Determinants of bilingualism predict dynamic changes in resting state EEG oscillations

Sergio Miguel Pereira Soares [a], Maki Kubota [b], Eleonora Rossi [c], Jason Rothman [b,d,*]

[a] *Department of Linguistics, University of Konstanz, Germany*
[b] *Department of Language and Culture, UiT The Arctic University of Norway, Norway*
[c] *Department of Linguistics, University of Florida, USA*
[d] *Centro de Ciencia Cognitiva, Universidad Antonio De Nebrija, Spain*

ABSTRACT

This study uses resting state EEG data from 103 bilinguals to understand how determinants of bilingualism may reshape the mind/brain. Participants completed the LSBQ, which quantifies language use and crucially the division of labor of dual-language use in diverse activities and settings over the lifespan. We hypothesized correlations between the degree of active bilingualism with power of neural oscillations in specific frequency bands. Moreover, we anticipated levels of mean coherence (connectivity between brain regions) to vary by degree of bilingual language experience. Results demonstrated effects of Age of L2/2L1 onset on *high beta* and *gamma* powers. Higher usage of the non-societal language at home and society modulated indices of functional connectivity in *theta*, *alpha* and *gamma* frequencies. Results add to the emerging literature on the neuromodulatory effects of bilingualism for rs-EEG, and are in line with claims that bilingualism effects are modulated by degree of engagement with dual-language experiential factors.

1. Introduction

Having more than one linguistic system in a single mind and, thus, managing the mental juggling of bilingualism—e.g., tension between activation, selection, and inhibition at many levels (e.g., Kroll et al., 2012)—requires some level of increased engagement of language control and domain-general executive functions (EFs). Although having knowledge of more than one language is a defining characteristic of bilingualism, it is dynamic. In other words, bilingualism is not a monolithic phenomenon. The label "bilingual" encompasses a considerable array of types of speakers, from simultaneous child acquirers in bilingual societies, to late adult second language learners in and outside of linguistic immersion, to minority (heritage) language speakers growing up in societal monolingualism and many more cases along a sizeable continuum. As a result, opportunities for engagement with experiences of bilingualism are not equal. Rather, they vary across a wide range of dimensions at aggregate and individual levels —e.g., age of onset, duration of bilingualism, intensity and degree of usage (in real and apparent time), (shifts) in linguistic dominance (over time), exposure to/training in literacy, variation in input (quantity and quality), social networks for language use, sociopolitical contexts (Surrain & Luk,

2019). Thus, it should come as no surprise that linguistic, social and/or neurocognitive outcomes of bilingualism display significant degrees of variation.

Although the relevant mechanisms underlying bilingual mind/brain adaptations are not yet fully understood, bilingualism has been shown to reshape the brain and modulate its ability to process information (e.g., Bialystok et al., 2012; Pereira Soares et al., 2019; see Pliatsikas, 2019 for review). While being bilingual is a necessary condition for relevant neurocognitive effects, it is clearly not a sufficient one. We know from recent work that variability in bilingual language experience is a good predictor for the existence, extent and degree of individual adaptation (DeLuca et al., 2019a; DeLuca, Segaert, Mazaheri, & Krott, 2020; Li, Legault, & Litcofsky, 2014; Pliatsikas, Moschopoulou, & Saddy, 2015). While cognitive effects, especially in executive functions behavioral performance, are not always attested (see Lehtonen et al., 2018; Nichols et al., 2020; Paap et al., 2015; Paap, 2016), several factors must be considered to understand their phantom-like appearance across studies (Bak, 2016; Bialystok, 2017; Leivada et al., 2021). While several (at least partially overlapping) factors are likely to contribute to the variability in result patterns (Grundy, 2020), one that has received particular attention in the past few years regards how bilingualism is defined,

---

operationalized and measured across studies (Luk & Bialystok, 2013; Surrain & Luk, 2019). Treating bilingualism as a binary variable, as has often been done in the literature, can lead to the washing out of dynamic factors, obscuring (the full picture of) what determinants of bilingualism lead to neurocognitive adaptations (Bialystok, 2016, 2017). Indeed, recent empirical work provides compelling evidence that a more nuanced approach to quantifying and qualifying bilingualism at the individual level matters a great deal. By situating individuals along a continuum of experiential variables and engagement with bilingual activity, data reveal the context-dependency of the social milieu of bilinguals to the opportunities individuals ultimately have for achieving mind/brain effects (DeLuca et al., 2019a; Gullifer & Titone, 2020; Luk & Bialystok, 2013; Sulpizio, Del Maschio, Del Mauro, Fedeli, & Abutalebi, 2020).

Couched within the growing literature seeking to unpack outcome variation across bilinguals themselves in the domain of neurocognition, the present study uses resting state EEG (henceforth rs-EEG) to investigate how bilingual experience affects underlying cognitive systems. In such an endeavor, variation in the pool of bilinguals considered is essential. Thus, the participants in the present study represent a set of diverse backgrounds with regards to various factors, including but not limited to type of bilingualism, age of onset, duration of bilingualism, intensity of engagement with language usage and geographical location. Differently from the more commonly used EEG technique of event related potentials (ERPs) associated with a specific task (linguistic or cognitive), rs-EEG measures the ongoing brain signal in a *task-free* context of wakeful rest. At the cellular level, rs-EEG represents the intrinsic synchronizing firing of neurons and, thus, the spontaneous, oscillatory, and endogenous functioning of the brain (Berger, 1929; Buzsáki et al., 2012). By recording the signal from the "resting" brain, we can extrapolate measures and information regarding the brain's intrinsic dynamics. Task and instruction free oscillatory brain activity has been linked to general neural functioning, that is, an indicator of the "readiness" of the neural system or a "signature" of an individual's neural functioning at any given point in time (Miall & Robertson, 2006; Raichle & Snyder, 2007; Raichle et al., 2001). Rs-EEG slowly shifts with increasing age, likely reflecting neural reorganization and cognitive development from infancy to young adulthood and aging (Anderson & Perone, 2018; Buzsaki, 2006; Doppelmayr et al., 2002; Klimesch, 1999). Importantly, however, it remains fairly stable over shorter periods of time (Anderson & Perone, 2018; Salinsky et al., 1991). As such, rs-EEG is likely to reflect past and more recent life experiences by modulating, maintaining and updating short and long-range brain pathways (Raichle & Snyder, 2007). In other words, the accumulating (mostly repeating) cognitively complex and engaging experiences during one's lifespan get intrinsically saved and imprinted in differential brain patterns. This allows one to be as ready as possible for present and future events. Rs-EEG (and MRI) has been widely used in the cognitive neuroscience literature to examine the potential role cognitive demanding life-style enrichment factors have on underlying cognitive/brain functioning in specialized groups such as athletes (e.g., Babiloni et al., 2010; Gong et al., 2019), musicians (e.g., Cantou et al., 2018; Kay et al., 2012) and meditators (e. g., Cahn & Polich, 2006; Xue et al., 2014) to name a few. However, only very recently has rs-EEG been applied to bilingualism, an interesting fact considering that half the world's population is at least to one type of bilingual (Bice et al., 2020). The present study adds new dimension to the nascent application of this method in our field by delving deeper into the role that individual level engagement with bilingual experiences has on the underlying readiness of the mind/brain.

A common way to analyze rs-EEG is to look at power differences in the frequency domains. The alpha rhythm (conventionally 8–12 Hz) is the dominant brain frequency and especially high over occipital electrodes (Berger, 1929; Buzsaki, 2006). Other brain rhythms include delta (0.5–4 Hz), theta (4–8 Hz), beta (12–30 Hz) and gamma (30–50 Hz) (Buzsaki, 2006). In general, low oscillation frequencies are associated with long-distance communication in the brain, whereas higher

frequencies are typically used for local processing (Von Stein & Sarnthein, 2000). Furthermore, the different EEG frequency bands (especially the most studied alpha and beta oscillations) have been linked to differential mechanisms that sustain relevant cognitive systems, such as working memory (Miller et al., 2018), inhibition/cognitive control (Jensen & Mazaheri, 2010; Klimesch et al., 2007; Strauss et al., 2014) and language processing (Bastiaansen & Hagoort, 2006; Bornkessel et al., 2004; Giraud & Poeppel, 2012) among others. These processes reorganize and modulate peak timing within and between different neuronal networks by linking and coordinating information that unfolds over time (Buzsaki, 2006).

Indeed, resting state measures within the neurocognitive study of bilingualism is not new, however, the vast majority of studies have been done using the MRI technique. Thus, the focus has been on where in the brain changes can be observed. The main question therein has been if the effects seen on the brain, specifically on domain general cognitive control, also show up in the absence of a specific task. A considerable amount of resting state literature has suggested that bilingualism permanently shifts underlying brain mechanisms, leading to long-term structural and functional changes (e.g., Berken et al., 2016; Grady et al., 2015; Gullifer et al., 2018; Luk et al., 2011; Sun et al., 2019; Yamasaki et al., 2018). This suggests that life experiences, such as bilingualism, can ultimately induce brain changes, which stretch beyond the ones observed directly in the lab while participants perform a specific task. For instance, volumetric changes, spatial distribution and functional connectivity, the most studied measures within resting state fMRI, are amenable to bilingualism, at least under certain conditions (e. g., Berken et al., 2016; Gullifer et al., 2018; Li et al., 2015; Sun et al., 2019). Although MRI resting state neural indices appear to be stable across time, they "only" provide information on which parts of the brain are modulated due to dual-language experience. Rs-EEG, therefore, complements rs-MRI by overcoming its issues of low temporal granularity. It also permits a better understanding of how and the extent to which past life linguistic experiences may modulate brain intrinsic mechanisms as well as which variables are implicated in the regulation of bilingual language control networks themselves. Differently from MRI, portable EEG systems facilitate more ecological testing to take place in different immersive environments, which in turn allow for higher cross population comparability, larger scaled multi-comparative studies and, in principle, foster greater access for underrepresented populations in empirical research. This is not a trivial point, as greater variability in data samples and increased representation across the board associated with a fine-grained brain methodology could give rise to new opportunities in the field of bilingualism research and (dis) confirm hypotheses based on limited data or non-representative groups (Luk et al., 2021). And so, within this context, rs-EEG has the potential to examine similar questions from a different perspective and with the breath of a relatively novel (to the field) methodology.

In the first study of its kind, Prat et al. (2016) were interested in how rs-EEG measures would predict language learning rate during an immersive French-training paradigm by means of a computerized learning environment. RS-EEG was recorded before the onset of the training and correlated to the learning outcomes. The findings revealed positive correlations between low (13–14.5 Hz) and mid-beta (15–17.5 Hz) rs-EEG frequencies over right temporoparietal regions and learning outcomes, explaining up to 60% of the learning variability. The results highlight the utility and advantages of using rs-EEG to study individual differences in new language learning in a construct-free paradigm. More recently, Prat et al. (2019) replicated and extended their previous findings in a larger sample of adult participants who were exposed to an 8-week French instruction through a virtual language and cultural immersion software. Their results showed that higher beta power recorded over the right hemisphere and coherence (functional connectivity) between right frontotemporal sites across all frequencies predicted posttest declarative memory retention and more variance in speech during learning. These two studies represent milestones, underscoring the

utility of rs-EEG. However, they cannot tell us (nor did they intend to address) the full applicability of rs-EEG in bilingualism studies, for example, the extent to which differences can be predicted by the life experience that is bilingualism. A first crucial step in this direction comes from Bice et al. (2020). The authors investigated if and how the demands of being bilingual has an impact on brain functioning. They recorded rs-EEG eyes-closed data from 106 bilinguals and 91 monolinguals. Findings revealed greater alpha power and coherence in the alpha and beta frequency ranges in bilinguals. Follow-up analyses showed that alpha frequency positively correlated with more second-language use, higher native-language proficiency, and earlier age of second-language acquisition. On the other hand, beta power was correlated to L1 proficiency bilaterally and theta power only in the left hemisphere. All in all, these results showed for the first time using rs-EEG that the linguistic and cognitive demands of bilingual language use reshape intrinsic brain activity.

Building on the insights from Bice et al. (2020), the present study brings together data from a large sample of bilinguals with diverse backgrounds to address the general question of whether bilingualism can have a significant impact on intrinsic brain processes measured via rs-EEG. Our focus, however, is not on any potential monolingual versus bilingual distinction, but rather seeks to understand differences across bilinguals of distinct types and intensity of engagement with potential determinants of bilingual effects on the brain. Recall that previous research has highlighted how brain power frequencies (mostly alpha and beta) are differentially involved in top-down control mechanisms. Specifically, they have been linked to general processes of cognitive control, inhibition and language processing, including bilingualism. Following this, we are interested in individual differences in various aspects of bilingual language experiences, both static (proficiency in the societal language, Age of L2 or 2L1 onset (AoA), and Length of exposure to the non-societal language) and active ones related to usage patterns (e.g., non-societal language exposure and use at home, non-societal language use in the society or community). In view of the small rs-EEG literature in bilingualism and the considerable emerging literature showing bilingual engagement differentially affecting mind/brain outcomes, we hypothesize to find positive correlations between linguistic variables and frequency bands (especially alpha and beta power), particularly reflected in posterior brain regions, and/or levels of mean coherence between brain regions to vary commensurable with language experience variables.

2. Methods

2.1. Participant's background information

Data was initially collected from 123 participants: 3 were excluded due to bad electrodes while recording, 2 due to high levels of skin artifacts, 8 due to bad post-processing signal and 7 were excluded due to missing background (LSBQ) information. This resulted in a total of 103 bilingual participants (Mean Age = 28.34, SD = 12.34; Female = 74), of which 55 were collected in Germany and 48 in Norway. Out of 55 participants in Germany, 25 were early bilinguals (Italian was the home (heritage) language). The remaining participants, 78 were late(r) second language (L2) bilinguals, residents in Germany (N = 30) and in Norway (N = 48). The participants in Norway all spoke Norwegian as their L1 and English as their L2 (with the exception of 2 participants who had Swedish and Spanish as their L2). The late bilinguals in Germany spoke German as their L1 and English as their L2 (the cut-off to be considered late bilinguals was set at least 6 years of age) and the early bilinguals had Italian as their L1 and either simultaneously acquired German as their second L1 (2L1) or acquired German at a very young age, always below the age of 4 (see Meisel, 2011). The age to first exposure to the L2/2L1 varied considerably within our participants (Mean = 6.25; SD = 3.58). Although it was the case that the majority of individuals were first exposed to the other language at a noticeably early age, this does not

mean that important variation afforded by context of an individual's bilingualism is washed out (as will be clear below). Given the ubiquity of the L2, English, timing of first exposure can be a bit misleading. While first exposure to a language like English can be universally low in the European context, this does not mean that quantity, quality and intensity of exposure and use is the same at such an early age across the board. Moreover, the context of heritage bilingualism brings with it important consequences for engagement and exposure, not least as the minority language is a native one that is naturalistically acquired and used in specific contexts despite the fact it is typically not the dominant language of the heritage bilingual in adulthood (e.g., Kupisch & Rothman, 2018; Polinsky, 2018; Rothman, 2009). On average, the participants were exposed to the L2/2L1 for 22.33 years (SD = 11.94). The participants' Socio-Economic Status (SES) was coded from 0 to 4 based on their mother's final education (0 = lower than a high school diploma, 4 = postgraduate degree). The participants' mean SES was 1.59 (SD = 1.42).

All participants completed the Language and Social Background Questionnaire (LSBQ) (Anderson et al., 2018), which documents the participant's language(s) exposure and use from early childhood to the present day in a variety of activities and settings. The LSBQ permits the computation of three factor scores: language use in the home environment (Home), language use in social contexts (Social), and language proficiency in the societal majority language (Proficiency). These are weighted aggregate scores which are derived from a set of relevant questions within the LSBQ. For Home and Social factors, a higher score indicates more engagement in the non-societal language (Italian or English) and a lower score indicates more use and exposure with the societal language in a given context. As for the Proficiency factor, higher scores suggest higher proficiency in the societal majority language. These three factor scores, in addition to age of onset to the non-societal language (AoA) and length of exposure to the non-societal language (LoE) were used for further analyses in predicting rs-EEG data. We observed a mean score of 0.05 for Social (SD = 11.36), a mean score of 14.88 for Home (SD = 10.51), and a mean score of −0.91 (SD = 5.51) for Proficiency (individual demographic data is represented in the Supplementary Table 1 in the Supplementary Materials).

2.2. Study procedure

All participants volunteered and provided informed consent to take part in the study and all procedures were approved by the ethical commission of the University of Konstanz and the Norwegian Center for Research Data (NSD). All procedures followed the same protocol and were done with the same EEG equipment in both countries. Data was collected either in a quiet room in a designated lab (University of Konstanz, Heinrich Heine University Düsseldorf, University of Cologne or UiT The Arctic University of Norway) or in a quiet room in a household (mostly in Konstanz, Cologne and Düsseldorf). This was possible because we employed a portable EEG system with active shielded electrodes (see below for more details). First, participants completed the LSBQ. Afterwards, the EEG set was fit and recoding proceeded. Five minutes of task-free eyes closed EEG data was recorded while the participants were sitting in a quiet room facing a computer screen with a blank display.

2.3. Resting state EEG data acquisition and processing

EEGs were continuously recorded from 32 Ag/AgCl scalp electrodes (LiveAmp32, Brain Products, Inc) and placed in an elastic cap in accordance with the 10–20 system. AFz acted as the ground electrode and FCz as online reference. Fp1 and Fp2, located on the forehead above the eyebrows, were employed to detect and monitor eyes movements and blinks. Impedances were kept below 25 kΩs. Signals were amplified using a Brain Vision LiveAmp amplifier continuously digitized at a 1000 Hz sampling rate. Offline processing of the data was done in a two-step manner. First, in Brain Vision Analyzer 2.0 (Brain Products, Inc), data

was downsampled to 128 Hz, re-referenced to the average of both mastoids (TP9 and TP10) and band-pass filtered from 0.1 to 45 Hz[1]. Horizontal eye movements and blinks were detected using the automatic independent component analyses (ICA) implemented in BVA. ICA was performed on the whole dataset with 512 steps and an infomax (Gradient) restricted algorithm.

Data was then exported in an R environment friendly format and fed to the publicly-available script on Github developed by Prat et al. (2016) in the Cognition and Cortical Dynamics Laboratory at the University of Washington (available online on https://github.com/UWCCDL/QEEG). In order to do so, the script was previously modified to accommodate the channel information from the LiveAmp32 system (i.e., different channel names and greater number of channels). A 2s sliding window with 50% overlap between segments was used to split each participant's data. Segments containing artifacts, defined by having more than 3 standard deviations from the average of the channel's activity, were excluded. A fast Fourier transform was applied on the data to decompose the signal into the frequency domain. Afterwards, the signals were averaged together. Log power measures at each frequency (see below) for each participant and electrode and the correlation of activity between electrodes in different scalp regions (i.e., coherence) were the measures used for further steps in the analysis.

The individual frequency bands method was used to calculate the boundaries between different frequency powers (see Bice et al. (2020) for the same approach in bilingualism). In summary, frequency bands were not fixed (frequently used measures are delta: 0–4 Hz, theta: 4–8 Hz, alpha: 8–12 Hz, beta: 12–30 Hz, and gamma: 30+ Hz) but adjusted to each person's individual alpha frequency (IAF; Klimesch, 1997). The IAF is the frequency where the brain spectrum peaks. It is predominantly between 8 and 14 Hz and stronger over occipital electrodes while measuring eyes-closed EEG. Once the IAF is calculated, the values for the frequency bands can be derived (delta was defined from 0 Hz to −6 Hz below the IAF, theta from −6 to below −2, alpha from −2 to plus 2, low beta from +2 to +10, high beta from +10 to +20, and gamma as anything equal or greater than 20 Hz above the IAF). These individualized frequency bands were used for all subsequent analysis of power and coherence. The process of identifying the IAF at the participant's level included several exclusion steps. First, any channels with unusually high or low activity in the frequency spectrum (bad channels) were removed. To do this, the log power within 1–40 Hz was averaged across all channels within each subject and then all channels with an average log power of ±2.5 standard deviations to the average of all channels were excluded. This resulted in the exclusion of 30 channels (0.79% of all data). Channels identified as bad through this process were excluded from all subsequent analysis (IAF, average power and coherence). Second, channels that did not show an alpha peak were also excluded from the IAF calculation. An increase of 0.2 $\log(mV^2)$ or higher within the frequency range 7.5–14 Hz was considered to be the sign of an alpha peak. A total number of 205 channels lacked an alpha peak (5.4% of all data). Different from the bad channels situation, the channels without an alpha peak were only removed for the estimation of the IAF but included afterwards for both the average power and coherence analysis, given that they did not show any abnormal deviations in relation to the averaged log power (see previous calculation). Finally, to allow more reliable and stable measures of power and coherence, all participants who had fewer than 80% of channels remaining (less than 24 channels) after the first two exclusion criteria were additionally removed from all subsequent calculations (8 participants, 7.77% of the total). Generally speaking, the majority of these participants were excluded because of a lack of detectable alpha peak in several electrodes and not due to a bad spectrum, which speaks to good quality of the data.

Data yielded from individual channels and frequency bands were grouped and averaged into 5 brain regions of interest: medial frontal (Fp1, Fp2, F3, F4, Fz, FC1, FC2), left/right fronto-temporal (F7, FC5, T7, FT9, C3 and right hemisphere homologues) and left/right posterior (P7, O1, P3, CP5, CP1 and right hemisphere homologues).

3. Results

3.1. The relationship between language background and power frequency

In order to examine whether the magnitude of power is modulated by dual-language experience, we first ran multiple regression analyses for each rs-EEG frequency bands: IAF, alpha, theta, low beta, high beta, and gamma (delta frequency was excluded from the analysis because of the low reliability due to the application of a 1 Hz low cut-off filter in participants with extensive sweating). All models had the same bilingual experience predictors: non-societal language exposure and use at home (Home), non-societal language use in the society or community (Social), proficiency in the societal language (Proficiency), Age of L2 or 2L1 onset (AoA), and Length of exposure to the non-societal language (LoE). Age at the time of testing was not included as a covariate in the models, since it highly correlated with LoE ($r = 0.96$, $p < 0.001$; See Table 1 for all correlations among continuous variables). We also included Sex (male or female), SES, and Location (Germany or Norway) as covariates. All continuous variables included in the model were centered around the mean. Treatment coding was applied to categorical variables.

The output of the regression models is summarized in Table 2. The only significant language background-related factor that predicted power was Age of L2/2L1 onset for high beta ($E = -0.18$, CI = -0.34 to -0.02, $p = 0.03$) and gamma ($E = -0.18$, CI = -0.34 to -0.02, $p = 0.03$). As illustrated in Figs. 1 and 2, the earlier the age of L2/2L1 onset was, the higher the powers were for high beta and gamma. No variables significantly predicted theta (p's < 0.15) or alpha (p's < 0.13) power. In terms of low beta, female participants had higher power than male participants ($E = -0.40$, CI = $-0.0.63$ to -0.16, $p = 0.001$). Moreover, participants in Norway had significantly lower IAF power than the participants in Germany ($E = -0.72$, CI = -1.30 to -0.15, $p = 0.015$).

3.2. The relationship between language background and power frequency among brain regions

The above analysis reveals that Age of L2/2L1 exposure (AoA)—essentially the timing of the onset of bilingualism—predicted high beta and gamma frequency power. That is, the earlier the speakers became bilingual, the higher their high beta and gamma powers were. In light of this finding, we were interested in examining whether these relationships are modulated across various brain regions of interest. In order to do so, we performed two linear mixed effects models with high beta and gamma powers as dependent variables, and five brain regions of interest (medial frontal (MR), left fronto-temporal (LF), right fronto-temporal (RF), left posterior (LP), and right posterior (RP)) and AoA as fixed factors, as well as the interactions between Brain Regions and AoA. Subject was included as a random intercept. Sum coding was applied to the Brain Regions variable, and AoA was centered around the mean. We performed mixed model ANOVA tables via likelihood ratio test using the afex package (Singmann et al., 2015) on the output of lmer models. If there are no significant interactions between Brain Region and AoA, then this indicates that the predictive power of AoA on high beta and gamma powers does not differ across different brain regions.

The output of the linear mixed effect model is summarized in Table 3. There were no significant interactions between AoA and Brain Region for both high beta (p's > 0.19) and gamma (p's > 0.36). This indicates that the relationships between power and AoA for high beta (Fig. 3) and gamma (Fig. 4) do not differ across distinct brain regions. In other words, the effect is broadly distributed.

---

[1] For 11 participants a low cut-off of 1 Hz (instead of 0.1Hz) was employed in order to filter out unwanted skin sweating artifacts.

Table 1
Correlation between predictor variables.

	Home	Social	Prof	AoA	SES	Age	LoE
Home		–	–	–	–	–	–
Social	0.218*		–	–	–	–	–
Prof	0.102	−0.235*		–	–	–	–
AoA	−0.693***	−0.096	−0.042		–	–	–
SES	−0.277**	0.169	−0.160	0.002		–	–
Age	−0.211*	−0.158	−0.033	0.303**	−0.182		–
LoE	−0.018	−0.138	−0.022	0.025	−0.191	0.960***	

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

3.3. The relationship between language experience and coherence

Finally, in order to examine the effects of bilingual experience on the functional connectivity between brain regions, we ran a linear mixed effects model with frequency band coherence (theta, alpha, low beta, high beta, and gamma) as a dependent variable and Home, Social, AoA, LoE, and brain region pairings (LFT & LP, LFT & MF, LFT & RFT, LFT & RP, LP & MF, LP & RFT, LP & RP, MF & RFT, MF & RP, and RFT & RP) as predictors as well as the interactions between each language background predictor and brain region pairings. We also included Sex, SES, and Location (Germany or Norway) as covariates. Subject was included as a random intercept. Sum coding was applied to the categorial variables, and continuous variables were centered around the mean. We performed mixed model ANOVA tables via likelihood ratio test using the afex package (Singmann et al., 2015) on the output of lmer models. In this analysis, we were particularly interested in examining the interactions between each language background predictor and brain region pairings. Significant interactions between these two variables indicate that coherence between specific electrode region pairing(s) is modulated by bilingual language experience. The output of the linear mixed effects model is summarized in the Supplementary material. Fig. 5 illustrates coherence maps showing connections between brain region pairings which were significantly modulated by various predictor variables.

3.3.1. Theta

There was a main effect of *Social* use scores on coherence in theta ($E = 0.01$, CI = 0.00–0.01, $p = 0.022$). This suggests that the connections among all brain regions were modulated by *Social use* scores—the more non-societal language the participants used outside the home, the stronger the connections were among brain regions (Fig. 6). Moreover, there was a significant interaction between Brain Region and *Social use* scores, indicating that coherence between LFT and RFT ($E = 0.01$, CI = 0.00–0.01, $p = 0.034$), LP and RP ($E = −0.01$, CI = −0.01 to −0.00, $p = 0.005$), as well as MF and RFT ($E = 0.01$, CI = 0.01–0.02, $p < 0.001$) were modulated by *Social use* scores to a greater extent than other brain region pairings. It should be noted however, that the relationship between LP and RP coherence and *Social use* scores was weaker than the other brain region pairings, as can be seen by the negative estimate value. There was also a significant interaction between Brain Region and Proficiency ($E = 0.01$, CI = 0.00–0.01, $p = 0.002$), which suggests that coherence between LFT and RFT was modulated by *Proficiency* in the societal language. We then ran simple correlations between the coherence of the aforementioned brain region pairings and the two predictors (i.e., *Social scores* and *Proficiency*). The only significant correlation was found between MF and RFT coherence and *Social use* scores ($r = 0.28$, $p = 0.006$).

3.3.2. Alpha

No main effect of predictors or covariates were found for coherence in alpha. However, there was a significant interaction between Brain Region and *Social use* scores, and the output shows that coherence

between MF and RFT was modulated by *Social use* scores to a greater extent than other brain region pairings ($E = 0.01$, CI = 0.00–0.01, $p = 0.003$). There was also a significant interaction between Brain Region and *Home Use* scores, indicating that coherence between LP and RP ($E = 0.01$, CI = 0.00–0.02, $p = 0.015$) as well as MF and RFT ($E = −0.01$, CI = −0.02 to −0.00, $p = 0.011$) were modulated by *Home use* scores. The negative estimate for the relationship between MF and RFT coherence and *Home Use* scores, however, suggests an unexpected directionality—that is, the less exposure the participants had to the non-societal language at home, the stronger the connections were between MF and RFT. Finally, there was also a significant interaction between Brain Region and *Proficiency*. Coherence between MF and RFT ($E = 0.01$, CI = 0.00–0.01, $p = 0.005$), LFT and MF ($E = 0.01$, CI = 0.00–0.01, $p = 0.017$), and LFT and RFT ($E = 0.01$, CI = 0.00–0.01, $p = 0.004$) were all modulated by *Proficiency* in the expected direction. The higher proficiency rating in the societal language, the stronger the connections were between the frontotemporal electrodes. A simple correlation analysis revealed no significant correlations between any of the brain region pairings and predictor variables (p's > 0.12).

3.3.3. Low beta

SES was the only significant fixed factor that predicted coherence in the low beta ($E = −0.01$, CI = −0.01 to −0.00, $p = 0.033$). No interactions were found between Brain Region and language background predictor variables (p's > 0.057).

3.3.4. High beta

There was a main effect of AoA on coherence in high beta ($E = −0.02$, CI = −0.03 to −0.00, $p = 0.040$), which indicates that general connections between brain regions were modulated by age of L2/2L1 onset (Fig. 7). This suggests that the younger the participants were exposed to the L2/2L1, the stronger their connections were between brain regions. Nevertheless, no interactions between Brain Region and AoA (as well as other language background predictors) were found, illustrating that the positive relationship between coherence and AoA does not vary across different brain region pairings.

3.3.5. Gamma

No main effect of predictors or covariates were found on the coherence in gamma. The only significant interaction was found between Brain Region and AoA. Coherence between LP and RP ($E = −0.01$, CI = −0.02 to −0.00, $p = 0.004$) as well as MF and RP was modulated by AoA ($E = −0.01$, CI = −0.02 to −0.00, $p = 0.005$), meaning earlier age of L2/2L1 onset predicted the strength of connection between MF and RP. Simple correlation analysis showed that the relationship between MF and RP coherence and AoA was nearly significant ($r = −0.19$, $p = 0.07$).

4. Discussion

Research has shown that bilingualism can be a potent neuromodulator (e.g., DeLuca et al., 2020; Li et al., 2014; Pliatsikas, 2019) and a potential factor in maintaining neural fitness and creating reserve

Table 2
Summary of regression models for each frequency band.

Predictors	IAF E	IAF CI	IAF p	Theta E	Theta CI	Theta p	Alpha E	Alpha CI	Alpha p	Low Beta E	Low Beta CI	Low Beta p	High Beta E	High Beta CI	High Beta p	Gamma E	Gamma CI	Gamma p
Intercept	10.89	10.50–11.29	**<0.001**	9.86	9.66–10.07	**<0.001**	10.26	9.95–10.57	**<0.001**	9.25	9.07–9.44	**<0.001**	8.52	8.32–8.71	**<0.001**	7.64	7.41–7.87	**<0.001**
Home	−0.16	−0.54–0.22	0.411	−0.02	−0.22 to 0.17	0.820	−0.03	−0.33 to 0.26	0.818	−0.13	−0.31 to 0.05	0.150	−0.13	−0.32 to 0.05	0.152	−0.18	−0.40 to 0.04	0.114
Social	−0.03	−0.32 to 0.25	0.810	0.10	−0.04 to 0.25	0.156	0.17	−0.05 to 0.38	0.131	0.05	−0.08 to 0.18	0.479	0.07	−0.07 to 0.20	0.331	0.08	−0.08 to 0.24	0.336
Prof	−0.03	−0.27 to 0.21	0.798	0.05	−0.07 to 0.17	0.426	0.11	−0.07 to 0.29	0.237	0.00	−0.11 to 0.11	0.983	−0.08	−0.20 to 0.03	0.154	−0.08	−0.22 to 0.05	0.223
AoA	−0.21	−0.54 to 0.13	0.222	0.02	−0.15 to 0.19	0.801	−0.06	−0.32 to 0.20	0.672	−0.09	−0.25 to 0.06	0.248	−0.18	−0.34 to −0.02	0.031	−0.25	−0.45 to −0.06	**0.011**
SES	0.15	−0.11 to 0.42	0.261	−0.01	−0.15 to 0.12	0.846	−0.01	−0.21 to 0.20	0.926	−0.04	−0.16 to 0.09	0.556	0.01	−0.12 to 0.14	0.911	−0.02	−0.17 to 0.14	0.840
LoE	−0.15	−0.39 to 0.08	0.203	−0.01	−0.14 to 0.11	0.813	0.05	−0.14 to 0.23	0.612	0.06	−0.05 to 0.17	0.316	0.09	−0.03 to 0.20	0.138	0.07	−0.07 to 0.21	0.324
Sex [Male]	−0.16	−0.66 to 0.35	0.543	−0.15	−0.41 to 0.11	0.247	−0.05	−0.44 to 0.34	0.791	−0.40	−0.63 to −0.16	**0.001**	−0.23	−0.48 to 0.01	0.061	−0.06	−0.35 to 0.23	0.685
Location [Norway]	−0.72	−1.30 to −0.15	**0.015**	−0.10	−0.39 to 0.20	0.511	0.14	−0.31 to 0.58	0.543	−0.15	−0.42 to 0.12	0.264	−0.18	−0.46 to 0.10	0.197	−0.21	−0.54 to 0.12	0.211
Obs	96			96			96			96			96			96		
R^2/R^2 adjusted	0.147/0.068			0.048/−0.039			0.061/−0.026			0.153/0.075			0.136/0.056			0.107/0.025		

in both healthy aging (Abutalebi et al., 2015; Borsa et al., 2018; Rossi & Diaz, 2016; Zhang et al., 2020) and in the face of pathology (Anderson et al., 2020; Gold, 2015; Voits et al., 2020). Most recently, we are beginning to better understand what determinants of variability in bi-multilingual language experience bring to bear on cognition and neuroplasticity. Variability in language experience modulates the neural adaptation at play in bilingual brains (Dash, Berroir, Joanette, & Ansaldo, 2019; DeLuca et al., 2019a; Pliatsikas, 2020). Furthermore, measures of social diversity, language use, and language entropy have been shown to shape brain connectivity at rest (Gullifer et al., 2018; Sulpizio et al., 2020; Tiv et al., 2020). As a result, studies in the field must incorporate a more dynamic view of bi-multilingual language use and its consequences for the mind and the brain. The present study engages in this dialogue, combining measures of varied bilingual experience in a diverse grouping of bilinguals with rs-EEG, a method emerging as one of the most useful to capture neural flexibility as a proxy for cumulative neural change in the short and long term (Luk et al., 2020).

4.1. The relationship between language background and power frequency

Previous findings reported greater alpha and high beta power for bilinguals compared to monolinguals and marginal effects on the gamma band (Bice et al., 2020). Higher alpha power was related to language control, which is consistent with the hypothesis that dual-language usage has a draw-back effect on the inhibitory control system. Interestingly, higher levels of alpha were found in those bilinguals who used their L2 more often, maintained higher native-language proficiency, and had an earlier L2 learning onset. This suggests that greater engagement with bilingualism is linked to better use of executive functions, which are necessary for bilingual language processing. Overall, our results indicate that AoA predicts modulations of high beta and gamma frequencies, which only partially overlaps with the ones from Bice et al. (2020). Below, we turn to unpacking why this might be the case.

Recall that previous research on rs-EEG has highlighted the key role of combined beta and gamma powers on L2 learning rates (Prat et al., 2016) as well as total speech attempts and willingness to speak during L2 learning (Prat et al., 2019). Furthermore, they are the main sources of long-range network synchronizers in the brain (Buzsáki & Schomburg, 2015; Von Stein & Sarnthein, 2000). We thus interpret our data to support a view whereby acquiring an L2 earlier might promote and strengthen, thorough beta and gamma regulation and modulation, inter-regional neural synchronization.

The active use of two languages imposes higher demands on the linguistic and cognitive systems. It has been shown that beta is at the center of cortico-basal ganglia loops (e.g., Brittain et al., 2014; Stein & Bar-Gad, 2013), which in turn are believed to regulate language processing (e.g., Kotz et al., 2009), especially bilingual language use (e.g., Seo et al., 2018; Stocco & Prat, 2014). Moreover, Bice et al. (2020) showed that bilinguals had greater beta compared to monolinguals in the right hemisphere and an ongoing study by Rossi and colleagues shows that intense learning of a new language over a short period of time produces observable beta (and alpha) frequency changes (Rossi et al., in preparation). Beta modulation is also found in task-based non-linguistic experiments. For example, Ambrosini and Vallesi (2016) found that participants who performed better in an attention task displayed more beta than alpha power, which they linked to sustained cognitive control processes. Tafuro et al. (2019), testing two age groups (younger and older adults) in a specialized Stroop task, found main effects of beta and theta in interference control. Interestingly, the young participants revealed a specific left-lateralized stroop effect in beta which appeared earlier in comparison to their elderly peers and was spread bilaterally over the scalp, thus revealing age-dependent differences in oscillatory correlates of cognitive control. Our data show that earlier AoA results in greater beta. In light of the studies above, it is not surprising that
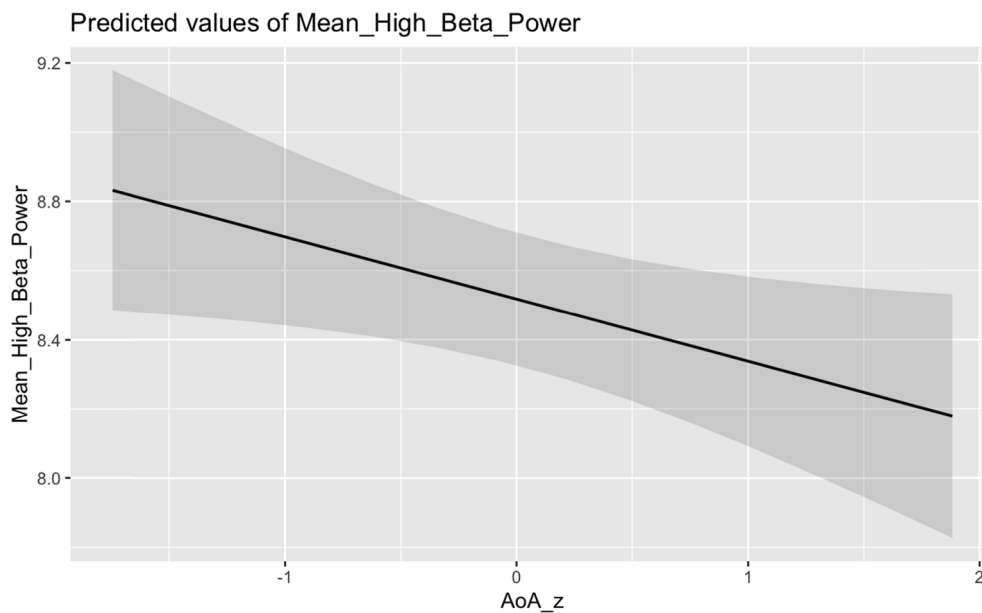
Predicted values of Mean_High_Beta_Power

Fig. 1. Predicted values of Age of L2/2L1 onset on high beta power.
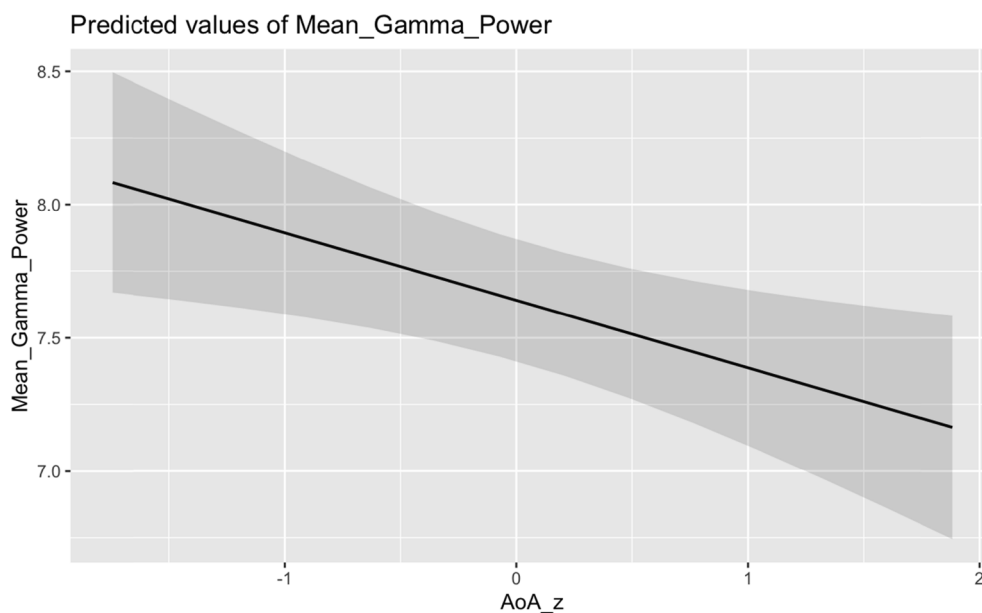
Predicted values of Mean_Gamma_Power

Fig. 2. Predicted values of Age of L2/2L1 onset on gamma power.

bilingualism itself, but moreover the age of its onset would impact the way and the time beta mechanisms are mobilized/engaged throughout the lifespan.

Gamma oscillation activity fluctuates over time, with an increase in children aged 3–4 (Takano & Ogawa, 1998) followed by a decrease in adolescence into young adulthood (Tierney et al., 2013). The linear decrease in gamma over the first decades of life mirrors that of grey matter volume (Whitford et al., 2007). The observed decline in gamma might indicate a decrease in synaptic density linked to synaptic pruning and reflect reorganization within brain circuits underlying language and cognitive processing (Tierney et al., 2013; see for a model on plasticity in the bilingual brain Pliatsikas, 2020). Our results indicate that engaging earlier in time with bilingualism relates to a higher degree of gamma power. Gamma activity has been linked to increases in linguistic and attentional abilities (Benasich et al., 2008) and to a higher functioning cognitive system (Fitzgibbon et al., 2004; Tarullo et al., 2017 in

children). Earlier onset of bilingualism, then, seems to confer maximized benefits for the executive function networks in the brain.

It is widely accepted that alpha is a reflection of cognitive integrity, highly correlated with memory performance and constitutes the majority of the brain's oscillatory pattern (Klimesch et al., 2007; Klimesch, 1999). Paradoxically, while alpha frequencies naturally decrease (desynchronize) on-task signifying better performance, and synchronize (i. e., increase) at rest, denoting less cognitive engagement, overall higher alpha measured at rest is connected to overall better cognitive performance. Given that Bice et al. (2020) report that bilinguals had significantly higher alpha, one might ponder why we do not see any effects in the alpha range in our data. Recall that previous literature showed a marked difference in alpha power and IAF for bilinguals compared to monolinguals, the latter of which is lacking in the present study. Indeed, our results do not show any modulation of IAF nor alpha power as a function of bilingual language usage predictors. This observation,

Table 3
Summary of regression models for gamma and high beta power.

| Predictors	High Beta			Gamma		
	Estimates	CI	p	Estimates	CI	p
(Intercept)	8.36	8.26–8.47	**<0.001**	7.52	7.39–7.64	**<0.001**
LFT	−0.01	−0.04 to 0.03	0.691	0.12	0.07–0.16	**<0.001**
LP	−0.13	−0.17 to −0.10	**<0.001**	−0.20	−0.25 to −0.16	**<0.001**
MF	0.26	0.22–0.29	**<0.001**	0.17	0.12–0.21	**<0.001**
RFT	−0.02	−0.06 to 0.01	0.238	0.09	0.04–0.13	**<0.001**
RP	−0.10	−0.13 to −0.06	<0.001	−0.17	−0.22 to −0.13	<0.001
AoA	−0.12	−0.22 to −0.01	**0.037**	−0.14	−0.27 to −0.01	**0.036**
LFT * AoA	−0.02	−0.06 to 0.01	0.194	−0.01	−0.05 to 0.04	0.748
LP * AoA	0.01	−0.02 to 0.05	0.527	0.01	−0.04 to 0.05	0.680
MF * AoA	0.02	−0.02 to 0.05	0.395	0.02	−0.03 to 0.06	0.450
RFT * AoA	−0.02	−0.05 to 0.02	0.293	−0.02	−0.07 to 0.02	0.361
RP * AoA	0.02	−0.02 to 0.05	0.386	0.00	−0.04 to 0.05	0.947
Random Effects						
σ^2	0.04			0.07		
τ_{00}	0.29 $_{Subject}$			0.41 $_{Subject}$		
ICC	0.88			0.86		
N	99 $_{Subject}$			99 $_{Subject}$		
Marginal R^2/Conditional R^2	0.090/0.887			0.084/0.874		
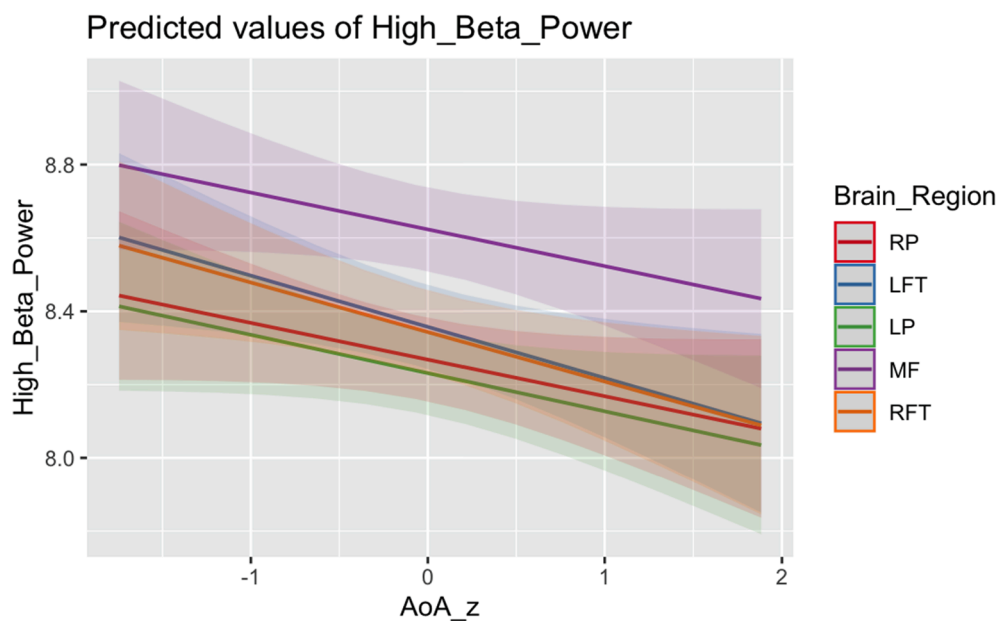
Fig. 3. Predicted values of Age of L2/2L1 onset on high beta power.

however, cannot speak to whether or not any (individuals) or all (as a group) of the bilinguals in the present study would show the same differences to (matched) monolinguals as in Bice et al. (2020). In this respect, it is relevant to mention that Bice et al. (2020) also showed that the higher the proficiency in the L2 the greater the alpha power was. Recall that the LSBQ composite score herein measures one's proficiency in the societal language (Norwegian for Norway and German for Germany) and that participants self-reported to be highly proficient in the societal language (mean = 80.0/100). Thus, such lack of variability may have contributed to finding no modulatory effects of proficiency on alpha power.

4.2. The relationship between language experience and coherence

Limited as they are, existent rs-EEG findings show a role of bilingualism as a life-style enrichment factor affecting underlying mean coherence of brain regions. However, previous studies have focused on comparing monolinguals to bilinguals. Herein, we move away from the monolingual-bilingual comparative approach to examine how differential bilingual experience itself may modulate rs-EEG. Overall, the present results demonstrate that rs-EEG coherence across brain regions and across frequency bands (theta, alpha, and gamma) is modulated by differential language experience, showing a number of significant interactions between language background predictors and brain region pairings at various frequencies.

Recall there was a main effect of non-societal language use in the community on overall brain connectivity. However, there was an interaction between electrode region pairings, suggesting frontal connectivity between MF and RFT, and RFT and LFT in the theta frequency. In other words, the more individuals engage in using the non-societal language in the community the greater the theta coherence across those ROIs. Recall that theta frequencies have been reported to promote long-distance communication pathways, even across brain regions that might not be directly connected (Von Stein & Sarnthein, 2000). As such, greater theta coherence associated with increased use of the non-societal language in the community could reflect the degree of interactive
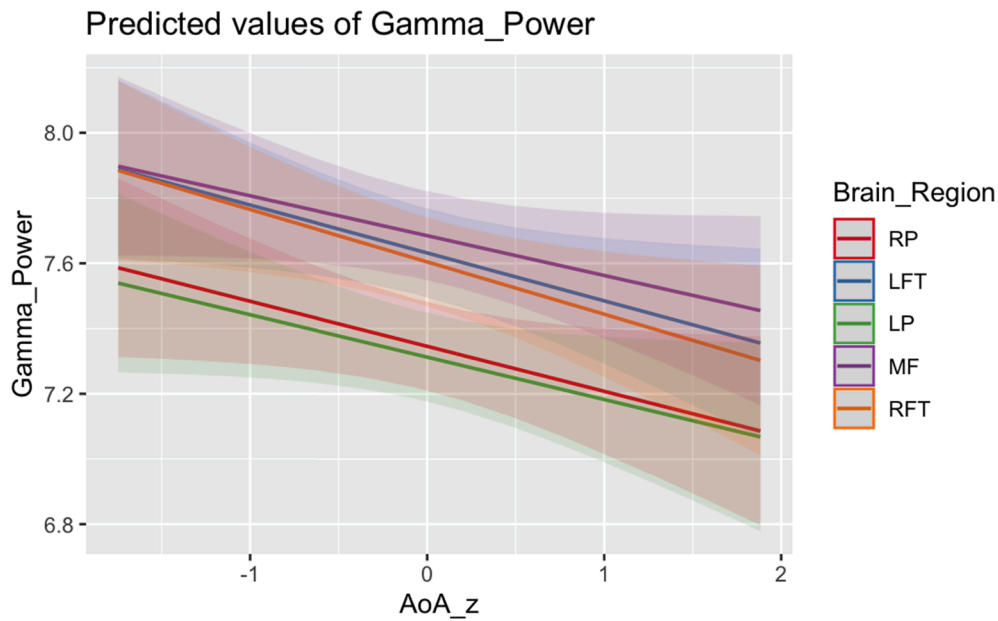
Fig. 4. Predicted values of Age of L2/2L1 onset on gamma power.
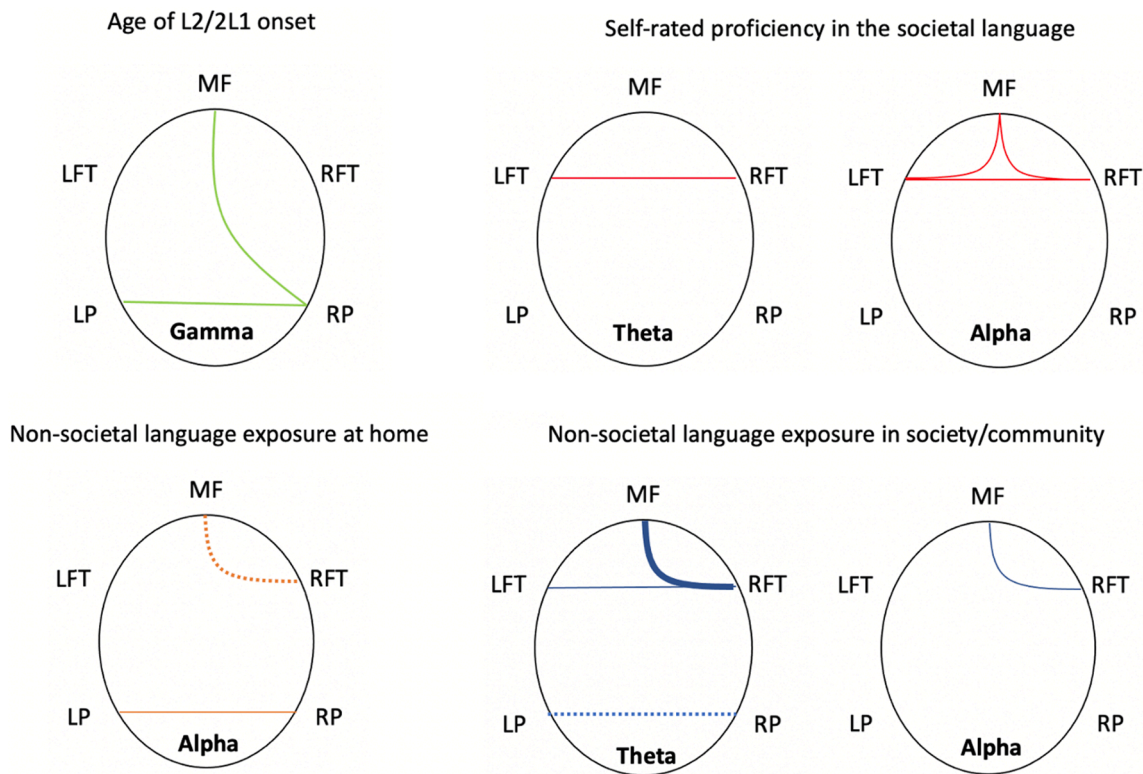

Fig. 5. Coherence maps showing connections between brain region pairings which were significantly modulated by various predictor variables (i.e., Age of L2/2L1 onset (AoA); Self rated proficiency in the societal language (Proficiency), Non-societal language exposure at home (Home), Non-societal language use in society/community (Society)). Thin lines indicate connections between brain region pairings that were significantly modulated by predictor variables in the expected direction (e.g., higher Home score predicts stronger connections between LP and RP). Dotted lines indicate connections between brain region pairings that were significantly modulated by predictor variables in the unexpected direction (e.g., lower Home score predicts stronger connections between MF and RFT). Bold lines indicate significant simple correlation between brain region coherence and language background predictor.

language use in a dual-language environment where inhibitory demands are at a maximum (Abutalebi & Green, 2016; Green & Abutalebi, 2013). In line with this interpretation, greater theta coherence measures have been reported to be positively correlated with bilateral caudate volume in MEG (de Frutos-Lucas et al., 2019). The caudate nucleus is a key structure highly implicated in bilingual language control (Pliatsikas & Luk, 2016; Rossi et al., 2021) and is at play especially while switching between languages (Abutalebi et al., 2008; Luk et al., 2012; Moritz-Gasser & Duffau, 2009). Even though no structural MRI data were collected in this study, a possible interpretation is that greater coherence
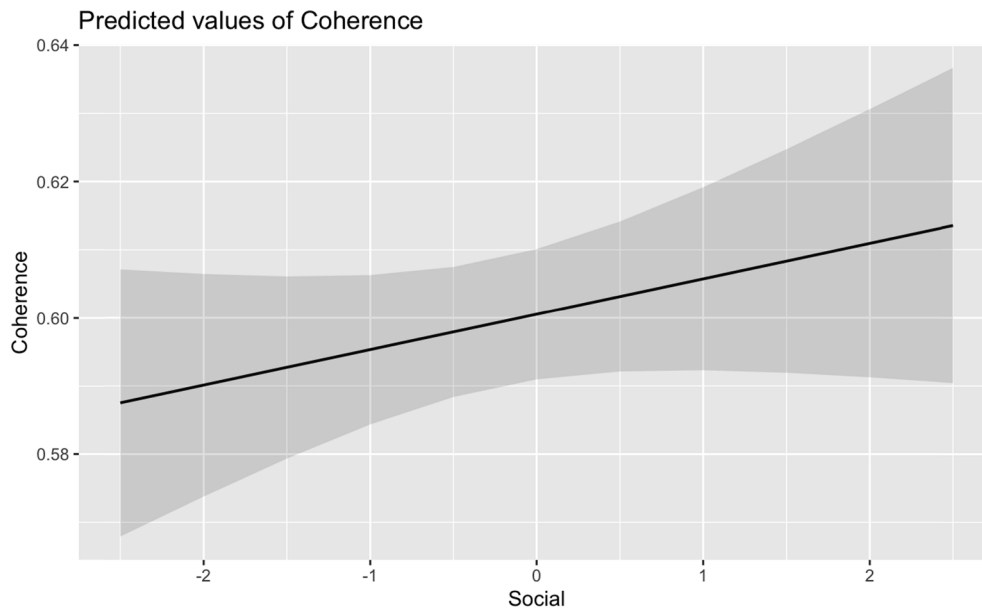
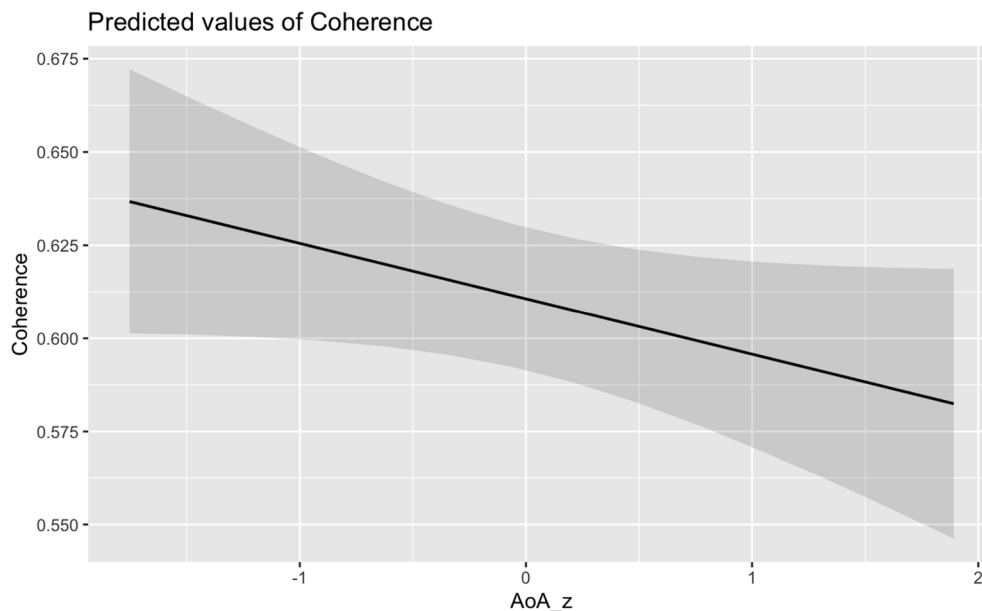**Fig. 6.** Predicted values of Social score on theta coherence.

Fig. 7. Predicted values of Age of L2/2L1 onset on high beta coherence.

in theta could be a proxy for greater caudate engagement, sparked by high interactive language use in the community. Another important result revealed that *Proficiency* in the societal language positively predicted rs-EEG coherence in the theta frequencies between the anterior left and right electrode clusters (LFT, RFT). A correlation of greater theta coherence in frontal regions with proficiency in the societal language can be reconciled with a need for greater recruitment of executive functions (Basharpoor et al., 2019).

Our results also demonstrated that alpha coherence was modulated by three language use predictors: *Proficiency* in the societal language, *Social* and *Home use*. *Proficiency* positively predicted greater alpha rs-EEG coherence between frontal left and right clusters and between left and right clusters and MF. Similarly, greater alpha coherence between RFT and MF was positively predicted by the rate of *Social use*. Recall that greater rs-EEG coherence in alpha was reported by Bice et al. (2020) for bilinguals relative to monolinguals, and was interpreted as bilinguals

having larger networks of neurons firing at rest. Our results are in line with this interpretation, yet they take this observation a step further, revealing what determinants of bilingualism drive this effect. In sum, alpha rs-EEG coherence is dependent on variations in the use of the bilinguals' languages. Bice et al. (2020) reported greater alpha coherence mostly in posterior clusters, while our correlations with the engagement of the societal language show greater coherence across frontal ones. Similarly, our data also show greater alpha rs-EEG coherence in posterior clusters which is positively predicted by non-societal language use at home. It is crucial to remember that in our sample, "non-societal language" includes both the heritage language spoken at home for early bilinguals, and the L2 learned past childhood for L2 speakers. Greater "non-societal language exposure at home" could then be a proxy for greater bilingual language use of the two languages at home.

Finally, our results demonstrated that there was a positive

correlation between gamma coherence between LP and RP, posterior right and frontal MF, and age of L2/2L1 acquisition. The earlier the L2/2L1 was acquired, the greater gamma coherence across electrode clusters. Higher levels of gamma coherence were also reported by Bice et al. (2020) for bilinguals relative to monolinguals. The current results point towards length of bilingual language use in the modulation of gamma synchrony. Gamma coherence is one of the main local inter-regional synchronizers across neural pools (Buzsáki & Schomburg, 2015; Von Stein & Sarnthein, 2000). Accordingly, we conclude that bilingualism, under specific conditions, promotes inter-regional neural synchronization, and also that length of bilingual experience might in turn maintain and strengthen this synchronization.

The current results show that age and variation in dual-language use in various contexts modulate both power and coherence measures for low- and high frequency ranges. Thus, a key question to be addressed in future investigations is if and how these neural signatures are maintained in older age, and most importantly if individual variability in bilingual language use continues to modulate them. This dataset was composed by relatively young adults. Given the vast literature pointing towards bilingualism as a key factor for cognitive and neural reserve (see Anderson et al., 2020; Gallo et al., 2020), we would expect bilingual older adults who have been utilizing two or more languages for a longer time to show similar neural modulations as those observed herein whereby effects also interact with how they engage with bilingual language use over the lifespan.

Expanding the emerging rs-EEG and bilingualism literature to include longitudinal studies would be especially welcome. Given that the main comparisons remain within-subjects, longitudinal studies represent an ideal ground to investigate how experience factors in bilingualism manifest and crucially develop over time in the brain in isolation (DeLuca et al., 2019b; Wong et al., 2016). The few longitudinal studies with (f)MRI so far have either honed in on intensive learning (i. e., early stages of L2 acquisition) of a new acquired language where participants get tested on several occasions during the process (Hosoda et al., 2013; Mårtensson et al., 2012; Stein et al., 2012) or focused longitudinally on the effects of naturalistic language use and immersion on the brain (DeLuca et al., 2019b; Mohades et al., 2015). Both types of methods found white and grey matter changes in the brain related to language experience factors, such as proficiency (Mårtensson et al., 2012), immersion and L2 age of acquisition (DeLuca et al., 2019b). Doing so with rs-EEG could be equally fruitful, if not more informative given its comparative ease and low cost.

Funding

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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2021.105030.

References

Abutalebi, J., Annoni, J.-M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., Lazeyras, F., Cappa, S. F., & Khateb, A. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex, 18*(7), 1496–1505.

Abutalebi, J., & Green, D. W. (2016). Neuroimaging of language control in bilinguals: Neural adaptation and reserve. *Bilingualism: Language and Cognition, 19*(4), 689–698.

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B. S. (2015). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia, 69*, 201–210.

Ambrosini, E., & Vallesi, A. (2016). Asymmetry in prefrontal resting-state EEG spectral power underlies individual differences in phasic and sustained cognitive control. *Neuroimage, 124*, 843–857.

Anderson, A. J., & Perone, S. (2018). Developmental change in the resting state electroencephalogram: Insights into cognition and the brain. *Brain and Cognition, 126*, 40–52.

Anderson, J. A., Hawrylewicz, K., & Grundy, J. G. (2020). Does bilingualism protect against dementia? A meta-analysis. *Psychonomic Bulletin & Review, 27*, 952–965.

Anderson, J. A., Mak, L., Chahi, A. K., & Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behavior Research Methods, 50*(1), 250–263.

Babiloni, C., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., Buffo, P., Cibelli, G., Soricelli, A., Eusebi, F., & Del Percio, C. (2010). Resting state cortical rhythms in athletes: A high-resolution EEG study. *Brain Research Bulletin, 81*(1), 149–156.

Bak, T. H. (2016). The impact of bilingualism on cognitive ageing and dementia: Finding a path through a forest of confounding variables. *Linguistic Approaches to Bilingualism, 6*(1–2), 205–226.

Basharpoor, S., Heidari, F., & Molavi, P. (2019). EEG coherence in theta, alpha, and beta bands in frontal regions and executive functions. *Applied Neuropsychology: Adult,* 1–8.

Bastiaansen, M., & Hagoort, P. (2006). Oscillatory neuronal dynamics during language comprehension. *Progress in Brain Research, 159*, 179–196.

Benasich, A. A., Gou, Z., Choudhury, N., & Harris, K. D. (2008). Early cognitive and language skills are linked to resting frontal gamma power across the first 3 years. *Behavioural Brain Research, 195*(2), 215–222. https://doi.org/10.1016/j.bbr.2008.08.049

Berger, H. (1929). Über das elektroenkephalogramm des menschen. *Archiv Für Psychiatrie Und Nervenkrankheiten, 87*(1), 527–570.

Berken, J. A., Chai, X., Chen, J.-K., Gracco, V. L., & Klein, D. (2016). Effects of Early and Late Bilingualism on Resting-State Functional Connectivity. *Journal of Neuroscience, 36*(4), 1165–1172. https://doi.org/10.1523/JNEUROSCI.1960-15.2016

Bialystok, E. (2016). The signal and the noise: Finding the pattern in human behavior. *Linguistic Approaches to Bilingualism, 6*(5), 517–534.

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin, 143*(3), 233.

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in Cognitive Sciences, 16*(4), 240–250.

Bice, K., Yamasaki, B. L., & Prat, C. S. (2020). Bilingual language experience shapes resting-state brain rhythms. *Neurobiology of Language, 1*(3), 288–318.

Bornkessel, I. D., Fiebach, C. J., Friederici, A. D., & Schlesewsky, M. (2004). "Capacity" reconsidered: Interindividual differences in language comprehension and individual alpha frequency. *Experimental Psychology, 51*(4), 279–289.

Borsa, V. M., Perani, D., Della Rosa, P. A., Videsott, G., Guidi, L., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2018). Bilingualism and healthy aging: Aging effects and neural maintenance. *Neuropsychologia, 111*, 51–61.

Brittain, J.-S., Sharott, A., & Brown, P. (2014). The highs and lows of beta activity in cortico-basal ganglia loops. *European Journal of Neuroscience, 39*(11), 1951–1959.

Buzsaki, G. (2006). *Rhythms of the Brain*. Oxford University Press.

Buzsáki, G., Anastassiou, C. A., & Koch, C. (2012). The origin of extracellular fields and currents—EEG, ECoG, LFP and spikes. *Nature Reviews Neuroscience, 13*(6), 407–420.

Buzsáki, G., & Schomburg, E. W. (2015). What does gamma coherence tell us about inter-regional neural communication? *Nature Neuroscience, 18*(4), 484–489.

Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin, 132*(2), 180–211.

Cantou, P., Platel, H., Desgranges, B., & Groussard, M. (2018). How motor, cognitive and musical expertise shapes the brain: Focus on fMRI and EEG resting-state functional connectivity. *Journal of Chemical Neuroanatomy, 89*, 60–68. https://doi.org/10.1016/j.jchemneu.2017.08.003

Dash, T., Berroir, P., Joanette, Y., & Ansaldo, A. I. (2019). Alerting, orienting, and executive control: The effect of bilingualism and age on the subcomponents of attention. *Frontiers in Neurology, 10*, 1122.

de Frutos-Lucas, J., López-Sanz, D., Cuesta, P., Bruña, R., de la Fuente, S., Serrano, N., López, M. E., Delgado-Losada, M. L., López-Higes, R., Marcos, A., & Maestú, F. (2019). Enhancement of posterior brain functional networks in bilingual older adults. *Bilingualism: Language and Cognition, 23*(2), 387–400. https://doi.org/10.1017/S1366728919000178

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019a). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences, 116*(15), 7565–7574.

DeLuca, V., Rothman, J., & Pliatsikas, C. (2019b). Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Bilingualism: Language and Cognition, 22*(5), 1160–1175.

DeLuca, V., Segaert, K., Mazaheri, A., & Krott, A. (2020). Understanding bilingual brain function and structure changes? U Bet! A Unified Bilingual Experience Trajectory model. *Journal of Neurolinguistics, 56*, Article 100930.

Doppelmayr, M., Klimesch, W., Stadler, W., Pöllhuber, D., & Heine, C. (2002). EEG alpha power and intelligence. *Intelligence, 30*(3), 289–302.

Fitzgibbon, S. P., Pope, K. J., Mackenzie, L., Clark, C. R., & Willoughby, J. O. (2004). Cognitive tasks augment gamma EEG power. *Clinical Neurophysiology, 115*(8), 1802–1809. https://doi.org/10.1016/j.clinph.2004.03.009

Gallo, F., Myachykov, A., Shtyrov, Y., & Abutalebi, J. (2020). Cognitive and brain reserve in bilinguals: Field overview and explanatory mechanisms. *Journal of Cultural Cognitive Science, 4*, 127–143.

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience, 15*(4), 511.

Gold, B. T. (2015). Lifelong bilingualism and neural reserve against Alzheimer's disease: A review of findings and potential mechanisms. *Behavioural Brain Research, 281*, 9–15.

Gong, A., Liu, J., Lu, L., Wu, G., Jiang, C., & Fu, Y. (2019). Characteristic differences between the brain networks of high-level shooting athletes and non-athletes calculated using the phase-locking value algorithm. *Biomedical Signal Processing and Control, 51*, 128–137. https://doi.org/10.1016/j.bspc.2019.02.009

Grady, C. L., Luk, G., Craik, F. I. M., & Bialystok, E. (2015). Brain network activity in monolingual and bilingual older adults. *Neuropsychologia, 66*, 170–181. https://doi.org/10.1016/j.neuropsychologia.2014.10.042

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology, 25*(5), 515–530. https://doi.org/10.1080/20445911.2013.796377

Grundy, J. G. (2020). The effects of bilingualism on executive functions: An updated quantitative analysis. *Journal of Cultural Cognitive Science*, 1–23.

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., & Titone, D. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia, 117*, 123–134. https://doi.org/10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., & Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism: Language and Cognition, 23*(2), 283–294.

Hosoda, C., Tanaka, K., Nariai, T., Honda, M., & Hanakawa, T. (2013). Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *The Journal of Neuroscience, 33*(34), 13663. https://doi.org/10.1523/JNEUROSCI.0410-13.2013

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. *Frontiers in Human Neuroscience, 4*, 186.

Kay, B. P., Meng, X., DiFrancesco, M. W., Holland, S. K., & Szaflarski, J. P. (2012). Moderating effects of music on resting state networks. *Brain Research, 1447*, 53–64. https://doi.org/10.1016/j.brainres.2012.01.064

Klimesch, W. (1997). EEG-alpha rhythms and memory processes. *International Journal of Psychophysiology, 26*(1–3), 319–340.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews, 29*(2–3), 169–195.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition–timing hypothesis. *Brain Research Reviews, 53*(1), 63–88.

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex, 45*(8), 982–990.

Kroll, J. F., Dussias, P. E., Bogulski, C. A., & Valdés Kroff, J. R. (2012). Juggling two languages in one mind: What bilinguals tell us about language processing and its consequences for cognition. In Psychology of learning and motivation (Brian H. Ross, Vol. 56, pp. 229–262).

Kupisch, T., & Rothman, J. (2018). Terminology matters! Why difference is not incompleteness and how early child bilinguals are heritage speakers. *International Journal of Bilingualism, 22*(5), 564–582.

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., De Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin, 144*(4), 394.

Leivada, E., Westergaard, M., Duñabeitia, J. A., & Rothman, J. (2021). On the phantom-like appearance of bilingualism effects on neurocognition:(How) should we proceed? *Bilingualism: Language and Cognition, 24*(1), 197–210.

Li, L., Abutalebi, J., Zou, L., Yan, X., Liu, L., Feng, X., … Ding, G. (2015). Bilingualism alters brain functional connectivity between "control" regions and "language" regions: Evidence from bimodal bilinguals. *Neuropsychologia, 71*, 236–247.

Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex, 58*, 301–324.

Luk, G., & Bialystok, E. (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *Journal of Cognitive Psychology, 25*(5), 605–621.

Luk, G., Bialystok, E., Craik, F. I. M., & Grady, C. L. (2011). Lifelong Bilingualism Maintains White Matter Integrity in Older Adults. *Journal of Neuroscience, 31*(46), 16808–16813. https://doi.org/10.1523/JNEUROSCI.4563-11.2011

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes, 27*(10), 1479–1488. https://doi.org/10.1080/01690965.2011.613209

Luk, G., Pliatsikas, C., & Rossi, E. (2020). Brain changes associated with language development and learning: A primer on methodology and applications. *System, 89*, Article 102209.

Luk, G., Anderson, J. A. E., Grundy, J., Pliatsikas, C., & Rothman, J. (2021). Letter to the editors: What have we learned about bilingualism? Regarding Nichols et al. (2020). *Psychological Science*.

Mårtensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lövdén, M. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage, 63*(1), 240–244. https://doi.org/10.1016/j.neuroimage.2012.06.043

Meisel, J. M. (2011). *First and second language acquisition: Parallels and differences.* Cambridge University Press.

Miall, R. C., & Robertson, E. M. (2006). Functional imaging: Is the resting brain resting? *Current Biology, 16*(23), R998–R1000.

Miller, E. K., Lundqvist, M., & Bastos, A. M. (2018). Working Memory 2.0. *Neuron, 100*(2), 463–475.

Mohades, S. G., Van Schuerbeek, P., Rosseel, Y., Van De Craen, P., Luypaert, R., & Baeken, C. (2015). White-matter development is different in bilingual and monolingual children: A longitudinal DTI study. *PLOS ONE, 10*(2), 1–16. https://doi.org/10.1371/journal.pone.0117968

Moritz-Gasser, S., & Duffau, H. (2009). Cognitive processes and neural basis of language switching: Proposal for a new model. *Neuroreport, 20*(18), 1577–1580.

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., & Owen, A. M. (2020). Bilingualism affords no general cognitive advantages: A population study of executive function in 11,000 People. *Psychological Science, 31*(5), 548–567.

Paap, K. R. (2016). The neuroanatomy of bilingualism: Will winds of change lift the fog? *Language, Cognition and Neuroscience, 31*(3), 331–334.

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex, 69*, 265–278.

Pereira Soares, S. M., Ong, G., Abutalebi, J., Del Maschio, N., Sewell, D., & Weekes, B. (2019). A diffusion model approach to analyzing performance on the Flanker task: The role of the DLPFC. *Bilingualism: Language and Cognition, 22*(5), 1194–1208.

Pliatsikas, C. (2019). Multilingualism and brain plasticity. In I. J. Schwieter (Ed.), *The handbook of the neuroscience of multilingualism* (pp. 230–251). Hoboken, NJ: Wiley-Blackwell.

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The dynamic restructuring model. *Bilingualism: Language and Cognition, 23*(2), 459–471.

Pliatsikas, C., & Luk, G. (2016). Executive control in bilinguals: A concise review on fMRI studies. *Bilingualism: Language and Cognition, 19*(4), 699–705.

Pliatsikas, C., Moschopoulou, E., & Saddy, J. D. (2015). The effects of bilingualism on white matter structure of the brain. *Proceedings of the National Academy of Sciences, 112*(5), 1334–1337.

Polinsky, M. (2018). *Heritage languages and their speakers* (Vol. 159). Cambridge University Press.

Prat, C. S., Yamasaki, B. L., Kluender, R. A., & Stocco, A. (2016). Resting-state qEEG predicts rate of second language learning in adults. *Brain and Language, 157*, 44–50.

Prat, C. S., Yamasaki, B. L., & Peterson, E. R. (2019). Individual differences in resting-state brain rhythms uniquely predict second language learning rate and willingness to communicate in adults. *Journal of Cognitive Neuroscience, 31*(1), 78–94.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences, 98*(2), 676–682.

Raichle, M. E., & Snyder, A. Z. (2007). A default mode of brain function: A brief history of an evolving idea. *Neuroimage, 37*(4), 1083–1090.

Rossi, E., & Diaz, M. (2016). How aging and bilingualism influence language processing: Theoretical and neural models. *Linguistic Approaches to Bilingualism, 6*(1–2), 9–42.

Rossi, E., Dussias, P. E., Diaz, M., van Hell, J. G., & Newman, S. (2021). Neural signatures of inhibitory control in intra-sentential code-switching: Evidence from fMRI. *Journal of Neurolinguistics, 57*, Article 100938.

Rothman, J. (2009). Understanding the nature and outcomes of early bilingualism: Romance languages as heritage languages. *International Journal of Bilingualism, 13*(2), 155–163.

Salinsky, M. C., Oken, B. S., & Morehead, L. (1991). Test-retest reliability in EEG frequency analysis. *Electroencephalography and Clinical Neurophysiology, 79*(5), 382–392.

Seo, R., Stocco, A., & Prat, C. S. (2018). The bilingual language network: Differential involvement of anterior cingulate, basal ganglia and prefrontal cortex in preparation, monitoring, and execution. *NeuroImage, 174*, 44–56.

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. S. (2015). afex: Analysis of factorial experiments. R Package Version 0.13–145.

Stein, E., & Bar-Gad, I. (2013). Beta oscillations in the cortico-basal ganglia loop during parkinsonism. *Experimental Neurology, 245*, 52–59.

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., Brandeis, D., & Dierks, T. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex, 48*(4), 458–465. https://doi.org/10.1016/j.cortex.2010.10.007

Stocco, A., & Prat, C. S. (2014). Bilingualism trains specific brain circuits involved in flexible rule selection and application. *Brain and Language, 137*, 50–61.

Strauss, A., Wöstmann, M., & Obleser, J. (2014). Cortical alpha oscillations as a tool for auditory selective inhibition. *Frontiers in Human Neuroscience, 8*, 350. Cerca Con Google.

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., & Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage, 205*, Article 116306.

Sun, X., Li, L., Ding, G., Wang, R., & Li, P. (2019). Effects of language proficiency on cognitive control: Evidence from resting-state functional connectivity. *Neuropsychologia, 129*, 263–275. https://doi.org/10.1016/j.neuropsychologia.2019.03.020

Surrain, S., & Luk, G. (2019). Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005–2015. *Bilingualism: Language and Cognition, 22*(2), 401–415.

Tafuro, A., Ambrosini, E., Puccioni, O., & Vallesi, A. (2019). Brain oscillations in cognitive control: A cross-sectional study with a spatial stroop task. *Neuropsychologia, 133*, Article 107190.

Takano, T., & Ogawa, T. (1998). Characterization of developmental changes in EEG-gamma band activity during childhood using the autoregressive model. *Pediatrics International, 40*(5), 446–452.

Tarullo, A. R., Obradović, J., Keehn, B., Rasheed, M. A., Siyal, S., Nelson, C. A., & Yousafzai, A. K. (2017). Gamma power in rural Pakistani children: Links to executive function and verbal ability. *Developmental Cognitive Neuroscience, 26*, 1–8. https://doi.org/10.1016/j.dcn.2017.03.007

Tierney, A., Strait, D. L., O'Connell, S., & Kraus, N. (2013). Developmental changes in resting gamma power from age three to adulthood. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 124*(5), 1040.

Tiv, M., Gullifer, J. W., Feng, R. Y., & Titone, D. (2020). Using Network Science to map what Montréal bilinguals talk about across languages and communicative contexts. *Journal of Neurolinguistics, 56*, Article 100913.

Voits, T., Pliatsikas, C., Robson, H., & Rothman, J. (2020). Beyond Alzheimer's disease: Can bilingualism be a more generalized protective factor in neurodegeneration? *Neuropsychologia*, Article 107593.

Von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: From local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology, 38*(3), 301–313.

Whitford, T. J., Rennie, C. J., Grieve, S. M., Clark, C. R., Gordon, E., & Williams, L. M. (2007). Brain maturation in adolescence: Concurrent changes in neuroanatomy and neurophysiology. *Human Brain Mapping, 28*(3), 228–237. https://doi.org/10.1002/hbm.20273

Wong, B., Yin, B., & O'Brien, B. (2016). Neurolinguistics: Structure, Function, and Connectivity in the Bilingual Brain. *BioMed Research International, 2016*, 7069274. https://doi.org/10.1155/2016/7069274

Xue, S.-W., Tang, Y.-Y., Tang, R., & Posner, M. I. (2014). Short-term meditation induces changes in brain resting EEG theta networks. *Brain and Cognition, 87*, 1–6. https://doi.org/10.1016/j.bandc.2014.02.008

Yamasaki, B. L., Stocco, A., & Prat, C. S. (2018). Relating individual differences in bilingual language experiences to executive attention. *Language, Cognition and Neuroscience, 33*(9), 1128–1151.

Zhang, H., Wu, Y. J., & Thierry, G. (2020). Bilingualism and aging: A focused neuroscientific review. *Journal of Neurolinguistics, 54*, Article 100890.