts activating different language control processes (e.g. Green & Abutalebi, 2013; Green, 2018). For example, one language is reserved for one speaker in the same social context in dual language contexts (Green & Abutalebi, 2013; Green, 2018), requiring inhibition of the non-target language and competitive language control. In the code-switching context, e.g. when conversing with other bilinguals, both languages can be used, requiring dynamic activation/inhibition with cooperative language control. The bilingual code-switching context in the current study was activated prior to the task itself and continued to involve a potential for spontaneous mixed language use throughout the task, from the participant's perspective. This could have potentially resulted in steeper alpha increase over the course of the sentence or even task, reflecting preparedness for mixed language use, along with the potential increase in working memory load (Jensen & Mazaheri, 2010) due to the complete coactivation of the two languages at all linguistic levels, including pragmatics.

A second explanation for the increase in alpha band power for the bilingual partner condition is that there are differences in attention between the two partner conditions. In the case of mind wandering or inward attention, the alpha band power increase likely corresponds to the inhibition of processing external stimuli (Boudewyn & Carter, 2018; Cooper et al., 2003; Scheeringa et al., 2012). Thus, the broadly distributed increase in alpha band power when doing the task with a bilingual may have been related to the task and potential greater attention to the internal state in this context. Recall that participants had to indicate after each sentence whether their partner understood it. When completing the task with a monolingual, who could understand unilingual, but not code-switched sentences, one would have to pay more attention to external stimuli, the unfolding sentence, and take into account the state of mind outside of their own to correctly respond to that question. When completing the task with a bilingual partner, who can presumably understand both unilingual and code-switched sentences, participants may turn attention more inward and still maintain high task performance.

3.3.4. Switch by partner interaction

Contrary to our predictions, the TFR switch effects in the beta, alpha and theta gamma band were not affected by the presence of a monolingual and bilingual partner. This is opposed to the LPC effects in Kaan et al., which showed a larger switch effect in the monolingual than the bilingual partner conditions. We will further discuss the apparent discrepancy between the ERP and TFR effects in the General discussion. Instead, TFRs showed a decrease in gamma band power for switches versus non-switches between about 950 and 1050 ms over posterior sites, but only in the bilingual partner condition. The following explanations for this novel effect remain speculative.

As discussed in relation to the general switch effect, gamma band power decreases have been related to semantic unification disruptions (Hald et al., 2006; Lewis et al., 2015; Lewis & Bastiaansen, 2015), with similar central distribution as the effect we observed. The lack of a switch effect in gamma band power when processing a code-switch with monolinguals could indicate that the semantic unification of some aspects of code-switches does not occur in this language context. Code-switches are not a random occurrence and can have various socio-pragmatic meanings and functions in bilingual discourse (Auer, 1995; Gumperz, 1982). Among others, code-switching can have a signaling function due to its patterns of cooccurrence with other structures in natural discourse, e.g. it can signal upcoming unexpected or negative taboo emotional information (e.g. lower-frequency word "hinge" vs. high-frequency word "door", and e.g. negative taboo word "shit" vs. emotionally neutral word "room"; Myslín & Levy, 2015; Tomić & Valdés Kroff, 2021b). The current study design did not manipulate the lexical or affective content of the words following the code-switch. Nevertheless, bilinguals continue to rely on these code-switch signaling functions, leading them to more often predict lower-frequency words and more easily process negative taboo words after a code-switch, even in artificial experiment conditions (Tomić & Valdés Kroff, 2021a, 2021b). In the presence of a fellow bilingual, the signaling function of code-switches may have been amplified and these additional semantic-pragmatic aspects of code-switches may have become more relevant and meaning-laden compared to when a monolingual was present, leading to more effortful semantic-pragmatic integration. A related alternative explanation for the CS gamma decrease effect with bilinguals, supported by its latency, could stem from the fact that mostly highly frequent, emotionally neutral words followed the first code-switched word. This could have disconfirmed the semantic prediction that a low frequency or negative word should follow a code-switch and caused the associated gamma decrease, especially in the presence of a bilingual who had activated the code-switching language schema.

4. General discussion

The goals of the present study were (1) to see if prior TFR findings to code-switches would generalize to other experimental contexts, using different materials, populations and analyses; (2) to see if social factors, in particular the presence of a bilingual or monolingual partner, have an effect on the changes in oscillatory activity to code-switches, as observed in the ERPs (Kaan et al., 2020).

In spite of the differences in design and analysis methods between our and prior studies (Fernandez et al., 2019; Litcofsky & Van Hell, 2017), we replicated previous findings that TFRs to code-switches showed a decrease in power in the beta band (Experiment 1 and 2) and alpha band (Experiment 2), and an increase in theta band (Experiment 2). This suggests that the beta band power modulation in particular is a robust finding in relation to code-switches. The power band modulations we observed in response to code-switches suggest that encountering a code-switch in isolated sentences remains unexpected, leads to a disruption of current semantic and syntactic integration processes, and triggers updating and revision processes.

In addition, we found two novel effects. The presence of a bilingual versus monolingual modulated the power in the alpha band, suggesting more dynamic, cooperative language control activation in the presence of a bilingual, or increased inhibition of external stimuli when processing with a bilingual due to the task characteristics. Furthermore, the switch effect was modulated by the presence of a monolingual or bilingual in the gamma band power. Although our interpretation remains speculative, this finding supports the view that code-switching is socially constrained: when processing code-switches with another bilingual, certain semantic-pragmatic aspects of code-switching may be processed more deeply or differently.

We should point out that the TFR findings do not openly contradict or merely mirror the pattern found in the ERPs (Kaan et al., 2020). This is, among other reasons, due to the differences in what type of activity is measured, differences in preprocessing procedures, epoch lengths and spatial constraints, and differences in statistical analysis methods. ERPs and TFR can uncover different types of neural activation, and therefore need not show a one-to-one correspondence (Regel et al., 2014). First, in Kaan et al. (2020, and other studies, see section 1.1), code-switches elicited an LPC compared to their non-switch controls. One could propose a relation between the LPC and beta band power, since beta band power systematically decreases for code-switches (Litcofsky & Van Hell, 2017). However, this is not a full correspondence: whereas the LPC to switches was found to be modulated by the type of partner in Kaan et al. (2020), the switch effect in the beta band power was not. Instead, the gamma band showed a difference between the switch and non-switch condition when a longer epoch was examined, but only when a bilingual was present. Second, despite the theta band power having been related to the N400 component (Davidson & Indefrey, 2007; Schneider & Maguire, 2018), we found that the TFR to switches showed an increase in theta band power in Experiment 2, but the ERPs in Kaan et al. showed no N400 effects of code-switching. This could be explained by N400 being generally smaller on function words (e.g., Nobre & McCarthy, 1994), or undetectable for highly habitual vs. non-habitual code-switchers (Gosselin & Sabourin, 2021). Nevertheless, a complementary TFR effect in the form of the theta increase could have been captured due to the TFR sensitivity to non-phase-locked activity, due to the fact that the TFR analysis included a longer epoch (including effects elicited by the content word following our target function word), and the fact that TFR at a certain time point necessarily encompasses activation before and after this time point. Hence, the TFR does not directly follow the patterns observed in the ERPs, but its results yield complementary information. TFR analysis is therefore a useful method in addition to ERPs to investigate the mechanisms underlying language processing.

Our findings add to recent observations that language processing, including the processing of code-switches, is dynamic, and that language users continuously adjust their processing and expectation to match the current (social) situation, including what they know about those who are co-present (Beatty-Martínez & Dussias, 2017; Blanco-Elorrieta & Pylkkänen, 2017; Kapiley & Mishra, 2019; Martin et al., 2016). Cognitive models of bilingual comprehension and the comprehension of code-switches therefore need to take such factors into account and specify their workings. An example is the Adaptive Control hypothesis and Control Process Model (Green & Abutalebi, 2013; Green, 2018; Green & Wei, 2014, 2016). In these accounts, the type of language situation proactively modulates attentional language control, which determines what type of items and from which language can appear in the output buffer. For instance, in a dual-language situation in which a different language is used for different speakers in the same context, e.g. work, attention is narrowly focused on the language in use to reduce competition from the other, requiring competitive language control. In a code-switching situation, attention and language control are broader, requiring open language control, as the items from both languages are admitted to the output buffer and compete for slots in the sentence, depending on social and structural factors. Such a model can easily be extended to comprehension in which lexical/structural items are activated differently depending on the language and wider situation (see also Blanco-Elorrieta & Caramazza, 2021). The recurrence of specific interactional contexts could lead to neural adaptations to their specific control demands (Calabria et al., 2018). The alpha band power increase we have seen in the context with a bilingual partner, who used code-switching prior to the experiment and activated the code-switching context, could have been partly related to sustained open language control. Our results provide additional evidence that social context can exert top-down influence on language control and attention processes, likely in interaction with task demands. Moreover, the results suggest that the same wider social context can differently affect subprocesses involved in language processing. For instance, whereas we did not find evidence that the type of partner modulated the integration and updating processes during code-switch processing reflected by the beta band, it did affect the semantic processes indexed by the gamma band.

The fact that the partner language background modulated global attention and language processing points to shifting appropriate task-set configurations depending on the social situation. Bilingual experience might thus involve the unique pressure to encode and activate specific language background of collocutors, potentially causing increased demands to retrieve this information whenever they shift collocutors (Peeters, 2020). The current study adds evidence to different social situations and potential collocutors placing unique (language) control and processing demands on bilinguals. Switching collocutors associated with specific language control and attention profiles could thus be one more task shifting and information retrieval demand for bilinguals, in addition to shifting languages, and a potential source of executive control and attention exercise for bilinguals contributing to bilingual advantage in certain executive control tasks (e.g. Bialystok, 2017).

To our knowledge, the current study is the first investigating oscillatory brain activity to the processing of code-switches as a function of a socio-cognitive manipulation, namely the presumed language knowledge of those co-present. We are however careful in interpreting these results, since only 24 data sets were included in the analysis. We may therefore have lacked the power to detect some effects. In addition, the task we used is rather artificial in that bilinguals read isolated sentences and, in Experiment 2, made *meta*-judgements concerning other people's understanding. Future studies with structurally and directionally more common code-switches in a more interactive situation should be conducted to see to what extent our results generalize to more naturalistic situations and different dominance directions.

CRediT authorship contribution statement

Aleksandra Tomić: Formal analysis, Visualization, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **Edith Kaan:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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