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# Riding the (brain) waves! Using neural oscillations to inform bilingualism research

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## Review Article

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## Abstract

The study of the brains' oscillatory activity has been a standard technique to gain insights into human neurocognition for a relatively long time. However, as a complementary analysis to ERPs, only very recently has it been utilized to study bilingualism and its neural underpinnings. Here, we provide a theoretical and methodological starter for scientists in the (psycho) linguistics and neurocognition of bilingualism field(s) to understand the bases and applications of this analytical tool. Towards this goal, we provide a description of the characteristics of the human neural (and its oscillatory) signal, followed by an in-depth description of various types of EEG oscillatory analyses, supplemented by figures and relevant examples. We then utilize the scant, yet emergent, literature on neural oscillations and bilingualism to highlight the potential of how analyzing neural oscillations can advance our understanding of the (psycho)linguistic and neurocognitive understanding of bilingualism.

## Introduction

The presence of more than one language in a single mind – i.e., bilingualism – has been shown to have consequences for (both) language(s) at the levels of linguistic representation, production and processing (e.g., Dussias & Sagarra, 2007; Verhoeven, van Leeuwe & Vermeer, 2011; Tsimpli, Peristeri & Andreou, 2016; Schulz & Grimm, 2019; Leivada, Westergaard, Duñabeitia & Rothman, 2021a). And while replication is consistently observed across studies, (degree of) dual language experience has often been shown to associate with behavioral effects on tasks tapping into domain-general cognitive functions (see Bialystok, 2021 for a recent review/opinion paper). Moreover, brain structure, functional connectivity at rest as well as recruitment patterns on tasks have been shown to calibrate to degree of bilingual language engagement (see Pliatsikas, 2019 for review). Substantial evidence supports the hypothesis that, when observed, linguistic and/or cognitive bilingual effects stem from underlying language competition and the cognitive demands to manage it (see Kroll & Bialystok, 2013; Kroll, Gullifer, McClain, Rossi & Martín, 2015; Kroll, Bobb, Misra & Guo, 2008; Rothman, Alonso & Puig-Mayenco, 2019; Bialystok & Craik, 2022).

We know that individual-level factors are deterministic for bilingual language exposure and each bilingual's engagement with their languages over time. It should come as no surprise, then, that these same factors condition/delimit opportunities for bilingual outcomes, be they linguistic or neurocognitive (Luk & Bialystok, 2013; Kupisch & Rothman, 2018; DeLuca, Rothman, Bialystok & Pliatsikas, 2019b; Leivada, Mitrofanova & Westergaard, 2021b). Many variables influence the individual likelihood for (any at all) or degree of linguistic and domain general neurocognitive adaptations, including but not limited to: (i) age-of-acquisition, (ii) duration of bilingualism, (iii) patterns of using both languages (separately and/or how they are interspersed in the same discourse) across an array of domains, (iv) size of the speech communities, (v) density of an individual's linguistic social networks, (vi) expected/normative choice and prestige of the languages in the society, (vii) what in the input (quality) can be taken in to form grammatical representations, (vii) levels of activation that relate to speed of processing and cross-linguistic influence. In other words, as opposed to an actual state of being, bilingualism is a spectrum of experience and opportunity. Where an individual's experiences place them along this spectrum determines what outcomes in language and mind/brain can be expected.

Over the past decade in particular, (psycho)linguistic and neurocognitive work on bilingualism has honed in on trying to identify and unpack the internal and external exponents of bilingualism, inclusive of how they interact, to make sense of the variation seen across bilingual groups and individuals. In this sense, the complexities and idiosyncrasies of bilingual language and cognitive systems, patterns of linguistic usage and processing as well as physical brains can serve as a rather special testing ground for uncovering a deeper understanding of the brain's organization (for language and of cognitive systems) more generally. Doing so requires diverse methodologies, from offline and online behavioral methods to various types of neuroimaging.

As we will discuss herein, electroencephalography (EEG) has proven to be an especially important tool in the psycholinguists' and cognitive scientists' language arsenal. As a neuroimaging method with excellent temporal resolution, it allows for a glimpse underneath the proverbial hood – that is, into how the brain processes information in real time. As such, it is an instrument that can be used for examining the processing of language itself, examining potential effects for non-linguistic general cognitive processing as well as the brain's functional connectivity that might be affected by (dual) language experience. Most, if not all, hypotheses regarding bilingual linguistic systems, processing and neurocognition offer predictions amendable to EEG. For example, if bilinguals have distinct representations for language or process language differentially as compared to monolinguals, this should show up as distinctions in neural corollaries of processing. Changes in brain structure and connectivity are reflected in changes in EEG patterns (McCarley, Nakamura, Shenton & Salisbury, 2008; Chang, Liu, Chen, Liu & Duyn, 2013). And so, if bilingual minds/brains adapt to accommodate the cognitive demands of being bilingual, then this should be measurable in the bilingual brain's neuroelectric activity during task performance or even at its baseline resting activation, relative to monolinguals and, perhaps more revealing, to one another based on individual degree of bilingualism. Although EEG is a well-used method in language research in general (Beres, 2017), most relevant studies use only one (of several) type(s) of EEG analyses – namely, Event Related Potentials (ERPs). While very good work has been done with ERPs, our focus here will be to discuss how and why examining the understudied oscillatory signatures of the bilingual brain is, at least, as informative for research on (bilingual) language processing and its effects on domain-general cognition. In fact, as we will show, doing so opens up new and exciting questions that ERPs are not best positioned to address. Relative to ERPs, the analysis of oscillatory dynamics is better suited for capturing the multidimensionality of language processing, which happens in synchrony with a number of domain general cognitive processes that enable it to unfold in a fluid and timely manner (e.g., working memory maintenance, memory encoding and retrieval, attention, prediction, maintenance of the current cognitive set). Indeed, investigating the properties of the spectral signal over time is a powerful analysis tool because it enables one to capture different subcomponents of complex cognitive processes that originate from the synchronization/desynchronization of neuronal activity at certain frequencies, times, and neural locations (Ward, 2003). Crucially, these methods highlight how distinct brain oscillations contribute to the formation of neural assemblies, which work in synchrony to support different aspects of linguistic processing (Bastiaansen, Mazaheri & Jensen, 2012). Given that other dimensions of the EEG signal (such as frequency, time, and phase) have been actively utilized in broader fields of cognitive neuroscience for a long time, taking advantage of this pre-existing knowledge enriches and advances the interpretation of the findings in the field of bilingualism while drawing it ever closer to other fields of cognitive neuroscience.

With the above as our backdrop, the main goal of this paper is to present and discuss an array of methodological tools gravitating around the construct of neural oscillations to help inform theories and clarify misconceptions and contradictory findings in bilingualism research. Importantly, we do not do so by diving too deeply into any specific analytical, computational or mathematical approach, even though we will provide extensive descriptions of the various methodologies and refer the reader to additional technical sources (see Cole & Voytek, 2019; Gross, 2014; Hurtado, Rubchinsky & Sigvardt, 2004; Maris & Oostenveld, 2007; Oostenveld, Fries, Maris & Schoffelen, 2011; Wacker & Witte, 2013 for examples of toolkits on analysis methods for EEG and neural oscillations). Rather, we focus on higher-level theoretical frameworks surrounding brainwaves. First, we introduce the theory behind brain oscillations, i.e., what they are, how they can be measured, what they are good for and how they differentially inform brain mechanisms in comparison to the more commonly used ERPs. We then apply this knowledge into the context of bilingualism research with particular interest on: bilingual language processing and neurocognitive correlates of bilingualism. We conclude by summarizing what we already know from the nascent literature regarding bilingualism and brainwaves, taking it further by offering potential new exploratory avenues for the field.

## Brain oscillatory measures: an introduction

Our everyday neurocognitive activities (including language comprehension and production) result from the brain absorbing, processing and integrating information surrounding us in real time. This is achieved via complex, continuous and bi-directional transformations of chemical to electrical signals in the brain, enabled by neuronal activity and facilitated by glial cells. The electrical signal of a single neuron (or local small circuits) is virtually undetectable unless it is directly recorded – for example, as multiunit activity (MUA), local field potentials (LFPs) or electrocorticography (ECoG) (Burns, Santaniello, Yaffe, Jouny, Crone, Bergey, Anderson & Sarma, 2014; De Hemptinne, Swann, Ostrem, Ryapolova-Webb, San Luciano, Galifianakis & Starr, 2015; Kajikawa & Schroeder, 2011; Land, Engler, Kral & Engel, 2013; Nuwer, 2010). In contrast, the resulting sum of the postsynaptic activity of thousands of neurons composes the EEG signal, picked up by electrodes placed on the scalp (Holmes & Khazipov, 2007; Kirschstein & Köhling, 2009). More specifically, EEG measures the superposition of postsynaptic currents produced by similarly oriented pyramidal neurons in the outer layers of the cerebral cortex (Olejniczak, 2006). Spontaneous fluctuations in the intracellular membrane potentials (caused presumably by voltage-gated ion channels/potentials) of these neurons (Wilson & Kawaguchi, 1996; Fernandez, Noueihed & White, 2019) can synchronize at particular frequencies resulting in the phenomenon of neural oscillations[1].

The EEG signal can provide frequency-specific information by means of a spectral analysis. In other words, using simple oscillatory functions (cosines and sines), the raw EEG signal can be analyzed by applying a series of mathematical (Fourier) transformations to decompose the temporal information into its constituent frequencies. There are five main recognized frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8-12 Hz), beta (13–30 Hz) and gamma (30–150 Hz) (Figure 1). Historically, they have been defined based on their distinguishing characteristics such as frequency, amplitude, morphology, topography, reactivity, etc. (Shackman, McMenamin, Maxwell, Greischar & Davidson, 2010; Brazier, 1961).

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[1] Although we focus here on time-series data recorded with EEG, it is worth mentioning that, in general, magnetoencephalography (MEG) has also been extensively used to study neural oscillations (via recording the fluctuations in the magnetic field produced by changes in the electrical activity of the brain: Hansen, Kringelbach & Salmelin, 2010).

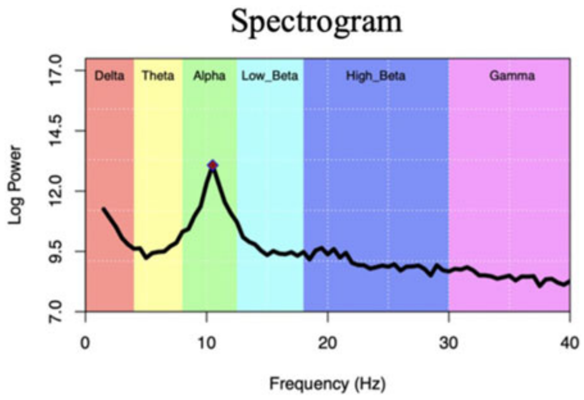
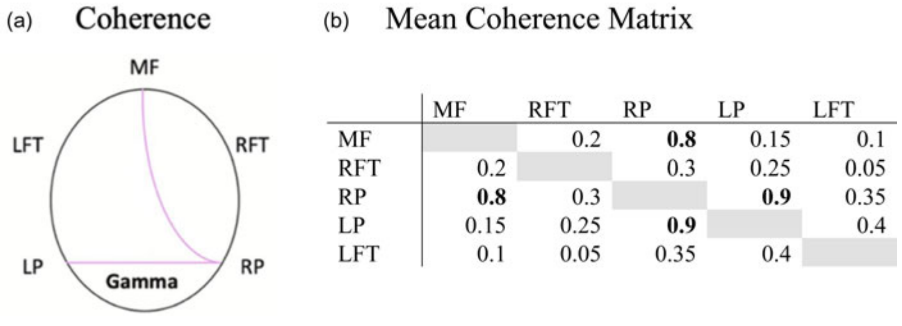


**Figure 1.** Spectrogram of (log) power over frequency depicting the five (to six) classical frequency bands appearing in different colors.

Each frequency band has been associated with a number of perceptual and cognitive processes (e.g., Buzsáki, 2006). Given the large number of recognized cognitive processes and the limited number of frequency bands, there is obviously no one-to-one mapping between a given band and a particular cognitive function. Neural oscillations are more likely to reflect more basic local computations (e.g., feedback, local encoding; see Siegel, Donner & Engel, 2012; Donner & Siegel, 2011), which, recruited by different brain regions, result in the cascading processes needed for various higher-level cognitive tasks. For example, higher frequencies (e.g., gamma) have been associated with local neural processes, whereas lower-frequency bands (e.g., theta) are argued to reflect longer-range cortical communication (Von Stein & Sarnthein, 2000).

There are different ways to examine the spectral content of the EEG signal. One approach is to look at the power spectral density (or simply power), i.e., the amount of rhythmic activity within each frequency band, either across time (time-frequency representation, TFR) or averaged for the time-window of interest. Increase in power at a given site (i.e., single electrode or clusters of electrodes) reflects local synchronous activation within neural assemblies, i.e., distributed local networks transiently linked to perform some basic computations (Varela, Lachaux, Rodriguez & Martinerie, 2001). Alternatively, one could examine mean coherence (or functional connectivity), by determining the degree of frequency band phase-alignment across distinct recording sites (single electrodes or clusters of electrodes) at the scalp or in the source space (see, Figure 2). While some researchers have raised concerns about determining functional connectivity via EEG (Marinazzo, Riera, Marzetti, Astolfi, Yao & Valdés Sosa, 2019), coherence has been interpreted, nonetheless, as reflecting increased synchrony between electrode sites, emerging when there is a stable phase difference between two (or more) recording sites (Varela et al., 2001; Jensen & Mazaheri, 2010). Both power and coherence analyses can be applied to data recorded during any given task-performance (for example, linguistic or cognitive) or at rest.

While time-frequency representations (TFRs) reflect changes in the amount of power for a time-locked event of interest as the cognitive process under investigation unfolds (see Figure 3) (Gröchenig, 2001; Sejdić, Djurović & Jiang, 2009; Papandreou-Suppappola, 2018), resting state EEG (rs-EEG) refers to data recorded at wakeful rest. As it is not associated with any particular task performance, it is argued to capture one's intrinsic neurophysiological activity. Thus, task-free brain oscillatory activity has been associated with overall brain functioning. As such, it is taken to be an indicator of neural readiness, a primary facilitator for the integration of past information into the brain networks for further (future) processing (e.g., Raichle & Snyder, 2007). Rs-EEG power activity is relatively stable over shorter time frames. However, it does shift with age in larger time-spans, accompanying general brain development from infancy through cognitive aging (Anderson & Perone, 2018; Boersma, Smit, de Bie, Van Baal, Boomsma, de Geus, Delemarre-van de Waal & Stam, 2011). Rs-EEG measures have been related to various (neurocognitive) states and processes, such as (i) cognitive decline in Alzheimer's disease and mild cognitive impairment (Cassani, Estarellas, San-Martin, Fraga & Falk, 2018; Meghdadi, Stevanović Karić, McConnell, Rupp, Richard, Hamilton, Salat & Berka, 2021; Stam, 2005), (ii) abnormalities in autism disorders (Murias, Webb, Greenson & Dawson, 2007; Heunis, Aldrich, Peters, Jeste, Sahin, Scheffer & De Vries, 2018; Wang Li, Li, Li, Han & Wan, 2013), (iii) schizophrenia (Kam, Bolbecker, O'Donnell, Hetrick & Brenner, 2013; Sponheim, Clementz, Iacono & Beiser, 2000), (iv) memory consolidation (Brokaw, Tishler, Manceor, Hamilton, Gaulden, Parr & Wamsley, 2016; Jabès, Klencklen, Ruggeri, Michel, Lavenex & Lavenex, 2021), and, critically for our discussion herein, (v) (multilingual) language learning, processing and use (Bice, Yamasaki & Prat,



| | MF | RFT | RP | LP | LFT |
|---|---|---|---|---|---|
| MF | | 0.2 | **0.8** | 0.15 | 0.1 |
| RFT | 0.2 | | 0.3 | 0.25 | 0.05 |
| RP | **0.8** | 0.3 | | **0.9** | 0.35 |
| LP | 0.15 | 0.25 | **0.9** | | 0.4 |
| LFT | 0.1 | 0.05 | 0.35 | 0.4 | |

**Figure 2.** (A) Graphical example of mean coherence or functional connectivity (pink line – see correspondent coherence Matrix highlighted values in panel B) in the gamma band between electrode scalp regions. Coherence was computed by grouping electrodes into five regions of interest (MF = Medial Frontal, LFT = Left Fronto-Temporal, RFT = Right Fronto-Temporal, LP = Left Parietal, RP = Right Parietal). Adapted from Pereira Soares et al. (2021). (B) Hypothetical mean phase coherence matrix of Figure 2A. Mean phase coherence represents statistic interdependencies (usually) between electrodes of pre-specified regions of interest (ROIs) and the degree of functional connectivity between them (Anderson & Perone, 2018; van Diessen et al., 2015). Mean coherence is expressed as a matrix of values in the 0 to 1 range (the closer the value is to 1, the stronger is the connectivity). Mean coherence can also be calculated between adjacent electrodes (i.e., in the same ROI). This, however, was not the case in this example (see grey cells).

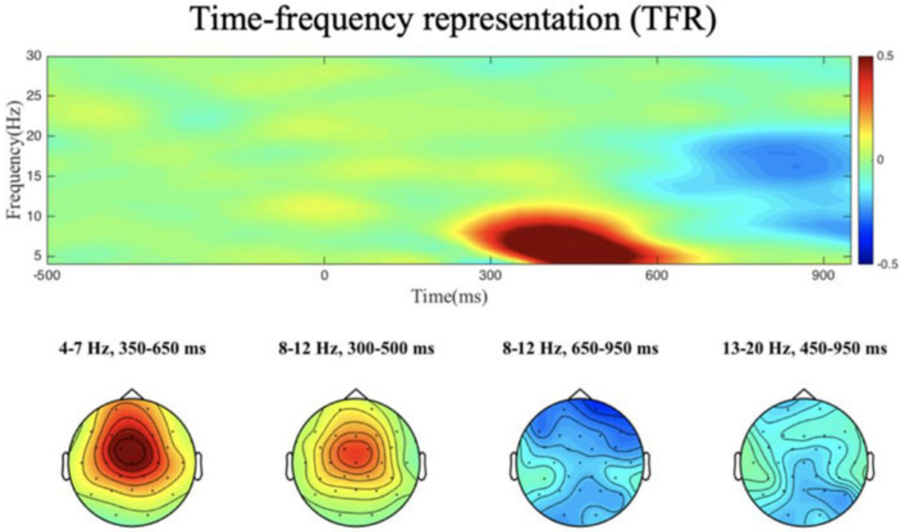


**Figure 3.** Time-frequency representation of a single electrode (upper panel) and its topographical distribution averaged for the time-frequency windows of interest (lower panel). Color in the plots indicates relative power change.

2020; Kliesch, Giroud & Meyer, 2020; Pereira Soares, Kubota, Rossi & Rothman, 2021; Prat, Yamasaki, Kluender & Stocco, 2016; Prat, Yamasaki & Peterson, 2019; Prat, Madhyastha, Mottarella & Kuo, 2020).

The utility of brain oscillatory analysis applying to language science is now well established (see Prystauka & Lewis, 2019 for discussion). While it offers significant opportunities to better understand links between theories and brain mechanisms (Buzsáki & Watson, 2012; Mazaheri, Segaert, Olichney, Yang, Niu, Shapiro & Bowman, 2018; Newson & Thiagarajan, 2019), there are important considerations to keep in mind before one seeks to adopt the method to specific domains, such as bilingualism. In this context, recent advances in neural computational modelling have highlighted some recurrent issues, including the exclusion/neglect of basic methodological assumptions of neural oscillations (see Donoghue, Schaworonkow & Voytek, 2021 for an overview). Failing to herald these concerns increases the risk of false interpretations and inconsistency of results. To offer just one example, many studies looking at brainwaves assume that oscillatory activity and its related power is omnipresent in EEG data. This assumption is not always true. Power in the EEG signal is also present in the form of aperiodic (1/f) activity (or by some initially called 'background noise' – Podvalny, Noy, Harel, Bickel, Chechik, Schroeder, Mehta, Tsodyks & Malach, 2015; Voytek, Kramer, Case, Lepage, Tempesta, Knight & Gazzaley, 2015), whereby power decreases exponentially as a function of frequency (f) (Donoghue, Haller, Peterson, Varma, Sebastian, Gao, Noto, Lara, Wallis, Knight, Shestyuk & Voytek, 2020; Freeman, Burke & Holmes, 2003; He, 2014). As a result, it cannot be *a priori* assumed that all apparent sources of power changes are universally brainwaves, since the power obtained by spectral analysis can also (or solely) derive from aperiodic activity (e.g., Cross, Corcoran, Schlesewsky, Kohler & Bornkessel-Schlesewsky, 2020; Immink, Cross, Chatburn, Baumeister, Schlesewsky & Bornkessel-Schlesewsky (2021) for studies relating 1/f to meaningful individual differences in language and visuomotor/learning domains).

## Unpacking the EEG signal

Although brain oscillations were first observed more than 100 years ago, with the advent of better recording devices and analysis techniques in the 1960s, researchers moved quickly from studying oscillatory phenomena to analyzing Event Related Potentials (ERPs), i.e., the EEG signal analyzed in the time domain and locked to task stimuli. The motivation behind this analytical shift likely relates to the very nature of the EEG signal. In fact, the EEG signal recorded during the execution of a cognitive task is composed of 'meaningful information' or 'signal' (cognitive processes) and 'noise' (background EEG information). Averaging the response signal across many trials from the same experimental condition increases the signal to noise ratio: significantly reducing the noise (assumed to be randomly distributed) and preserving the signal (assumed to be stationary) (Handy, 2005; Luck, 2012). It would be reasonable to say that within EEG applications in psycho-neurolinguistics research, ERP studies have dominated the landscape over the past few decades (Luck & Kappenman, 2011; Steinhauer, Connolly, Stemmer & Whitaker, 2008). There is no doubt that ERP research has provided significant foundational discoveries about both the time course and the neural basis of various underlying cognitive processes, including those involved in or conditioned by language.

In recent years however, interest in the spectral content of the EEG signal has resurged. This renewed interest is borne of the reality that much information inevitably gets lost when the EEG signal is averaged in the time domain. This is especially the case when related to coupling and decoupling (i.e., the dynamic segregation of brain circuits into transiently reconfigured functional networks) mechanisms of neural pools involved in cognitive processes (e.g., Varela et al., 2001). Interestingly, the upsurge of studies looking at brainwaves parallels the development and incremental use of modern (f)MRI imaging techniques that focus on network dynamics and functional connectivity (Sulpizio, Del Maschio, Fedeli & Abutalebi, 2020). This parallel development demonstrates the growing perception in cognitive neuroscience that functional network dynamics sit at the core of human cognition (Fell, 2007; Luck & Kappenman, 2011).

When examining the EEG response as a function of an experimental event, one can observe two different types of oscillatory activity changes: phase-locked (evoked) and non-phase-locked (induced). Whereas time-locked oscillatory activity is intrinsically bound to an event, the same is not (always) true for non-phase-locked activity. This is the case because oscillations exist in the absence of external stimuli and their phase varies at the onset of the events throughout the experiment. Averaging across trials will reduce, if not cancel, non-phase-locked responses (see Figure 4).

The non-phase-locked signal is particularly informative when relating to patterns of synchronization and desynchronization of neuronal activity across neural networks/pools. Evidence over the past few decades has revealed that neural (de)synchronization strictly relates to coupling and decoupling of functional networks in the brain (e.g., Pfurtscheller & Berghold, 1989; Singer, 1999; Varela et al., 2001). Underlying this claim is the observation that synchronous, repetitive neuronal firing facilitates the activation of functional brain networks, which, in turn, increases the likelihood of neuronal entrainment and subsequent synchronous firing (e.g., König & Schillen, 1991). Additionally, elements belonging to the same functional network tend to fire synchronously at any given frequency. This frequency specificity permits neuronal pools to participate at different times in different representations. Thus, the synchronous oscillatory activity in many frequencies plays a crucial role in connecting areas that belong to the same functional network. More importantly, not only does oscillatory neuronal synchrony serve the purpose of recruiting all the relevant elements in a network, it also binds together the information within these different elements (Gray, König, Engel & Singer, 1989). Given that a base level of synchrony in neural firing is constantly present, oscillatory activity dominates raw EEG data.

To sum up, experimental stimuli/events occur at random phases of the ongoing oscillatory cycle and will modulate these oscillations, giving rise, therefore, to non-phase-locked responses. That is, different from phase-locked responses (ERPs), non-phase-locked ones mostly reflect synchronization of underlying neuronal and network activity. Since (de)synchronization activity is a proxy for coupling and decoupling of functional networks, it follows that non-phase-locked oscillatory EEG responses provide researchers with a window into functional (network) brain dynamics, which is especially useful to researchers working within the cognitive neuroscience of bi-/multilingualism.

Furthermore, for researchers who primarily use ERPs to study linguistic processing, it is useful to highlight both the overlap (where the two index the same thing) and improved complementarity of TFRs to ERPs (where TFR provides extra information to what ERPs can show). For example, going back to one of the classic ERP components found in psycholinguistic studies, the N400, applying a TFR approach to the ERP has been shown to manifest as delta and theta power increase (Roehm, Schlesewsky, Bornkessel, Frisch & Haider, 2004; Steele, Bernat, Van Den Broek, Collins, Patrick & Marsolek, 2013). Additionally, there is research suggesting the relationship between N400 and beta power (Wang, Jensen, Van den Brink, Weder, Schoffelen, Magyari, Hagorrt & Bastiaansen, 2012), however, the results are mixed (Lewis, Schoffelen, Hoffmann, Bastiaansen & Schriefers, 2017). In this respect, further scrutinizing the relationship between ERPs and TFR components will move the field of cognitive neuroscience of language and bilingualism closer to understanding the neural mechanisms underlying these common EEG signatures. Given the (partial) translateability, one does not have to sacrifice the information provided by ERPs if a TFR approach is adopted. In the case that both are applied, they can provide a confirmatory approach – that is, adopting both and probing for overlap (e.g., that the N400, in fact, translates to power in the delta, theta or beta domain(s)) can improve the ecological validity of what one or the other show in isolation. However, ERPs are incapable of providing information regarding induced power (see Figure 4). Induced power refers to neural activity modulated by an event of interest, yet not phase-locked to it. This potentially occurs more prevalently than what one might expect given that research has shown that the phase of an oscillation induced by an event can vary significantly across trials (Donoghue et al., 2021). This is important to bear in mind as it means that some significant information could be missed by an ERP approach. In the case of TFRs, increased granularity and relevant sensitivity is to be expected.With an eye specifically on application of oscillatory dynamics in bilingual research, what does it bring to the table above and beyond what ERPs have

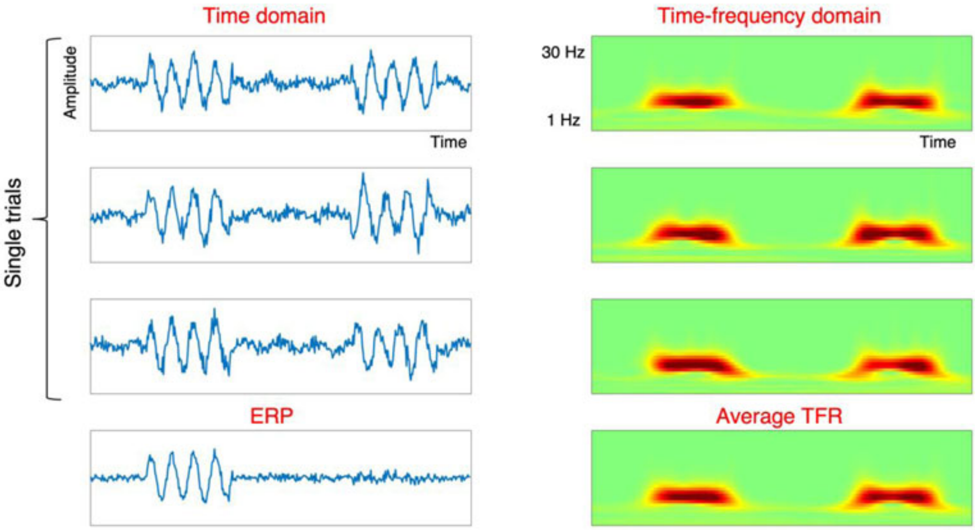


**Figure 4.** Demonstration of phase-locked (evoked) and non-phase-locked (induced) activity in the simulated EEG time series (on the left) and in the time-frequency domain (on the right), both in individual trials (the upper three panels) and in the average response (the bottom panel). The plots in the bottom panel demonstrate how the phase-locked response is preserved in both the ERP and the average TFR responses, and how the non-phase-locked response is cancelled out in the ERP but is preserved in the average TFR. Adapted from Bastiaansen et al. (2011), implemented based on the code from Cohen, 2014.

already told us? First, its augmented sensitivity means that it is able to capture signal changes that vary in time and phase across trials and participants (Kielar, Meltzer, Moreno, Alain & Bialystok, 2014). As Kielar and colleagues (2014) point out, when the observed ERP effect is qualitatively different (as observed in non-native language processing, especially at lower levels of L2 proficiency e.g., Foucart & Frenck-Mestre, 2012; Morgan-Short, Steinhauer, Sanz & Ullman, 2012; Martin, Thierry, Kuipers, Boutonnet, Foucart & Costa, 2013; Gabriele, Fiorentino & Alemán-Bañón, 2013; Alemán-Bañón, Fiorentino & Gabriele, 2018), strong conclusions are often made. For example, it has been claimed on the basis of such evidence that acquisition/processing is fundamentally different between natives and non-natives (Foucart & Frenck-Mestre, 2012). In actuality, it is spurious to make such sweeping conclusions as differences might rather reflect reduced neural activity or greater phase variability in a particular population. Instead, looking at the power of the induced (non-phase-locked) activity can help discriminate between competing interpretations.

Second, introducing a(n additional) frequency dimension to the analysis of the EEG signal multiplies the number of ways we can look at the data and enables us to ask new –different – questions ERPs alone cannot address. Let us consider a few examples here. First, one can use brainwave analysis to examine changes in rs-EEG as a function of bilingual experience – that is, (how) does (the degree of) dual language exposure and usage patterns affect cumulative neural change in the bilingual brain in the short and long terms (Luk, Pliatsikas & Rossi, 2020; Pereira Soares et al., 2021). Second, frequency analysis permits the exploration of the role exponents of bilingualism (e.g., different language use profiles) play in how brain oscillations might differentially synchronize with physical (e.g., syllable rate) and abstract (e.g., syntactic structure) linguistic units (Blanco-Elorrieta, Ding, Pylkkänen & Poeppel, 2019). Given that neural oscillations have been extensively studied in broader fields of cognitive neuroscience for a considerably long time, bringing them to the bilingualism domain opens up several possibilities. TFRs are, thus, poised to improve interpretations of apparent bilingual effects on linguistic processing, brain and cognition in the context of the broader neuroscience literatures on memory, attention, cognitive control, motivation, etc.

## Using brain oscillations to examine language processing: general findings and new applications to bilingualism

The contemporary upsurging trend of analyzing neural oscillations in language processing is fairly recent (Meyer, 2018; Prystauka & Lewis, 2019). This work has revealed important insights for investigating the underlying domain-general and language-specific subcomponents of linguistic processing, from the lower levels (e.g., segmentation and identification of phonological units) to higher levels of information (e.g., comprehension of lexical, semantic, and syntactic information). Despite some variability, research shows relatively consistent patterns of oscillatory activity for different aspects of language processing. For example, theta oscillations have been linked to lexical-semantic retrieval (Bastiaansen & Hagoort, 2003), while beta and gamma oscillations have been connected to syntactic and semantic structure building, respectively (Bastiaansen & Hagoort, 2006; see Prystauka & Lewis, 2019 for a more comprehensive review). However, theta, beta and gamma have also been associated with a multitude of domain general cognitive processes. To name a few, theta power with a frontocentral topography has been associated with cognitive control (Cavanagh & Frank, 2014) and short-term memory (Hsieh & Ranganath, 2014). Alpha oscillations are thought to play a role in inhibiting task-irrelevant information by means of 'gating by inhibition' (Jensen & Mazaheri, 2010) and 'inhibition-timing' (Klimesch, Sauseng & Hanslmayr, 2007). Beta oscillations have been proposed to reflect maintenance of the current cognitive set (Engel & Fries, 2010) and the top-down propagation of predictions to lower levels of processing. Moreover, gamma oscillations might reflect the matching of top-down prediction and bottom-up input processing (Herrmann, Munk & Engel, 2004; Bastos, Usrey, Adams, Mangun, Fries & Friston, 2012).

One of the ways in which neural oscillations have been used to study language processing has been to investigate the phenomenon of entrainment (phase-resetting and alignment) of neural oscillations to discrete phonological units in the speech stream (Luo & Poeppel, 2007; Giraud & Poeppel, 2012). Such entrainment has been speculated to support the identification of linguistically meaningful segments (phonemes, syllables and phrases), used by higher-level processing mechanisms for syntactic and semantic structure-building. Previous research suggests that gamma oscillations track the phonemic rate of speech, theta oscillations are modulated by the syllabic structure, and delta oscillations are sensitive to phrase boundaries (for review, see Kösem & van Wassenhove, 2017), phase-locking of neural oscillations to the phase of external physical stimuli such as speech – and intrinsic synchronization reflecting the generation of predictions of abstract linguistic units such as morphemes and words (see Meyer, Sun & Martin, 2020; Meyer, Grigutsch, Schmuck, Gaston & Friederici, 2015; and related commentaries). At higher levels of language processing, neural oscillations have been used to study: (i) semantic and syntactic structure building, including scenarios where such structure building is disrupted by semantic and syntactic anomalies (Bastiaansen, Magyari & Hagoort, 2010; Davidson & Indefrey, 2007; Lewis, Schoffelen, Schriefers & Bastiaansen, 2016; Kielar et al., 2014; Kielar, Panamsky, Links & Meltzer, 2015), (ii) anticipatory (Piai, Anderson, Lin, Dewar, Parvizi, Dronkers & Knight, 2016; Rommers, Dickson, Norton, Wlotko & Federmeier, 2017) and referential processing (Meyer et al., 2015; Nieuwland & Martin, 2017), (iii) situationally dependent and nonliteral language (Akimoto, Takahashi, Gunji, Kaneko, Asano, Matsuo, Ota, Kunugi, Hanakawa, Mazuka & Kamio, 2017; Canal, Pesciarelli, Vespignani, Molinaro & Cacciari, 2017) and (iv) working memory pertaining to sentence level meaning comprehension (Meltzer & Braun, 2011; Vassileiou, Meyer, Beese & Friederici, 2018; Rommers & Federmeier, 2018) as well as the role of the sensorimotor networks in language comprehension (Lam, Bastiaansen, Dijkstra & Rueschemeyer, 2017; Moreno, de Vega & León, 2013; Moreno, de Vega, León, Bastiaansen, Lewis & Magyari, 2015).

Despite the utility of neural oscillations within the native-language processing literature, its application in bilingualism remains a relatively uncharted territory. In our view, this is a missed opportunity. As framed in what follows, experimental paradigms utilizing oscillations have the potential to reveal, if not eventually disentangle, the relative roles/contributory weightings of cognitive and linguistic mechanisms recruited during bilingual language processing. To date, only a few bilingual studies have sought to capitalize on the (time-)frequency dimension of electrophysiological signals. Starting with the lower levels of language processing, Blanco-Elorrieta et al. (2019) used MEG to examine syllable and phrase tracking by bilingual speakers with varying degrees of language proficiency under different noise conditions. They found that syllable tracking, as reflected in theta power, was affected by noise equally in Mandarin-natives with various degrees of English L2 proficiency. In contrast, phrase tracking (reflected in delta power) was modulated by both noise strength and language proficiency, such that with increasing proficiency L2 speakers were better able to track phrases under more severe noise conditions. These results suggest that processing an L2 might differ from processing one's native language, starting already at lower levels of parsing out the incoming speech stream into its building blocks (McCauley, Isbilen & Christiansen, 2017). Segmentation difficulties at this level could then have upstream effects for higher-level semantic and syntactic processing, explaining differences observed among speakers with different levels of proficiency. This work highlights how examining the frequency domain can open up new avenues for exploring the interaction between low- and high-level processing. In particular, it speaks to how this interaction potentially changes as a function of language experience and use, a topic with significant implications for bilingual sentence processing (and any neurocognitive dual language effects) more generally. For example, this could mean that some evidence taken to reflect *bona fide* or apparent patterns of shallow L2 processing (Clahsen & Felser, 2006; 2018) at a higher level might begin at a much lower level, at least under noise in the lab (if not the NOISE of the real world).

We should bear in mind that the Blanco-Elorrieta et al. (2019) study involves entrainment. Entrainment is conceptually distinct from other relevant approaches using brain oscillations of equal importance and contextual appropriateness for examining (bilingual) language processing. As mentioned above, entrainment examines synchronization of neural oscillations to the rhythmic properties of the external signal (i.e., speech). However, an approach more suited for examining brain activation as a function of more abstract linguistic manipulations is the analysis of power fluctuations over time.

While the linguistic and the cognitive bases of bilingual language acquisition/processing and coactivation have been extensively studied using behavioral, ERP, and other neuroimaging methods (Tolentino & Tokowicz, 2011; DeLuca, Miller, Swanson & Rothman, to appear; DeLuca, Miller, Pliatsikas & Rothman, 2019a for reviews), only a few bilingual studies have used neural oscillations. A particularly illustrative example is the study by Bakker, Takashima, Van Hell, Janzen and McQueen (2015) investigating changes in oscillatory dynamics during novel word learning. Participants were exposed to new words during a learning phase that were designed to phonologically compete with existing English words (i.e., *cathedruk*, competing with the existing word *cathedral*). In the recall phase, participants were exposed to the newly learned words plus novel ones. It was predicted that if the new words are encoded and consolidated in memory they should compete for selection with existing (English) lexical items, as signaled by higher RTs during the memory recall phase (tested 24 hours later). As hypothesized, newly learned words showed longer RTs than unfamiliar, completely novel words, suggesting that the former started to compete for selection with existing lexical items. Crucially, oscillation results revealed an increase in theta frequencies (4-8 Hz) for the newly learned words, interpreted as theta-band oscillations playing a role in lexicalization and memory encoding.

The results of Bakker et al. (2015) were supported by a follow-up study using MEG (Bakker-Marshall, Takashima, Schoffelen, Van Hell, Janzen & McQueen, 2018), demonstrating a modulation of theta after novel word consolidation and connecting the source of the oscillation to the left posterior middle temporal gyrus (pMTG), which is involved in lexical storage (see Nozari & Pinet, 2020 for a review). In line with their previous results, the authors concluded that theta synchronization may enable lexical access by activating the distributed semantic, phonological, and orthographic representations of the newly learned words.

The general finding that theta is connected to memory consolidation is supported by other data (Lisman, 2010; Lisman & Jensen, 2013), including a study on word translation in English–German bilinguals (Grabner, Brunner, Leeb, Neuper & Pfurtscheller, 2007). Grabner et al. (2007) showed modulations in theta specifically for higher frequency words, which could reflect a greater role of memory for lexical items that have larger semantic networks. These results are similar to those of Bastiaansen, Van Berkum and Hagoort (2003), for which increased theta for semantically rich versus semantically impoverished words in monolingual speakers was observed. This was argued to suggest that theta increase may be reflective of the "activation" of larger semantic networks. As discussed below, beyond the single word level, modulations of theta power and coherence (together with alpha, beta and gamma) have been proposed to reflect the coordination of working memory and the selection/retrieval of networks during sentence processing (Bastiaansen & Hagoort, 2006; Hagoort, 2005), and the overall engagement of working memory resources (see Meyer, 2018 for a review).

At the sentence level, Kielar et al. (2014) conducted one of the first studies on differences in oscillatory patterns during sentence processing between bilinguals and monolinguals, reanalyzing a dataset from Moreno, Bialystok, Wodniecka and Alain (2010). The original EEG data was collected for an ERP study comparing sentences that were grammatical (and felicitous) with some that were semantically infelicitous or syntactically incorrect. Kielar et al. (2014) revealed decreases in alpha-beta frequencies across the monolingual and bilingual groups for both semantic and syntactic violations. Moreover, delta and theta increases were observed only for the semantic violation condition. Of note, bilinguals had a smaller decrease in alpha and beta bands to syntactic violations compared to monolinguals, which was interpreted as reflecting more efficiency for bilinguals in the face of equal behavioral performance.

Rossi and Prystauka (2019) investigated the time-course of oscillatory activity during the processing of Spanish gender and number (expressed via agreement on clitic pronouns) in native speakers of Spanish and in English second language (L2) learners of Spanish. The results demonstrated that both native and L2 speakers showed a decrease in alpha and beta bands when agreement on the clitic was violated. Critically, the two groups differed in the duration of the observed effect, such that the oscillatory effect in Spanish native speakers lasted longer than the one observed in L2 learners. This difference was explained in the context of the updated theory of Hebb's cell assembly framework (Hebb, 1949), whereby cell assemblies have two distinct phases of activation: a fast ignition phase and a reverberation phase. The authors hypothesize that differences in processing would manifest in the reverberation phase as decreased duration of the oscillatory response to morpho-syntactic violations in bilinguals relative to monolinguals. In light of previous work showing that syntactic processing can be constrained by working memory (WM) (Vos, Gunter, Kolk & Mulder, 2001; Coughlin &

Tremblay, 2011), one explanation could be that the reverberation phase is decreased in bilinguals because of the higher working memory load due to competing information from their coactivated second language (Kroll, Bobb & Wodniecka, 2006; Blumenfeld & Marian, 2007).

## Using oscillations as a window to understand bilingual language control

A hallmark finding of neurocognitive bilingualism research is the pervasive, simultaneous co-activation of the two languages (Blumenfeld & Marian, 2013; Green, 1998; Hoshino & Thierry, 2011), even at the earliest/lowest stages of proficiency. In fact, relevant ERP studies have shown that L2 learning can be rapid and efficient (Bakker et al., 2014, 2015; Morgan-Short et al., 2012), even in the absence of evidence in behavioral performance (McLaughlin, Osterhout & Kim, 2004; Osterhout, Poliakov, Inoue, McLaughlin, Valentine, Pitkanen, Frenck-Mestre & Hirschensohn, 2008; Tokowicz & MacWhinney, 2005). For example, speakers can learn and consolidate new words in a novel language in the span of only 24-48 hours. Crucially, those new words immediately begin to compete for selection with the native language, revealing the plasticity of the linguistic system (Bakker et al., 2015).

Moreover, given the ample evidence of coactivation in all instances of bilingual language acquisition, one of the key questions that has driven neurocognitive bilingual research in general has been to understand the behavioral and neural mechanisms that enable bilingual speakers to manage dual language competition. Simultaneous language coactivation requires a mechanism of control to manage contextually appropriate language selection. Indeed, managing and resolving competition is vital for target language selection, a crucial and necessary aspect for successful speech production and comprehension (Kroll, Dussias, Bogulski & Valdés-Kroff, 2012). Early models of bilingual language processing proposed that the relevant mechanism is domain-general cognitive control (e.g., the Inhibitory Control Model, Green, 1998; Levy, McVeigh, Marful & Anderson, 2007; Linck, Kroll & Sunderman, 2009; Philipp, Gade & Koch, 2007). The proposal that inhibition (potentially attention more broadly, see Bialystok & Craik, 2022) is at the center of successful bilingual language control is supported by a significant neuroimaging literature. Available work is largely consistent with the claim that continuous juggling of two (or more) languages in the brain engages neural networks involved in domain general cognitive control, especially those that overlap with language control. Research has consistently shown that dual language use, at least past a certain threshold of experience, impacts cortical (Abutalebi, Della Rosa, Green, Hernandez, Scifo, Keim, Cappa & Costa, 2012; Mechelli, Crinion, Noppeney, O'Doherty, Ashburner, Frackowiak & Price, 2004; Pereira Soares, Ong, Abutalebi, Del Maschio, Sewell & Weekes, 2019; Pliatsikas, Johnstone & Marinis, 2014; Stein, Federspiel, Koenig, Wirth, Strik, Wiest, Brandeis & Dierks, 2012) and subcortical/basal ganglia (Burgaleta, Sanjuán, Ventura-Campos, Sebastian-Galles & Ávila, 2016; Pliatsikas, DeLuca, Moschopoulou & Saddy, 2017; Zou, Ding, Abutalebi, Shu & Peng, 2012), white matter tracts (Kuhl, Stevenson, Corrigan, van den Bosch, Can & Richards, 2016; Mohades, Van Schuerbeek, Rosseel, Van De Craen, Luypaert & Baeken, 2015; Rossi, Cheng, Kroll, Diaz & Newman, 2017), functional adaptations (Luk, Anderson, Craik, Grady & Bialystok, 2010; Olulade, Jamal, Koo, Perfetti, LaSasso & Eden, 2015; Rossi, Newman, Kroll & Diaz, 2018), resting state functional connectivity (e.g., Grady, Luk, Craik & Bialystok, 2015; Luk, Green, Abutalebi & Grady, 2012; Rodríguez-Pujadas, Sanjuán, Ventura-Campos, Román, Martin, Barceló, Costa & Ávila, 2013) and even the chemical composition of the brain (Pliatsikas, Pereira Soares, Voits, DeLuca & Rothman, 2021; Weekes, Abutalebi, Mak, Borsa, Pereira Soares, Chiu & Zhang, 2018). These neuroimaging findings have been fairly consistent across studies (see Pliatsikas, 2020; Zhang, Wu & Thierry, 2020 for recent reviews).

More recently, studies have turned to address the complex and dynamic nature of bilingualism as a set of individual difference factors proxying for the relative opportunities and intensity one has with engaging dual language control. In other words, bilingualism and any potentially ensuing effects are viewed as spectral (continuous variables) as opposed to absolute (e.g., Luk & Bialystok, 2013; Li, Abutalebi, Zou, Yan, Liu, Feng, Wang, Guo & Ding, 2015; Beatty-Martínez & Dussias, 2019; DeLuca, Rothman, Bialystok & Pliatsikas, 2019b; DeLuca, Segaert, Mazaheri & Krott, 2020; Gullifer, Chai, Whitford, Pivneva, Baum, Klein & Titone, 2018; Kuhl et al., 2016; Sulpizio et al., 2020). With the above as a backdrop, the question of how EEG analyses have contributed and/or should contribute to this general program comes to the fore. In many ways, EEG is ideal for studying similar things that much of the MRI literature reviewed in brief above has showed. While EEG and MRI as methods have (some) functional overlap, making EEG a complementary (also a more time and cost effective approach) tool to MRI, there are things that EEG is potentially better positioned to address. Moreover, EEG predictions and their correspondences to those of (f)MRI stemming from models of bilingual neurocognitive adaptations – for example, the Adaptive Control Hypothesis (ACH, Abutalebi & Green, 2016) and the Bilingual Anterior to Posterior and Subcortical Shift model (BAPSS, Grundy, Anderson & Bialystok, 2017) – have recently been offered by the Unifying Bilingual Experience Trajectory model (UBET, DeLuca et al., 2020). And yet, comparatively few studies have opted to use EEG over MRI.

Recall that EEG allows one to capture processes as they unfold in real time and, thus, not observable with MRI (a tool primarily concerned with a final observable outcome). Several early ERP components have been identified that relate to the increased effort required while performing demanding cognitive tasks: (i) the fronto-central N200 and fronto-central/parietal P300, which have mostly been associated with information updating, attention and inhibition of processing costs (e.g., Groom & Cragg, 2015; Heil, Osman, Wiegelmann, Rolke & Hennighausen, 2000), (ii) the Error Related Negativity (ERN), which indexes conflict monitoring (e.g., Botvinick, Braver, Barch, Carter & Cohen, 2001; Gabrys, Tabri, Anisman & Matheson, 2018) and (iii) the N450, which reflects both conflict monitoring and inhibition (Larson, Kaplan, Kaushanskaya & Weismer, 2020; Zahedi, Abdel Rahman, Stürmer & Sommer, 2019) (see Cespón & Carreiras, 2020 for a review on bilingualism, cognition and ERPs). Findings so far in this literature are mixed with regard to bilingual brain adaptations. Whereas some have found no differences between monolinguals and bilinguals (e.g., Fernández, Tartar, Padron & Acosta, 2013; Kousaie & Phillips, 2012; Moreno et al., 2015), others have shown either only neurophysiological adaptations (e.g., Bice et al., 2020; Morrison, Kamal & Taler, 2019), behavioral effects (e.g., Zunini, Morrison, Kousaie & Taler, 2019; Morales, Yudes, Gómez-Ariza & Bajo, 2015), or both (e.g., Barac, Moreno & Bialystok, 2016; Kousaie & Phillips, 2017).

While ERP studies in this domain are already scarce, there are even fewer studies analyzing neural oscillations. To the best of our knowledge, only four studies have been published to date. Given this small number, in what follows, we summarize in some detail the entirety of the available data. Inspired by work done on second language learning (Prat et al., 2016, 2019), Bice et al. (2020) investigated the effects of bilingual language use on the brain using rs-EEG correlates (both power and mean coherence). Results from a large sample of bilinguals (106) and monolinguals (91) revealed that bilinguals had increased alpha power and more pronounced and greater coherences in both alpha and beta frequency bands. Furthermore, data showed that alpha positively correlated with individual difference variables: i.e., more second language use, higher native-language proficiency, and earlier age of second-language acquisition. Similarly, beta power corresponded to non-native proficiency and theta to native-language proficiency (left-lateralized). These findings highlight the significant relationship between (the degree of) language use and the intrinsic plasticity of neurocognitive brain correlates. As such, these data add an important piece to the growing literature connecting neurocognitive adaptations and bilingualism.

Adopting a bilingual-centric approach where bilingualism is treated as a continuum regressed to experiential variables of dual language engagement and, thus, sidesteps the more traditional monolingual comparison (Luk & Bialystok, 2013; DeLuca et al., 2019a, 2020; Gullifer & Titone, 2020), Pereira Soares et al. (2021) collected rs-EEG data from a diversified pool of 106 bilinguals. Participants varied across several key dimensions, e.g., early versus late bilinguals (heritage (minority) language speakers and adult L2 learners), geographical location (Germany and Norway), age of onset, cumulative duration of bilingualism, social and home distribution of their language use and more). It was predicted that rs-EEG measures (power and functional connectivity) would vary across individuals as a function of degree of bilingual engagement. As predicted, results showed effects of AoA of bilingualism on high beta and gamma powers and greater usage of the non-societal language in and out of the home to modulate mean coherence indices in theta, alpha and gamma powers. These findings fortify the view of rs-EEG as a complementary measure for the neuroscience of bilingualism, and are consistent with claims that variability in dual-language engagement modulates observed neurocognitive effects.

Two recent studies using time frequency representation (TFR) analysis find complementary results. Calvo and Bialystok (2021) tested bilingual and monolingual participants on a Proactive Interference Task in both verbal and nonverbal conditions while behavioral and EEG measures were recorded. Behavioral findings replicated related studies in the literature, showing faster RTs for bilinguals in comparison to monolinguals during interference trials, especially in the nonverbal condition. An ERP analysis revealed a larger N200 and decreased late positive component (LPC) amplitude for bilinguals in comparison to the matched monolingual group in the verbal condition. These findings were interpreted as bilinguals having more efficient task performance. Demonstrating the utility and complementarity of combining ERP and TFR, the TFR analysis showed differential patterns of results for the two groups. For the bilinguals, the nonverbal condition induced higher beta activity for interference trials, whereas theta and gamma frequencies were observed in relation to the verbal condition. For the monolingual group, oscillatory activity measures were associated with facilitation trials. All together, these different measures indicate a complex impact of bilingualism on neural networks and highlight differential processing/strategies and allocation of attentional resources to avoid interference for the two groups.

Similarly, with a subset of the participants from Pereira Soares et al. (2021), Pereira Soares, Prystauka, DeLuca and Rothman (2022) used TFRs to investigate how different types of bilinguals perform on a task of inhibitory control (i.e., Flanker task). The difference between incongruent and congruent trials was computed and used to (i) compare brain correlates between HSs and L2 learners (ii) look into individual differences in language experience of bilingualism at the individual and group (bilingual type: early versus late) level (iii) investigate if neural measures predict behavioral performance. No differences were found at the brain level in the between-group comparison. However, regressions of bilingual experiential factors (within each group) to the neuronal data revealed that specific oscillatory correlates of inhibitory control (mainly theta activation and alpha suppression) were modulated by certain experience variables within a given bilingual type. Finally, opposing signatures were observed in the relationship between oscillatory data and RTs. All together, these findings indicate differential shifting and adaptations of brain network recruitment to cope with the cognitive demands involved in variation in bilingual language experience. However, these brain adaptations seem to follow differential trajectories across early versus late bilinguals, highlighting how bilingual experience matters across the board, including the age at which individuals first become bilingual.

## Conclusions and Future directions

The study of the brain's oscillatory activity has only very recently started to be utilized to study bilingualism and its neural underpinnings. Herein, we provided a description of the characteristics of the human oscillatory signal, and an in depth description of the various types of analyses that pertain to the EEG oscillatory signal. With these tools explained, we explored the emerging literature on neural oscillations and bilingualism, highlighting how analyzing the human EEG signal through neural oscillations can continue to advance our knowledge and understanding of the dynamicity inherent to linguistic and cognitive processes underlying bilingualism.

As revealed by the most recent literature in the field, language processing and neurocognitive effects are highly variable, especially in bilingualism for which internal and external variables condition the way speakers acquire and use their languages across the lifespan. Recent research in bilingualism has already underscored how differences in bilingual language use can be harnessed to better understand how individuals engage linguistic and cognitive functions differentially. The overall findings from the emerging research in the field indicate that the oscillatory activity of the brain informs processes of neural network recruitment and brain processing adaptations likely due to individual-level demands on bilingual language processing and control. The reduced cost (relative to other neuroimaging), relative accessibility and flexibility of conducting EEG studies in combination with the increased temporal resolution afforded by the analysis of neural oscillations, and the capability of neural oscillations to better discriminate across underlying neural linguistic and cognitive components offers an opportunity to make significant breakthroughs in the study of the effects of bilingualism on linguistic representation, language processing and effects on cognition and brain function. In particular, not least since EEG is portable, neural oscillation analyses (coupled with ERPs) stand out as a method of promise to gather data from more participants with a wider and more representative sampling (i.e., potential for increasing statistical power, Brysbaert, 2021, and diversifying the pools of participants, the contexts of bilingualism and the language pairings considered). In addition, as we look at a growing literature in neural oscillations and bilingualism, it will be possible to link the emerging results to other data in human neurocognition, enabling greater connections between neural and behavioral data across fields in human cognition.

To conclude, we welcome the wider diffusion of this technique in the field as a yet additional tool of validity for data found with complementary methods while simultaneously injecting greater ecological validity in bilingual language research at multiple levels. If the goal of the article was successful, researchers interested in bilingualism and the brain/linguistic processing will have the basis required to find their way through the covered growing literatures and apply the theoretical knowledge acquired to inform bilingualism research moving forward.

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