Is there electrophysiological evidence for a bilingual advantage in neural processes related to executive functions?

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Abstract

Over the last two decades, a large number of studies have concluded that bilingualism enhances executive functions. However, other studies have reported no significant results. In addition, it is not clear how bilingualism might modulate specific executive control processes. Event-related potentials (ERP) are an excellent technique for identifying whether the neural correlates of executive control processes are strengthened by bilingualism, given their high temporal resolution. On the basis of previous research into the ERP correlates of executive functions, we hypothesize that specific ERP differences between monolinguals and bilinguals can be considered to indicate a bilingual advantage in executive functions. We then review the very limited number of studies that have investigated ERP differences between monolinguals and bilinguals during the performance of executive control tasks. Overall, we conclude that the existence of a bilingual advantage in neural processing related to executive functions remains uncertain and further studies are required. We highlight the utility of investigating several ERPs that have been ignored by previous studies.

Keywords: executive functions; event-related potentials; cognitive reserve; bilingualism.

1. Introduction and scope of the study

In recent years, a number of scientists and the mass media have promoted the idea that bilingualism (i.e., the ability to fluently communicate in two different languages) strengthens executive functions, a set of cognitive processes that allow for flexible planning and implementation of goal directed actions crucial for performing daily activities (Chan et al., 2008; Diamond, 2013). This has been termed the *bilingual advantage*[1], an advantage sometimes claimed to protect bilinguals from dementia. In fact, the existence of such benefits remains controversial. On the one hand, over the last two decades, a large number of studies have reported that bilingualism improves executive functions. This improvement has been ascribed to daily practise in inhibiting the non-target language during conversation and to switching attention between languages (Bialystok, 2017). If true, such findings would have important socio-economic implications since they imply that bilingualism may enhance cognitive reserve (Bialystok et al., 2016). The development of cognitive reserve relies on exposure to cognitively stimulating experiences, which optimize brain function and delay the onset of dementia (Stern, 2012). A substantial number of studies in elderly individuals have established relationships between higher cognitive reserve and enhanced executive functioning (Cabral et al., 2016; Corral et al., 2006; Darby et al., 2017; Roldán-Tapia et al., 2012). Interestingly, several cognitive reserve questionnaires (e.g., León et al., 2016; Rami et al., 2011) include bilingualism/multilingualism as a dimension of cognitive reserve. According to this view, bilinguals exhibit higher cognitive reserve than monolinguals when matched for all cognitive reserve factors except the number of spoken languages. In line with these claims, some studies have reported that bilingualism delays the onset of clinical Alzheimer's disease (AD) for several years (Alladi et al., 2013; Bialystok et al., 2007; Gollan et al., 2011). This protective effect has been attributed to increased levels of cognitive reserve in bilinguals compared to monolinguals (Bialystok et al., 2016). On the other hand, recent comprehensive reviews (Paap et al., 2015) and meta-analytical

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[1] In this manuscript, for the sake of simplicity, we will use the term "bilingual advantage" to mean facilitation in tasks that tap into cognitive processes related to executive functions.

studies (Lehtonen et al., 2018) have shown that bilingualism does not enhance executive functions. Critically, it has also been argued that publication bias is responsible for the higher number of published studies that claim a positive relationship between bilingualism and executive function (de Bruin et al., 2015). Moreover, several longitudinal studies have not found any differences between the age of AD onset in monolinguals and bilinguals (Lawton et al., 2015; Yeung et al., 2014; Zahodne et al., 2014). However, some studies suggest that the relationship between bilingualism and the onset of dementia relies on a specific type of bilingualism. For instance, Atkinson (2016) reported that bilingualism acquired during childhood may protect against dementia, while bilingualism acquired during adulthood does not seem to have any such effect.

While there are a considerable number of behavioural studies showing evidence for a bilingual advantage in *inhibition* or the ability to suppress irrelevant information (Bialystok et al., 2004; Bialystok et al., 2008; Bialystok et al., 2014) and in *switching* abilities or the ability to disengage attention from one stimulus or set of features and deploy it to others (Grundy et al., 2017b; Prior and Macwhinney, 2010; Vega-Mendoza et al., 2015), there are also a substantial number of studies showing no behavioural differences in inhibition (Antón et al., 2016; Kirk et al., 2014) or switching (Mor et al., 2015; Ramos et al., 2017). Several studies have also investigated other executive functions, specifically, *working memory* and *conflict monitoring*. Working memory includes a set of cognitive processes that let us encode, store, maintain, retrieve, and manipulate information for a short period of time (Baddeley, 2003). Conflict monitoring refers to a set of processes involved in conflict detection that signal the need to enhance cognitive control in order to achieve a goal or accomplish a task (Botvinick et al., 2001). Previous research has reported inconsistent results regarding bilingual advantages for these functions: Grundy and Timmer (2017) found evidence for an advantage in working memory, while Lukasik et al. (2018) found no such evidence; Costa et al. (2009) found evidence for an advantage in conflict monitoring, while Kirk et al. (2014) found no such evidence.

Behavioural measures represent the final output of interactions among several cognitive processes in the performance of a given task. Importantly, neurophysiological techniques are potentially more sensitive than behavioural measures because they allow us to detect modulations of a specific correlate of a single process along the chain of cognitive processing. Thus, they could advance our understanding of the underlying differences between monolinguals and bilinguals and resolve some of the inconsistencies reported in behavioural studies. Some researchers have used structural magnetic resonance imaging (MRI) and functional MRI (fMRI) to identify brain correlates of the purported bilingual advantage in executive functions. In a recent review, Grundy et al. (2017a) summarizes this evidence. However, these studies must be considered with caution. First, structural MRI has revealed a considerable number of differences between monolinguals and bilinguals that correlate with a bilingual advantage in executive functions. Critically, while executive functions were mainly related to prefrontal areas and fronto-parietal networks (Takeuchi et al., 2013), a high number of the reported differences were located in other neural regions (García-Pentón et al., 2016). This suggests that if there are indeed differences between monolinguals and bilinguals, they may not necessarily—or exclusively—relate to executive functions. Second, as indicated by several authors (e.g., Duñabeitia and Carreiras, 2015; Paap et al., 2015), ambiguous patterns in fMRI results (e.g., brain activity changes in the absence of behavioural differences) have sometimes been interpreted as evidence for a bilingual advantage. Critically, MRI techniques are unable to adequately capture the high speed of the cognitive processes that take place during the performance of cognitive tasks. By contrast, the high temporal resolution of event-related brain potentials (ERP) is suitable for isolating the neural correlates of specific executive functions that occur during the performance of executive control tasks. In fact, in the last few years, ERP has emerged as a viable new approach in this field of research.

In the present study, we first review how modulations of ERP components related to executive functions are usually interpreted. This provides a foundation to specify what ERP differences between monolinguals and bilinguals support the existence of a bilingual advantage in neural processing related to specific executive functions. We then focus on ERP studies that have investigated the neural correlates of the bilingual advantage in executive functions. Finally, we discuss to what extent these studies provide evidence for a bilingual advantage in neural processing during the performance of executive tasks. This review includes all the available ERP studies comparing monolinguals and bilinguals on their performance of executive control tasks. However, given the correlational nature of these studies, it is not possible to strictly establish the existence of a cause-effect relationship between bilingualism and enhanced executive functioning.

2. Main ERPs during executive tasks: formulating hypotheses

ERP studies may shed light on the hypothesized bilingual advantage in executive functions by specifying neural correlates of cognitive processes that differ for monolinguals and bilinguals but cannot be isolated using behavioural measures. Moreover, ERPs may reflect differences in neural processing that are not strong enough to produce differences in behavioural performance. In this sense, differences between monolinguals and bilinguals might be more consistently observed in ERP components than in behavioural data. However, we will argue that only specific types of differences (not just any difference) in ERP latencies and/or amplitudes would provide convincing support for a bilingual advantage.

In general, an ERP component may be associated with executive functions when delayed latencies and/or modulated amplitudes are closely related to the increased effort required on highly demanding trials or situations in the performance of executive tasks. In the subsequent subsections, we provide evidence for links between the reviewed ERPs and executive functions. ERP studies testing the bilingual advantage hypothesis have focused on the N200 and P300 components during the performance of stimulus-response compatibility (SRC) tasks (e.g., Kousaie and Phillips, 2012) such as the Simon task (participants respond to a feature of a lateralized stimulus while ignoring its location), the Flanker task (participants respond to a central stimulus while ignoring the information provided by flanker stimuli), the Stroop task (participants respond to the ink of a word while ignoring its meaning), as well as Go/No-Go tasks (e.g., Fernández et al., 2013) (participants respond to a target stimulus but withhold their response to a non-target stimulus). Recent studies have also investigated the N200 and P300 in attentional switching (e.g., López-Zunini et al., 2019) and working memory tasks (e.g., Morrison et al., 2019). In addition, some studies have investigated the amplitudes of the N450 (also labelled the N400 and N4) during the performance of Stroop tasks and the error-related negativity (ERN) during the performance of Go/No-Go and SRC tasks.

In this section, we provide a general introduction to N200, P300, ERN, and N450 components and summarize how modulations of these ERPs are usually interpreted. Subsequently, we hypothesize, for each ERP component, what differences between monolinguals and bilinguals should be observed to support a bilingual advantage in neural processing during executive tasks.

2.1. Fronto-central N200

2.1.1. Fronto-central N200 modulations

The fronto-central N200 is a stimulus-locked ERP that appears 200-350ms after stimulus presentation. Most studies have focused on fronto-central N200 amplitudes since no differences between experimental groups have been observed for N200 latencies when groups are matched for age (for a review, see Folstein and Van Petten, 2008). Even so, fronto-central N200 latencies have sometimes been modulated by specific experimental conditions in a task, as we detail below. Depending on the experimental paradigm used, the fronto-central N200 has been related to inhibition, conflict detection, or switching processes, as detailed in the following paragraphs.

The fronto-central N200 was first reported in a study including young adult samples performing Go/No-Go tasks (Pfefferbaum et al., 1985). This pioneering study showed larger amplitude in No-Go than Go trials, an effect interpreted as increased neural activity deployed to inhibit responses to non-target stimuli (Pfefferbaum et al., 1985). Subsequent studies using the Go/No-Go paradigm replicated Pfefferbaum et al.'s findings again concluding that increased fronto-central N200 amplitudes in the No-Go condition were related to inhibition activity (Bokura et al., 2001; Falkenstein et al., 1999; Jodo and Kayama, 1992).

The amplitude of the fronto-central N200 has largely been studied during the performance of SRC tasks, mainly the Flanker task. Some studies have related the fronto-central N200 not only to inhibition but also to *conflict detection* processes. Specifically, they have reported increased N200 amplitudes for trials with conflicting compared to non-conflicting information (Heil et al., 2000; Kopp et al., 1996; Liotti et al., 2000). The N200 amplitude has also been found to increase in SRC tasks that simultaneously combine several types of conflicting information (Masaki et al., 2012). Additionally, after consecutive presentation of incompatible trials, researchers have found both decreased N200 amplitudes (Clayson and Larson, 2011) and decreased anterior cingulate cortex activity (Durston et al., 2003). These findings suggest reduced interference effects due to conflict adaptation (Larson et al., 2014) and are in line with other ERP studies (Clawson et al., 2013; Forster et al., 2011; Kamijo and Takeda, 2013).

Other studies have reported that the fronto-central N200 is modulated by attentional *switching*. In general, the N200 is larger and/or delayed on “switch trials” compared to “repeat trials” in attentional switching tasks (Jamadar et al., 2015; Periañez and Barceló, 2009; for a recent review see Gajewski et al., 2018). Overall, previous research in young adults has related larger fronto-central N200 amplitudes to longer reaction times (RT) during the performance of inhibition and switching task paradigms.

On the other hand, several studies with elderly subjects have shown no differences between N200 amplitudes for conflicting and non-conflicting conditions during the performance of cognitive control (Clawson et al., 2017) and switching (Gajewski et al., 2018) paradigms. The absence of differences between conflicting and non-conflicting conditions in the elderly is due to decreased N200 amplitudes for conflicting trials compared to young subjects (Clawson et al., 2017; Gajewski et al., 2018). In line with these results, a study with an elderly sample showed that fronto-central N200 amplitudes increased and performance was improved after a cognitive training intervention

(Küper et al., 2017). Therefore, in the elderly, larger fronto-central N200 amplitude is usually related to improved performance. This result exemplifies the adaptive role of increased frontal activity in the elderly (Grady, 2012; Park and Reuter-Lorenz, 2009), which may be (at least partially) a result of the posterior to anterior shift of brain activity observed during the performance of cognitive tasks with physiological ageing (Davis et al., 2008). Some studies on age-related changes occurring in the fronto-central N200 have attributed decreased N200 amplitudes in non-conflicting trials to the impaired ability of the elderly to detect conflicting information (Clawson et al., 2017). However, it is unclear why an impaired ability to detect conflicting information would result in larger behavioural interference for elderly subjects since such interference is caused by the detection/processing of conflict. Another view is that reduced N200 amplitudes in the elderly reflect lower integration in neural systems related to executive functions (Gajewski et al., 2018). That is, decreased temporal summation of neural firing rates would explain reduced N200 amplitude in conflicting trials. In fact, lower N200 amplitude was reported for elderly compared to young subjects even in No-Go trials, which do not contain conflicting information (Cheng et al., 2019).

In summary, in the young, increased fronto-central N200 amplitudes may be related to greater effort and the deployment of neural activity during trials requiring inhibition or switching. Overall, high cognitive functioning individuals show less neural activity on a given task condition than low cognitive functioning individuals (Dunst et al., 2014). However, in the elderly, increased fronto-central N200 amplitude may also be related to an enhanced cognitive system or adaptive processes, such as the ability to detect conflicting information or enhanced integration of neural systems related to executive functioning. In this context, increased frontal activity has frequently been associated with enhanced cognitive performance (Park and Reuter-Lorenz, 2009). These findings point to the importance of establishing correlations between the fronto-central N200 amplitude and behavioural outcomes in order to reach reliable conclusions on the functional meaning of differences observed between monolinguals and bilinguals in fronto-central N200 amplitudes.

2.1.2. Hypotheses for fronto-central N200

N200 *latency* for bilinguals than monolinguals in conflicting trials (i.e., trials requiring implementation of inhibition or switching processes) together with no differences in non-conflicting trials would support a bilingual advantage in neural processing associated with inhibition or switching processes (even so, note that differences between groups of subjects matched for age usually did not produce differences in fronto-central N200 latencies).

As for N200 *amplitude*, studies with young subjects suggest that a bilingual advantage in neural processing associated with inhibition or switching abilities should be accompanied by lower fronto-central N200 amplitudes for bilinguals than monolinguals in conflicting conditions (with no differences for non-conflicting trials). This would suggest greater neural efficiency in bilinguals than monolinguals when inhibiting irrelevant information and performing attentional switches, respectively. However, in the elderly, a bilingual advantage in neural processing should produce increased differences between conflicting and non-conflicting trials in fronto-central N200 amplitudes. Importantly, as previously stated, establishing correlations between N200 amplitudes and behavioural performance would clarify whether any specific N200 amplitude difference between monolinguals and bilinguals suggests a bilingual advantage.

On the other hand, if differences in N200 latencies and amplitudes occur in conflicting as well as non-conflicting conditions, the bilingual advantage may be related to conflict monitoring rather than to inhibition or switching abilities. This hypothesis would align with the behavioural prediction about a bilingual advantage in conflict monitoring, which suggests that bilinguals outperform monolinguals in conflicting and non-conflicting trials (Hilchey and Klein, 2011).

2.2. P300

The P300 is a positive component peaking between 300ms and 600ms after stimulus presentation (Polich, 2007), which has been extensively studied during the performance of working memory and

SRC paradigms. In these task paradigms, the P300 shows a parietal topographical distribution (i.e., the *parietal P300*). The P300 has also been studied in inhibition control tasks (i.e., Go/No-Go and Stop-signal tasks). In these paradigms, the P300 shows a fronto-central topographical distribution (i.e., *fronto-central P300*) for No-Go and Stop trials. In the following subsections, we first summarize findings for the parietal P300 and then recap findings regarding the fronto-central P300.

2.2.1. Parietal P300 modulations

The latency of the parietal P300 has been related to the speed of cognitive processes involved in updating *working memory* contents during the performance of working memory (Polich, 2007) and SRC (Leuthold, 2011) tasks. According to the episodic retrieval hypothesis (Chen and Melara, 2009; Spapè et al., 2011; Spapè and Hommel, 2014), sequential congruency effects observed during SRC tasks (i.e., longer RTs when S-R mappings or bindings on "n" and "n-1" trials differ rather than remain the same) result from switching the S-R binding that is active in working memory.

It has been reliably established that the amplitude of the parietal P300 increases as working memory load (i.e., task difficulty) is reduced (Dong et al., 2015; Pratt et al., 2011; Watter et al., 2001; Wintink et al., 2001). Further, studies using SRC tasks have frequently reported that the P300 is larger for non-conflicting than conflicting conditions (Cespón et al., 2013a; Galashan et al., 2008; Leuthold, 2011). Thus, the P300 is larger for less demanding tasks or experimental conditions of the task. Also, previous studies have shown that larger parietal P300 amplitudes correlate with better cognitive functioning (Amin et al., 2015; Polich, 2007).

Some studies investigating sequential congruency effects during the performance of SRC tasks—which involve *switching* attention from the previous to the current S-R mapping—have reported longer P300 latencies in trials that required switching the previous S-R mapping (i.e., the S-R mappings in "n" and "n-1" trials did not match) than trials that required retrieving the previous S-R mapping (i.e., the S-R mappings in "n" and "n-1" trials were the same) (Hoppe et al., 2017; Spapè et al., 2011). These results support the view that the P300 is a neural correlate of the time it takes to switch an S-R mapping (Adrover-Roig and Barceló, 2010). Studies have reported larger parietal P300 amplitudes for repeat than for switch trials (Karayanidis et al., 2011; Kieffaber and Hetrick, 2005; Nicholson et al., 2005). Increased parietal P300 amplitudes have also been associated with decreased task difficulty during attentional switching tasks (Gajewski et al., 2018). Thus, in attentional switching tasks, faster and/or larger parietal P300s were observed in easier task conditions and better performers.

2.2.2. Hypotheses for parietal P300

If bilinguals show faster parietal P300 *latencies* than monolinguals during conflicting trials that require inhibition or switching abilities but show no differences in non-conflicting trials, this would provide evidence for bilingual advantages in neural processes related to inhibition or switching, respectively. If bilinguals exhibit faster P300 latencies than monolinguals in working memory tasks (e.g., n-back tasks), this would provide evidence for a bilingual advantage related to updating/manipulating working memory contents.

If bilinguals exhibit larger parietal P300 *amplitudes* than monolinguals during conflicting trials (i.e., inhibition or switching trials) but not in non-conflicting trials, this would suggest a bilingual advantage for processes associated with inhibition and switching, respectively. Also, larger P300 amplitudes in bilinguals compared to monolinguals during the performance of working memory tasks would evidence a bilingual advantage related to updating/manipulating working memory contents.

2.2.3. Fronto-central P300 modulations

The fronto-central P300 is thought to be a marker of response *inhibition* processes (Groom and Cragg, 2015; Kropotov et al., 2011) and is obtained in No-Go or Stop conditions during the performance of Go/No-Go and Stop-signal tasks (Barry et al., 2016; Bokura et al., 2001; Fallgatter and Strik, 1999). The vast majority of investigations on the fronto-central P300 have focused on amplitudes. Studies have shown that the amplitude of the fronto-central P300 is larger in No-Go (as well as successful Stop trials) than Go conditions (Enriquez-Geppert et al., 2010; Groom and Cragg, 2015). Some studies have reported that, the more difficult it is to implement the inhibition, the larger the amplitude of the fronto-central P300 (Huster et al., 2013). Also, associations between enhanced performance and larger fronto-central P300 amplitudes have been reported; specifically, studies have shown larger fronto-central P300 in subjects with fast than subjects with slow RTs in Stop-signal (Dimoska et al., 2006) and Go/No-Go (Smith et al., 2006) tasks. In other words, higher fronto-central P300 amplitudes are associated with enhanced performance. Therefore, the fronto-central P300 is larger in high than in low performers and, unlike the parietal P300, the fronto-central P300 is usually larger for highly demanding trials.

In the elderly, there are inconsistent results with respect to the functional interpretation of fronto-central P300 amplitude modulations. This again underscores the importance of establishing correlations between fronto-central P300 amplitudes and performance in order to understand the functional meaning of the differences found between elderly monolinguals and bilinguals in No-Go trials. Specifically, some studies have shown larger fronto-central P300 in young relative to elderly subjects (Cheng et al., 2019; Hämmerer et al., 2010). These results were interpreted as reflecting the impaired ability of the elderly to detect conflicting information (Hämmerer et al., 2010) and deploy inhibitory activity (Cheng et al., 2019). However, other studies have reported larger fronto-central P300 in elderly than in young. These results were attributed to compensatory deployment of inhibitory activity (e.g., Hsieh et al., 2015) and the presence of response-related activity in No-Go trials (Vallesi, 2011). In their recent review on N200 and P300 components in the Go/No-Go task paradigm, Cheng et al (2019) suggest that variables such as No-Go probability or the complexity of the task may lead to the inconsistent results noted above.

2.2.4. Hypotheses for fronto-central P300

Faster fronto-central P300 *latencies* in bilinguals than monolinguals during trials requiring inhibition abilities along with no differences in non-conflicting trials would evidence a bilingual advantage in neural processes related to inhibition.

According to previous studies, larger fronto-central P300 *amplitudes* in bilinguals than monolinguals in No-Go trials would suggest a bilingual advantage in inhibition processes in samples of young adults. Nevertheless, in the elderly, given reports with opposite patterns of results and divergent interpretations, correlations between fronto-central P300 amplitudes and performance must be demonstrated before concluding that fronto-central P300 differences between monolinguals and bilinguals indicate a bilingual advantage in inhibition.

2.3. Error-related negativity (ERN)

2.3.1. ERN modulations

The ERN is a response-locked ERP component that emerges 50-100ms after response execution and relates to conflict *monitoring* activity (Botvinick et al., 2001). The vast majority of studies have focused on the amplitude of ERN since differences in latency associated with experimental groups or conditions are rarely observed (Larson et al., 2014; Wessel, 2012).

An early study conducted by Gehring et al (1993) showed the ERN after incorrect responses. These authors showed that ERN was larger in tasks emphasizing accuracy than in tasks emphasizing speed of response and related this component to a neural system involved in detecting conflict and triggering signals to other regions involved in correcting erroneous behaviours (Kerns, 2006). Subsequent studies reported an analogous ERN component with smaller amplitude, the medial frontal negativity (MFN), which is obtained after correct responses (Bartholow et al., 2005; Luu et al., 2000; Masaki et al., 2007; Nessler et al., 2007). An accepted explanation is that both the MFN and ERN reflect cognitive control to monitor conflicting information, an executive process that involves the detection of conflict and the activation of specific mechanisms that promote adaptation to continuously changing environmental demands (Gabrys et al., 2018). In other words, the commission of a behavioural error is just an extreme form of response conflict (Botvinick et al., 2001; Van Veen and Carter, 2002). In fact, a greater degree of conflict has been associated with larger ERN amplitudes (Botvinick et al., 2001; Yeung et al., 2004) although the ERN may be modulated by other factors such as motivation to accurately perform the task (Hajcak et al., 2005). Other studies have related the ERN to error detection or a negative reinforcement signal (for a review on the ERN, see Larson et al., 2014).

Several studies have tried to establish relationships between ERN amplitudes and cognitive performance across various groups of subjects. In this context, a previous study reported that increased ERN were related to better academic performance in young adults (Hirsh and Inzlicht, 2010). This would be in line with ERN amplitude increases across neurodevelopment (for a review, see Tamnes et al., 2013) and consistent with findings obtained by Reinhart and Woodman (2014). These authors reported that ERN and performance increased after applying anodal transcranial direct current stimulation (tDCS) whereas ERN and performance decreased after applying cathodal tDCS in a sample of young adults performing Go/No-Go type tasks with a stop signal. Other studies have reported that increased attention and executive functioning correlated with increased ERN amplitudes (Larson and Clayson, 2011; Miller et al., 2012) and reduced levels of impulsivity (Potts et al., 2006; Ruchsow et al., 2005).

Most studies have reported that ERN amplitudes reduce with ageing (Endrass et al., 2012; Mathalon et al., 2003; Schreiber et al., 2011; Themanson et al., 2006), which is in line with the above mentioned relationships between ERN amplitudes and performance. Even so, some investigations have not found significant differences between young and elderly subjects in ERN amplitudes (Eppinger et al., 2008; Larson et al., 2016).

In summary, increased ERN amplitudes indicate increased efforts to manage conflicting information during the performance of a cognitive task. Importantly, when comparing groups of subjects, previous research has generally related increased ERN to greater ability to implement cognitive control mechanisms since the amplitude of ERN correlates positively with performance. Also, both performance and ERN amplitudes usually decrease with ageing.

2.3.2. Hypotheses for ERN

A bilingual advantage in neural processing during executive tasks should be accompanied by larger ERN *amplitudes* in bilinguals than monolinguals for both conflicting and non-conflicting conditions. We predict differences in both conditions because the ERN is a correlate of conflict monitoring and, in most cases, the argument for a bilingual advantage in conflict monitoring has been based on an observed behavioural bilingual advantage for both conflicting and non-conflicting conditions of the task. Even so, as the ERN can be modulated by various factors such as the motivation to perform a task accurately and age of participants, establishing correlations between performance and ERN amplitudes would lead to more precise conclusions.

2.4. N450

2.4.1. N450 modulations

The N450 (sometimes labelled the N400 or N4) is another fronto-centrally distributed ERP component, typically studied by using the Stroop task paradigm. Like the fronto-central N200, the N450 is related to *conflict monitoring* as well as *inhibition* activity during the performance of the Stroop task (Larson et al., 2014). Most studies investigating the N450 have focused on its amplitude, as differences related to experimental groups or conditions have not generally been observed for the N450 latency (Larson et al., 2014; Sahinoglu and Dogan, 2016).

The N450 is an ERP component that peaks between 400 and 600ms after stimulus presentation. It has been related to conflict monitoring activity in the anterior cingulate cortex (Szucs and Soltész, 2010) when processing the Stroop conflict (Larson et al., 2014; Liotti et al., 2000; West et al., 2005; Zahedi et al., 2019). Some studies have suggested that the cognitive control required to inhibit irrelevant information also contributes to the N450 waveform (Chen et al., 2011).

Accordingly, several studies investigating ERP correlates of the Stroop task have reported that the N450 is larger in incongruent than congruent conditions (Bekçi and Karakaş, 2009; Ergen et al., 2014; Rebai et al., 1997; Szucs and Soltész, 2010). Moreover, increased levels of conflict have been related to an increase in N450 amplitudes (Chouiter et al., 2014; Nalyor et al., 2012; West and Alain, 2000a).

The amplitude of the N450 reduces with ageing (West and Alain, 2000b). Moreover, Stroop interference increases while differences in N450 amplitudes for congruent and incongruent conditions are reduced in elderly subjects (West and Alain, 2000b). In line with these results, a recent study showed that elderly subjects at risk of cognitive impairment did not show the typical N450 effect during a Stroop task even if the behavioural Stroop effect was greater in the at-risk compared to the healthier group (Sánchez-Moguel et al., 2018). Overall, studies in elderly have related enhanced performance during the Stroop task to greater differences between congruent and incongruent conditions in N450 amplitudes. This may be related to a preserved ability to detect conflicting information or enhanced integration of neural systems involved in inhibitory control.

2.4.2. Hypotheses for N450

In young people, a bilingual advantage in inhibition should be accompanied by larger N450 *amplitudes* in monolinguals than bilinguals for incongruent conditions but no differences for congruent trials. The N450 has been related not only to inhibition but also to processing conflicting information. Thus, correlations between N450 amplitudes and behavioural performance would help relate N450 amplitude differences between monolinguals and bilinguals to a bilingual advantage in neural processing. However, in the elderly, a bilingual advantage may be revealed by greater differences between congruent and incongruent conditions in N450 amplitudes in bilinguals than monolinguals. As the N450 seems to be associated with inhibition as well as conflict detection activity, correlations between N450 amplitudes and behavioural performance would provide important evidence for a bilingual advantage in related cognitive processes.

2.5. Summarizing hypotheses

In general, interpreting ERP latencies as evidence for or against a bilingual advantage in specific executive functions is relatively straightforward. Thus, ERP latencies are a highly useful parameter in the absence of behavioural differences. Specifically, faster ERP latencies in bilinguals than monolinguals in a working memory (e.g., n-back) task would suggest a bilingual advantage in working memory abilities. Similarly, faster ERP latencies in bilinguals than monolinguals during conflicting trials in addition to no differences in non-conflicting trials in inhibition and switching tasks can be interpreted as a bilingual advantage in inhibition and switching abilities, respectively. Instead, in line with previous behavioural studies (Hilchey and Klein, 2011), faster ERP latencies in bilinguals than monolinguals during conflicting and non-conflicting trials in inhibition and switching tasks can be interpreted as a bilingual advantage in conflict monitoring. Finally, the absence of a speed-accuracy trade-off should be demonstrated before making a convincing claim for the existence of a bilingual advantage on the basis of ERP latencies.

Obtaining evidence for a bilingual advantage in executive functions from differences between monolinguals and bilinguals in ERP amplitudes is more complex than obtaining such evidence from differences observed in ERP latencies. As graphically represented in Figure 1, a bilingual advantage may correspond to either increased or decreased ERP amplitudes depending on the specific ERP component and the age of the subjects. Importantly, as previously argued, correlations between ERP amplitudes and behavioural performance are sometimes needed in order to reach reliable conclusions. In general, as stated for ERP latencies, if ERP amplitude differences suggest a bilingual advantage in the conflicting trials but not in the non-conflicting trials, this would imply that the advantage is specifically related to inhibition or switching abilities. If, however, ERP amplitude differences suggest a bilingual advantage on both types of trials (i.e., conflicting and non-conflicting), this would instead suggest that the advantage relates to conflict monitoring.

Figure 1 about here

3. ERP studies of bilingual advantage: Testing hypotheses

Few ERP studies have investigated the hypothesised bilingual advantage in executive functions. Most studies on executive functions have focused on the neural correlates of cognitive control when irrelevant information has to be inhibited in SRC (Coderre and Van Heuven, 2014; Heidlmayr et al., 2015; Kousaie and Phillips, 2012; Kousaie and Phillips, 2017) and Go/No-Go (Barac et al., 2016; Fernández et al., 2013; Fernández et al., 2014; Morales et al., 2015; Moreno et al., 2014) tasks. Recently, some studies have investigated switching (López-Zunini et al., 2019) and working memory (Morrison et al., 2019) processes. Importantly, in these studies, bilingual samples differed on various important characteristics. Table 1 summarizes how bilingualism was defined in each study as well as some relevant contextual characteristics of the bilingual samples.

Table 1 about here

Most of these studies have focused on samples of young adults. There are only two studies that have tested elderly subjects (Kousaie and Phillips, 2017; López-Zunini et al., 2019) and only one that has investigated differences between monolingual and bilingual children (Barac et al., 2016). All of these studies are summarized in Table 2. In the following pages, we will discuss the extent to which the reported differences between monolinguals and bilinguals in the N200, P300, ERN, and N450 (i.e., the main ERPs studied in the field of bilingualism and executive functions) can be interpreted as a bilingual advantage in neural processing related to specific executive functions. To shed light on this question, we discuss the ERP findings summarized in Table 2 in relation to the hypotheses formulated in the previous section. As previously discussed, modulations of neural activity in the absence of behavioural differences may lead to ambiguous conclusions. For instance, we could not to interpret the amplitude of an ERP or the magnitude of brain activity in a given area in the absence of any theoretical framework or knowledge about the contribution of this brain activity to cognitive processing. Even so, neural differences between monolinguals and bilinguals can frequently be interpreted even when behavioural differences are not observed.

Table 2 about here

3.1. Fronto-central N200

3.1.1. Fronto-central N200 latency

We hypothesized that a faster N200 in bilinguals than monolinguals in conflicting conditions (i.e., trials requiring inhibition of switching processes) would be consistent with a bilingual advantage in neural processing. There are two studies using inhibition tasks that show partial evidence for this hypothesis: one conducted with children (Barac et al., 2016) and the other with elderly samples (Kousaie and Phillips, 2017).

Barac et al (2016) showed bilinguals had faster N200 latencies as well as better performance than monolinguals in a Go/No-Go task. Moreover, N200 latencies correlated with enhanced performance. Therefore, faster deployment of processes related to the N200 component led to enhanced performance in bilingual children. Nevertheless, it is unclear why the N200 was also faster in bilinguals than monolinguals in the Go condition, which does not require implementation of inhibition processes. This result might be related to a bilingual advantage in conflict monitoring. Studies analysing ERN/MFN components (specifically related to conflict monitoring) might help confirm this hypothesis.

Kousaie and Phillips (2017) reported smaller Stroop effects and faster N200 latencies in bilinguals than monolinguals during the performance of a Stroop task in both experimental conditions (i.e., in the congruent and incongruent conditions, which raises the same concern as that mentioned above in relation to the study by Barac and colleagues) and during the performance of a Flanker task in the incompatible condition. However, N200 latency differences between monolinguals and bilinguals were not observed during the performance of the Simon task. Kousaie and Phillips (2017) thus obtained evidence for a bilingual advantage in neural processing related to inhibition in the Flanker but not in the Simon task. For the Stroop task, evidence for a bilingual advantage in neural processing was obtained but not necessarily related to inhibition processes since differences were found in both congruent and in incongruent conditions.

Studies in samples of young adults did not reveal any differences in N200 latency in tasks requiring inhibition (Fernández et al., 2013; Fernández et al., 2014: Heidlmayr et al., 2015; Kousaie and Phillips, 2012; Morales et al., 2015; Moreno et al., 2014), switching (López-Zunini et al., 2019, who also did not find differences in elderly subjects), and working memory (Morrison et al., 2019) abilities. Therefore, studies investigating inhibition, switching, and working memory in young adults did not show any difference between monolinguals and bilinguals in N200 latencies.

In sum, results for the N200 latency suggest that bilingualism may be related to improved neural processing efficiency during the performance of inhibition tasks in children (Barac et al., 2016) and the elderly (Kousaie and Phillips, 2017) but not in young adults. However, these positive results should be considered with caution since hypothesised outcomes have only partially been fulfilled. Also, we have to take into account the small number of studies (i.e., only one ERP study in children and one in elderly has examined inhibition abilities) and the mentioned publication bias (De Bruin et al., 2015). Thus, findings reported in the children and elderly should be replicated and extended to other tasks before conclusions are drawn about what experimental conditions (if any) give rise to a bilingual advantage associated with executive functions in neural processes related to N200 latencies.

3.1.2. Fronto-central N200 amplitude

We argued that correlations between the N200 amplitude and behavioural performance should be demonstrated in order to relate N200 amplitude differences between monolinguals and bilinguals to a bilingual advantage in neural processing. Unfortunately, available studies have not reported such correlations even if most published studies have shown differences between monolinguals and bilinguals in N200 amplitudes; specifically, bilinguals have frequently demonstrated larger N200 amplitude than monolinguals in No-Go trials of Go/No-Go task paradigms (Fernández et al., 2013; Fernández et al., 2014; Morales et al., 2015; Moreno et al., 2014).

Morales et al (2015) showed a larger fronto-central N200 accompanied by enhanced performance in bilinguals compared to monolinguals in No-Go trials of a Go/No-Go task although correlations between N200 amplitudes and enhanced performance were not reported. Unfortunately, we cannot consider these results from Morales et al (2015) as evidence for a bilingual advantage in neural processing since they did not find correlations between the N200 amplitude and performance and the pattern of results was opposite to predictions based on previous literature. We had hypothesised a lower fronto-central N200 amplitude in bilinguals than monolinguals, due to greater neural efficiency in deployment of inhibition processes (i.e., we had argued that bilinguals would allocate less neural resources than monolinguals to achieve the same or better performance).

Other studies using the Go/No-Go paradigm did not show behavioural differences between monolinguals and bilinguals (Fernández et al., 2013; Fernández et al., 2014; Moreno et al., 2014). Surprisingly, these studies related larger N200 amplitude in bilinguals than in monolinguals to an enhanced ability to detect conflict and/or inhibit irrelevant information in the bilingual group. In line with this interpretation, a recent review argued that larger N200 and lower MFN/ERN in bilinguals than monolinguals would indicate greater brain efficiency in the bilingual group, which resolves conflict at an earlier stage in processing (Grundy et al., 2017a). However, interpreting increased ERP amplitudes accompanied by similar performance in terms of neural efficiency is not appropriate since neural efficiency specifically entails using fewer brain resources to achieve the same or a better outcome (Barulli and Stern, 2013; Clawson et al., 2017). For instance, Clawson et al. (2017) studied children, young, and elderly subjects while performing a Flanker task and showed that young adults exhibited the lowest N200 and ERN amplitudes along with the best performance.

The authors concluded that young adults showed higher neural efficiency than the children and elderly.

There are also studies that have shown the opposite pattern of results for N200 amplitudes; that is, a larger N200 in monolinguals than bilinguals (and no behavioural differences) when performing Stroop (Kousaie and Phillips, 2012) and Simon (Kousaie and Phillips, 2017) tasks. Thus, a larger N200 might indicate the use of different strategies to deal with conflicting information rather than an advantage. Results from Moreno et al (2014) support this interpretation. Moreno et al (2014) reported, in the absence of behavioural differences, larger N200 amplitudes in bilingual non-musicians than monolingual non-musicians and larger N200 amplitudes in monolingual non-musicians than in monolingual musicians. The authors concluded that being bilingual and playing music impact cognition. However, assuming a positive relationship between N200 amplitude and neural efficiency, these results from Moreno et al (2014) would have suggested that playing music impairs neural processing during executive control tasks.

Studies in elderly focusing on the N200 amplitude were reported by Kousaie and Phillips (2017) and López-Zunini et al (2019). Kousaie and Phillips (2017) showed larger N200 in monolinguals than bilinguals during the Simon task (in both compatible and incompatible trials) but no differences in Flanker and Stroop tasks. Thus, these N200 findings do not support a bilingual advantage in inhibitory control for any of the inhibitory control tasks used by Kousaie and Phillips (2017). By using an attentional switching task, López-Zunini et al (2019) showed faster RTs in bilinguals than monolinguals in the switch condition and larger N200 amplitude in bilinguals than monolinguals in both switch and non-switch conditions. Thus, it is unclear whether or not ERP differences occurring in both conditions can be related to behavioural differences between monolinguals and bilinguals in switch trials. Indeed, the authors interpreted increased N200 amplitude as evidence for enhanced conflict monitoring in the bilingual group. Regrettably, the authors did not report correlations between N200 amplitude and behavioural data to support their interpretation.

In sum, the available studies do not constitute evidence that a bilingual advantage in neural processing is revealed by N200 amplitudes. Future studies should establish correlations between N200 amplitudes and behavioural performance to determine whether the obtained differences between monolinguals and bilinguals are consistent with a bilingual advantage in neural processing.

3.2. P300

3.2.1. Parietal P300 latency

We hypothesized that faster P300 latency in bilinguals than in monolinguals during working memory tasks or in trials requiring inhibition or switching skills would be consistent with a bilingual advantage in neural processing underlying the corresponding executive functions.

There are several studies that examined parietal P300 latency in young and elderly adults. Overall, these studies did not find differences between monolinguals and bilinguals in P300 latency in SRC tasks (specifically, Flanker and Simon tasks (Kousaie and Phillips, 2012) and Stroop task (Kousaie and Phillips, 2017), switching task (López-Zunini et al., 2019), and n-back tasks (Morrison et al., 2019). Yet, there are some positive relationships between faster P300 latency and bilingualism. Specifically, Kousaie and Phillips (2012) reported faster P300 latency in bilinguals than in monolinguals during the performance of a Stroop task. Moreover, in samples of elderly, these authors showed faster P300 latencies in bilinguals than monolinguals during the performance of Simon and Flanker tasks (Kousaie and Phillips, 2017). However, these differences did not occur specifically on conflicting trials. For the Stroop (Kousaie and Phillips, 2012) and Simon (Kousaie and Phillips, 2017) tasks, differences between monolinguals and bilinguals in parietal P300 were found for both compatible and incompatible conditions; for the Flanker task, differences between monolinguals and bilinguals in parietal P300s were found only in the compatible condition (Kousaie and Phillips, 2017). Consequently, as previously argued, these differences cannot be interpreted as an advantage in inhibitory control.

In short, there is no evidence for a bilingual advantage in executive functions based on neural processes related to the parietal P300 latency. Even so, the number of studies is very limited. Thus, additional research would be needed to confirm the results obtained by the reviewed studies and to clarify whether and why specific experimental conditions might lead to differences between monolinguals and bilinguals in parietal P300 latencies.

3.2.2. Parietal P300 amplitude

We argued that larger P300 amplitudes in bilinguals than monolinguals during working memory tasks or in trials demanding inhibition or switching skills would be consistent with a bilingual advantage in neural processing during the corresponding executive tasks.

Two studies analysing the amplitude of parietal P300 provide some evidence for a bilingual advantage. In young adults, the parietal P300 was larger in bilinguals than monolinguals during the performance of n-back tasks (Morrison et al., 2019). According to previous studies (Dong et al., 2015; Polich, 2007), higher P300 amplitudes would suggest greater cognitive resources and lower subjective difficulty when updating working memory contents. Accordingly, results from Morrison et al (2019) would be in line with a bilingual advantage in working memory. In elderly subjects, the parietal P300 was larger in bilinguals than monolinguals during the performance of a Stroop task (Kousaie and Phillips, 2017). Interestingly, differences reported by Kousaie and Phillips (2017) in the Stroop task occurred only in the incongruent condition. Therefore, these differences are consistent with a bilingual advantage in neural processes related to the parietal P300. Nevertheless, this study did not detect any difference in the amplitude of the parietal P300 during the performance of Simon and Flanker tasks (Kousaie and Phillips, 2017).

In contrast to the evidence cited in the previous paragraph, differences between parietal P300 amplitudes in monolinguals and bilinguals were not found in both Flanker and Stroop tasks in samples of young adults (Kousaie and Phillips, 2012). Surprisingly, smaller P300 amplitudes in bilinguals than monolinguals were reported during the performance of a Simon task (Kousaie and

Phillips, 2012) and in an attentional switching task (López-Zunini et al., 2019). According to the hypotheses formulated in the previous section, these findings suggest a bilingual disadvantage in P300-related neural processes.

In summary, contradictory evidence has been obtained regarding modulation of the parietal P300 by bilingualism. Additional research is needed to reveal the experimental tasks and conditions (if any) that may consistently lead to faster and/or larger parietal P300 in bilinguals than monolinguals.

3.2.3. Fronto-central P300 latency

We hypothesized that faster fronto-central P300 latency in bilinguals than monolinguals during No-Go trials would indicate a bilingual advantage in neural processes related to inhibition.

The only study implemented in samples of children reported faster fronto-central P300 latencies in bilinguals than monolinguals during a Go/No-Go task paradigm (Barac et al., 2016). Furthermore, the P300 latency correlated with enhanced performance in bilinguals (Barac et al., 2016). Critically however, faster P300 latencies in bilinguals than monolinguals were not specific to No-Go trials. Therefore, as for the N200 latency, it remains unclear why the P300 was faster in bilinguals than monolinguals in the Go condition, which does not require inhibition. Thus, these results from Barac et al. (2016) only partially satisfied the results expected for a bilingual advantage in inhibition, that is, faster P300 in bilinguals than monolinguals for No-Go but not for Go trials. It would be interesting to investigate whether these results may be a result of a bilingual advantage in processes related to conflict monitoring. To determine this, future studies should focus on ERP components that specifically relate to conflict monitoring activity (i.e., the ERN/MFN).

Studies implemented in young adults did not show any differences in fronto-central P300 latencies between monolinguals and bilinguals (Fernández et al., 2013; Morales et al., 2015; Moreno et al., 2014). This indicates that the speed of deployment of inhibition processes indicated by this component did not differ between monolinguals and bilinguals. In elderly subjects, there are no studies focusing on differences in fronto-central P300 latencies between monolinguals and bilinguals. Thus, the only evidence for a bilingual advantage in neural processes related to the fronto-central P300 latency was obtained in samples of children.

3.2.4. Fronto-central P300 amplitude

Larger fronto-central P300 amplitudes in bilinguals than monolinguals in No-Go trials would suggest a bilingual advantage in inhibition processes in young subjects although, particularly for the elderly, correlations between fronto-central P300 amplitudes and behavioural performance are needed before reliable conclusions can be drawn.

As regards the fronto-central P300, the only study was implemented in children and reported bilinguals had larger frontal P300 than monolinguals during a Go/No-Go task (Barac et al., 2016). Also, P300 amplitudes at central sites correlated positively with performance in the bilingual group. However, differences between monolinguals and bilinguals were not specific to the No-Go condition, which raises the same concern as described for the P300 latency: are these neural differences a result of enhanced inhibition or conflict monitoring in the bilingual group? As previously argued, studies focusing on ERPs specifically related to conflict monitoring (i.e., ERN/MFN) might shed light on this question. On the other hand, in samples of young adults, research has not shown differences between monolinguals and bilinguals in the amplitude of the fronto-central P300 (Fernández et al., 2013; Morales et al., 2015; Moreno et al., 2014).

In sum, by analyzing the fronto-central P300 in Go/No-Go tasks, some evidence for enhanced neural processing by bilinguals compared to monolinguals was found in samples of children although it remains unclear whether these reported differences were related to an advantage in inhibition or conflict monitoring. In young adults, studies provided inconsistent results. Thus, further studies are required. Correlations between the P300 and behavioural performance would help to clearly establish whether increased fronto-central P300 amplitudes relate to enhanced performance.

3.3. ERN

In order to demonstrate a bilingual advantage in conflict monitoring, greater ERN amplitudes should be observed in bilinguals than monolinguals along with correlations between ERN and behavioural performance.

Only two studies have focussed on ERNs when investigating the relationship between bilingualism and executive functions (Kousaie and Phillips, 2012; Morales et al., 2015). The obtained results were not in line with a bilingual advantage in the cognitive processes associated with ERN. Specifically, Morales et al (2015) reported that bilinguals outperformed monolinguals in a Go/No-Go task, as revealed by behavioural outcomes. However, ERN did not differ on the basis of experimental group. Kousaie and Phillips (2012) showed no differences in ERN for Simon and Stroop tasks whereas contrasting ERN modulations were reported for the Flanker task. That is, ERN was larger in monolinguals than bilinguals in the compatible Flanker condition, but it was larger in bilinguals than monolinguals in the neutral and incompatible conditions. Thus, the two available studies in samples of young adults do not provide clear evidence for the existence of a bilingual advantage in neural processes related to the ERN.

3.4. N450

We had hypothesized larger N450 amplitudes in monolinguals than bilinguals in the incongruent condition along with no differences in the congruent condition.

Two studies, carried out in samples of healthy young subjects, investigated a potential bilingual advantage in the Stroop task using the N450 (Coderre and Van Heuven, 2014; Heidlmayr et al., 2015). These studies did not find any evidence for a bilingual advantage in executive functions. Specifically, Heidlmayr et al (2015) showed a Stroop effect on N450 amplitude in monolinguals but not in bilinguals; this was interpreted as a bilingual advantage in neural processing. It is unclear why these authors failed to replicate a well-established finding (i.e., a larger

N450 in incongruent than congruent Stroop task conditions) previously obtained in samples of bilinguals (e.g., Naylor et al., 2012). Critically, differences in N450 amplitudes between monolinguals and bilinguals in the incongruent condition were not significant and, accordingly, behavioural differences between monolinguals and bilinguals were not observed. In another study relating bilingualism to the ERP correlates of the Stroop effect, Coderre and van Heuven (2014) showed no differences in the Stroop effect but faster RTs in a no-conflict control condition. Authors interpreted this result as evidence for superior cognitive monitoring by bilinguals compared to monolinguals even in the absence of conflict. This is a surprising conclusion since in the absence of conflict there would be no need for cognitive monitoring, which specifically involves processing and resolving conflicting information. Thus, so far, there is no evidence for a bilingual advantage in cognitive processes related to the N450 component.

4. Integration of findings and future directions

In general, studies showing faster ERP latencies in bilinguals than monolinguals are consistent with a bilingual advantage in neural processing. In contrast, ERP amplitude differences between monolinguals and bilinguals are often difficult to interpret, unless they correlate with performance or match clear predictions based on empirical studies. Two opposite theoretical views in the cognitive neuroscience of ageing illustrate the difficulty of identifying differences in neural activity as enhanced or reduced efficiency in neural processing. Specifically, increased brain activity related to ageing during the performance of a cognitive task has been interpreted both as a compensatory mechanism (Cabeza et al., 2002) and as the result of less efficient neural processing associated with increased neural noise (Li et al., 2001). Table 3 summarizes whether evidence for a bilingual advantage was obtained for each study, paradigm, and ERP parameter.

Table 3 about here

In young adults, there was only one study that fulfilled our requirements for claiming a bilingual advantage in neural processing that underpins specific executive functions (Morrison et al., 2019). This study revealed larger parietal P300 amplitude in bilinguals than monolinguals during the performance of a working memory (specifically, n-back) task. Relating these findings to a bilingual advantage in working memory would align with increased parietal P300 amplitude during performance of working memory tasks in high performing individuals (Amin et al., 2015; Polich, 2007). Even so, studies in young adults have not consistently supported the existence of a bilingual advantage in neural processing linked to executive functions. In fact, clear evidence has not been shown in most studies carried out so far (Coderre and van Heuven, 2014; Fernández et al., 2013; Fernández et al., 2014; Heidlmayr et al., 2015; Kousaie and Phillips, 2012; López-Zunini et al., 2019; Morales et al., 2015; Moreno et al., 2014).

The only ERP study conducted in children (Barac et al., 2016) and some results from a study implemented with elderly subjects (Kousaie and Phillips, 2017) are consistent with a bilingual advantage in neural processing related to inhibition. Specifically, Barac et al (2016) reported faster RTs and ERP latencies in bilinguals than monolinguals in a Go/No-Go task and these ERP differences correlated with performance (Barac et al., 2016). Similarly, Kousaie and Phillips (2017) showed faster N200 latencies in bilinguals than monolinguals for incompatible trials in a Flanker task. Another study implemented in both young and elderly adult subjects (López-Zunini et al., 2019) showed faster RTs and ERP latencies in bilinguals than monolinguals during an attentional switching task. Even so, we cannot interpret ERP results from López-Zunini et al (2019) as an advantage in neural processing underlying switching abilities, since ERP differences between monolinguals and bilinguals were obtained for both the switch and non-switch conditions of the task. In line with López-Zunini et al (2019), we might hypothesize that these ERP differences reflect an advantage in conflict monitoring rather than switching abilities. Nevertheless, this interpretation is inconsistent with the behavioural results, which showed an advantage only for switching trials. Further research focusing on ERP components specifically related to conflict monitoring (e.g., ERN/MFN) would be necessary to shed light on this issue.

As a whole, the available ERP studies may be consistent with a bilingual advantage in executive functions in children and the elderly but not in young adults (Bialystok et al., 2012). Nevertheless, studies showing a bilingual advantage in behavioural and/or ERP latencies should be considered with caution. First, as stated by Paap et al (2015), it is unclear why several tasks that are thought to measure the same executive process do not consistently lead to the same result. For instance, Kousaie and Phillips (2017) used three different tasks to investigate inhibition (i.e., Stroop, Flankers, Simon) and found a bilingual advantage in the Flanker and Stroop but not the Simon task. Second, there are an overwhelming number of recent meta-analyses that show no behavioural differences between monolinguals and bilinguals in executive functions (e.g., Donnelly et al., 2019; Lehtonen et al., 2018; Paap, 2019). In fact, according to these meta-analyses, we predict that upcoming ERP studies will not show consistent differences between monolinguals and bilinguals at the behavioural level. The open question is whether or not future ERP studies will show consistent differences in the latency or amplitude of specific ERP components.

To a certain extent, inconsistent results might be related to different types of bilingualism or the ways in which bilingualism has been defined in each study, as summarized in the Table 1. Also, the relatively low sample size used in the studies reviewed here—typically 20-25 participants per group—may be an important reason for inconsistent findings. In this regard, it is important to mention that Button et al. (2013) estimated that only 8% to 31% of neuroscientific studies are adequately powered. Critically, as these authors explain, low sample sizes undermine the capacity of meta-analytical investigations to reach reliable conclusions about a given effect. Therefore, upcoming research should consider sample size as a very important methodological issue which must be addressed to assure high quality research and reduce inconsistencies between studies. Multisite studies may be very useful for establishing synergies among research groups and obtaining adequately-powered samples. Nevertheless, there are some crucial variables, such as the specific languages spoken by samples recruited in different places, the age of language acquisition, frequency of use of each language, and socio-cultural level of the participants, among others, which must be controlled before starting a multisite study in this field of research. Another methodological limitation which prevents us from concluding that bilingualism strengthens executive functions is the correlational nature of most studies. In this context, it may be pertinent to note that longitudinal studies which follow participants during their acquisition of a second language would allow us to overcome this limitation.

On the other hand, we are aware that experimental studies may produce patterns of results that partially or totally contradict the hypotheses formulated in Section 2. According to the specific pattern of obtained data, differences between monolinguals and bilinguals which go in the opposite direction to the formulated predictions (e.g., faster ERP latencies in monolinguals than bilinguals) might be interpreted as a bilingual disadvantage, as has been reported in a number of behavioural studies (Arizmendi et al., 2018; Paap and Greenberg, 2013; Paap and Sawi, 2014). Such claims have contributed to polarising the debate over the possible existence of a bilingual advantage/s in executive function/s.

There are several ERPs that have not yet been analysed in research into the relationship between bilingualism and executive functions. Studies focusing on these ERPs promise to substantially advance this field of research, providing important information on how neural correlates of specific cognitive processes occurring during executive tasks are modulated by bilingualism. For instance, in the SRC and Go/No-Go tasks, correlates of interference have often been studied using the lateralized readiness potential (LRP) (Coles et al., 1988; Smulders and Miller, 2012). The LRP is a neural marker of competition between conflicting responses and has been used to study neural correlates of response preparation processes (Cespón et al., 2013b; Vallesi and Stuss, 2010). Surprisingly, there are no studies on bilingual advantage that analyse the LRP, which could provide important information on covert response preparation processes. Moreover, future studies could relate N200 amplitude in No-Go trials to the magnitude of the subthreshold incorrect response preparation indicated by the LRP. This would provide information on how N200 amplitude relates to the strength of sub-threshold incorrect response preparation, contributing to a better understanding of the functional meaning of N200 amplitude modulations.

In spatial SRC tasks, the negativity central contralateral (N2cc) could be used as a correlate for inhibition (Cespón et al., 2012; Praamstra, 2006; Praamstra and Oostenveld, 2003). In detail, N2cc is an ERP correlate of dorsal premotor activity involved in preventing the response spatial tendency and, interestingly, it is also sensitive to cognitive changes related to ageing (Amenedo et al., 2012; Cespón et al., 2015). Additionally, future studies may focus on the MFN, which is functionally equivalent to the ERN (Masaki et al., 2012; Stemmer et al., 2003; Watanabe et al., 2016). The amplitude of the MFN is modulated by the amount of conflicting information that needs to be kept under control during the performance of a task (Masaki et al., 2012; Watanabe et al., 2016). Importantly, analysing the MFN will allow us to identify potential differences in conflict monitoring activity between monolinguals and bilinguals during correct-response trials. The MFN may be an important tool for investigating to what extent differences between monolinguals and bilinguals in conflicting and non-conflicting conditions (as reported for example by López-Zunini et al., 2019) can be attributed to a bilingual advantage in conflict monitoring.

There are a substantial number of studies that have investigated the parietal P300 in elderly subjects. In the elderly, parietal P300 latencies are delayed and their topographical distribution becomes more anterior during the performance of SRC (in both conflicting and non-conflicting conditions) (van der Lubbe and Verleger, 2002; Zurrón et al., 2014) and working memory (Daffner et al., 2011; Friedman et al., 1997; Saliasi et al., 2013; van Dinteren et al., 2014) tasks. These results have been ascribed to over-recruitment of frontal areas to compensate for an age-related impairment in neural processing supported by posterior regions (Friedman et al., 1997; van Dinteren et al., 2014). So, for elderly samples performing SRC and working memory tasks, the available research suggests the importance of studying the P300 not only in parietal but also in frontal regions. Also, it may be interesting to extend the analysis of the fronto-central P300 that occurs during Go/No-Go tasks (Barac et al., 2016; Morales et al., 2015; Moreno et al., 2014) to attentional switching paradigms, in which this component is also modulated (Lange et al., 2015).

Finally, we should mention that some electrophysiological studies have used measures other than ERPs. For instance, Grundy et al (2017c) analysed multiscale entropy in monolinguals and bilinguals performing a task-switching paradigm. This study showed no behavioural differences between monolinguals and bilinguals. However, bilinguals showed greater brain signal complexity than monolinguals in occipital regions, which was interpreted as evidence for more efficient processing (Grundy et al., 2017c). However, the patterns of brain connectivity associated with greater brain efficiency are just starting to be understood and are subject to methodological caveats (Sakkalis, 2011). Converging evidence from other well-established electrophysiological measures (e.g., ERPs) would help to support such interpretations. Even so, this approach could be a promising avenue for future investigations.

In summary, some studies have interpreted ambiguous differences between monolinguals and bilinguals in ERP parameters related to executive functions as evidence for a bilingual advantage. However, interpreting differences in ERP amplitudes as evidence for a bilingual advantage is not appropriate unless such differences correlate with performance or match hypotheses formulated on the basis of well-established empirical evidence. Therefore, to date, the available ERP studies show scarce evidence for a bilingual advantage in neural processes related to executive functions. Even if some promising evidence has been reported for children and elderly subjects, the very small number of studies (only one ERP study in children and two ERP studies in the elderly) along with recent behavioural meta-analyses showing null effects obliges us to consider these results with caution. Further research is needed to investigate whether or not ERP parameters show more consistent results than behavioural measures. It is particularly important to ascertain this for samples of children and the elderly, which represent groups more prone to show differences related to bilingualism. Future studies should also explore ERP components such as the LRP, N2cc, or MFN, which represent neural correlates of key cognitive processes that occur during the performance of executive tasks.

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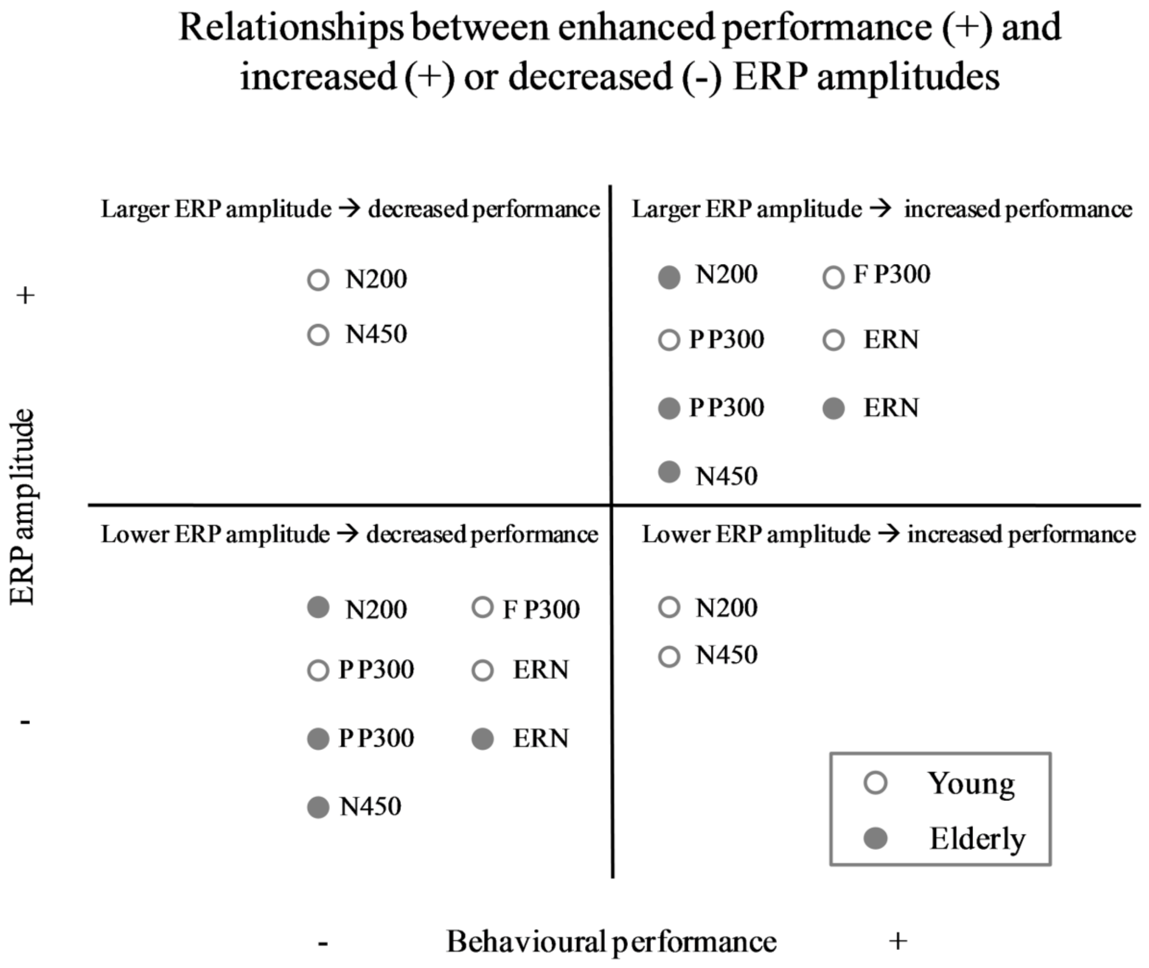
Figure caption

Figure 1. This figure schematically recaps whether enhanced performance is related to larger (+) or smaller (-) ERP amplitudes for each reviewed ERP component. Note that we have represented associations between increased ERP amplitude and performance as well as between decreased ERP amplitude and performance (such relationships are represented in opposite quadrants). For *inhibition* and *switching* abilities, ERP differences should only occur in conflicting trials whereas for *conflict monitoring* ERP differences should occur in conflicting and non-conflicting trials. Note that, in elderly, for fronto-central P300, contrasting results were reported by previous literature. So, we did not formulate any specific prediction about fronto-central P300 amplitude in elderly. Abbreviations: P P300 (parietal P300); F P300 (fronto-central P300).

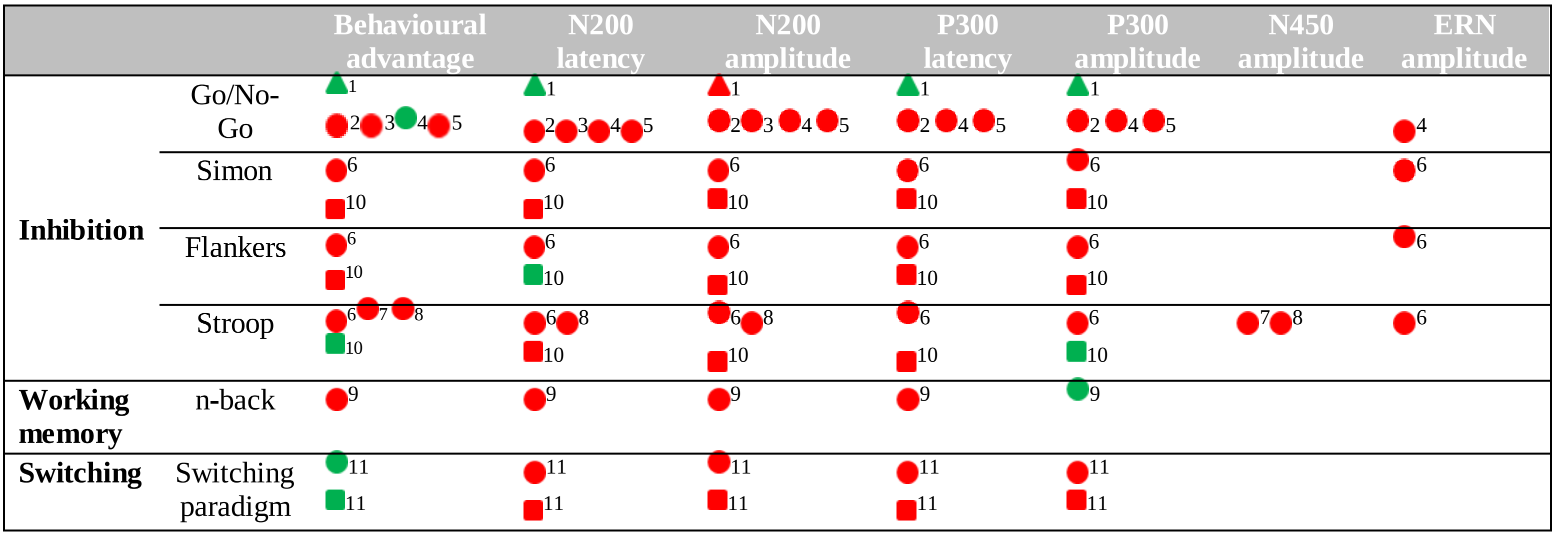


Study / Samples	How bilingualism was determined	Languages and contextual factors	L2 acquisition
CHILDREN			
Barac et al 2016 31 ML (63.5months±5.5) 19 BL (65.7months±5.4)	Questionnaire filled by parents about children's comprehension and production of language/s.	Monolinguals: English; Bilinguals: English plus Spanish (7), French (4), Mandarin (3), Greek (2), Korean (2), Ukrainian (1), Cantonese (1), Vietnamese (1), Tagalog (1), Russian (1), German (1), Polish (1). All bilinguals but 4 were born in Canada.	9 bilinguals learned simultaneously both languages from birth; 8 had English as a first language; 8 spoke the non-English language first.
YOUNG ADULTS			
Fernández et al 2013 15 ML (22.6 ± 4.7) 13 BL (20.4 ± 1.5)	Language questionnaire designed by the authors.	Monolinguals: English; Bilinguals: English and Spanish. Most bilinguals (11/13) were born in central and south America and lived in United States in a bilingual household.	Most bilinguals spoke Spanish before than English (10/13). Mean age of L2 acquisition (6.00±2.16).
Fernández et al 2014 17 ML (20.4 ± 2.4) 18 BL (22.0 ± 3.8)	Language questionnaire designed by the authors. Oral vocabulary subtest	Monolinguals: English; Bilinguals: English and Spanish. Most bilinguals (11/18) were born in Central or South America and lived in United States in a bilingual household.	Most bilinguals spoke Spanish before than English (15/18). Mean age of L2 acquisition (6.22±4.80).
Morales et al 2015 27 ML (22 ± 3.4) 25 BL (26 ± 4.2)	Language history questionnaire	Monolinguals: Spanish; Bilinguals: Spanish plus Arabic (2), Catalan (6), Czech (1), English (6), French (1), Galician (1), German (5), Italian (1), Romanian (1), Russian (1). Participants were living in Spain. 7 bilinguals came from Spanish regions with two official languages, 14 bilinguals were immigrants.	Bilinguals acquired the second language before 6 years old.
Moreno et al 2014 15 ML (23.6) 13 ML musicians (26.5) 15BL (23.0)	Receptive vocabulary test in English (all the participants), Hebrew (9), and French (4).	Monolinguals were born and raised in Canada or USA. Bilinguals were born in Canada (n=5), Russia (n=1), Romania (n=1), and Israel (8) and spoke English and Hebrew (9), Russian (1), Romanian (1), and French (4).	Mean age of second language learning: 7.2.
Kousaie & Phillips 2012 25 ML (23.8±4.7) 26 BL (24.5±3.4)	Self-report L2 proficiency and animacy judgment task to obtain an objective measure of proficiency in L1 and L2.	Monolinguals: English; Bilinguals: English and French living in Canada.	Bilingualism acquired before the age of 7 years old.
Coderre & Van Heuven 2014 28 ML (22.2±5.4) 25 BL (23.4±4.0)	Language background questionnaire. Test on native and foreign language skills.	Monolinguals: English; Bilinguals: English and Mandarin Chinese. All the participants were living in United Kingdom.	L2 acquired at 10 years old ± 3.4.
Heidlmayr et al 2015 22 ML (25.5±4.4) 22 BL (26.9±5.5)	Self-evaluation and language test.	French (monolinguals) and French-German (bilinguals) living in France. L2 reported regular use of German during the past 3 years. Criterion for classifying participants as monolinguals was having had little use of other language than French in the last 3 years.	Bilinguals had started to study German at secondary school in France. Mean age of acquisition (10.6±0.7).
Morrison et al 2019 23 ML (19.7±2.3) 21 BL (19.7±1.6)	Self-rated proficiency scale and Boston naming test in English and French. Language history and usage questionnaire.	Monolinguals: English; Bilinguals: English and French. Participants were living in Canada.	Age of acquisition before 13 years old. Mean age of acquisition: 4.05 (2.27).
ELDERLY ADULTS			
Kousaie & Phillips 2017 21 ML (71.7±6.8) 22 BL (68.7±5.2)	Self-report L2 proficiency and animacy judgment task to obtain an objective measure of proficiency in L1 and L2.	Monolinguals: English; Bilinguals: English and French. Participants were living in Canada.	Bilingualism acquired before the age of 18 years old (mean age of acquisition: 4.9±5.1 years old) mean age of fluency: 9.95±3.28.
López-Zunini et al 2019 23 ML (22.8±3.3) 20 BL (22.7±2.8) 18 ML (71.7±3.5) 18 BL (71.4±4.0)	Self-rated proficiency in listening, reading, speaking, and writing.	Monolinguals: English; Bilinguals: English and French. All the participants were living in Canada.	Not reported.

Table 1. This Table recaps how bilingualism was determined on each study and some contextual factors and information regarding (L2) acquisition. Mean age of samples is reported in years old (mean and standard deviation within parentheses) except for Barac et al, where age is reported in months old. Abbreviations: ML (monolinguals), BL (bilinguals).

Study	Sample	Task	Neural measures	Bilingual advantage	Main findings
CHILDREN					
Barac et al (2016)	31 ML (63.5m ± 5.5); 19 BL (65.7m ± 5.4)	Visual Go / No-Go	N2, P3	Yes (in accuracy and RT)	BL outperformed ML. Faster N2 and P3 latencies and larger P3 amplitude in BL than in ML in Go and No-Go trials. ERP parameters correlated with performance.
YOUNG ADULTS					
Fernández et al (2013)	15 ML (22.6y ± 4.7); 13 BL (20.4y ± 1.5)	Auditory Go / No-Go	N2, P3	No	No behavioural differences. N2 was larger in BL than in ML during No-Go trials. N2 amplitude correlated with L2 proficiency.
Fernández et al (2014)	17 ML (20.4y ± 2.4); 18 BL (22.0y ± 3.8)	Auditory Go / No-Go Visual Go / No-Go	N2	No	No behavioural differences. N2 was larger in auditory No-Go trials in BL than in ML. No differences in visual modality.
Morales et al (2015)	27 ML (22y ± 3.4) 25 BL (26y ± 4.2)	Visual Go-No/Go (AX CPT task)	N2, P3, ERN	Yes (in the more difficult trials)	BL outperformed ML in trials demanding proactive and reactive control. N2 was larger in BL than in ML.
Moreno et al (2014)	15 ML (23.6y); 13 ML musicians (26.5y); 15 BL non-musicians (23.0y)	Visual Go / No-Go	P2, N2, P3	No	No behavioural differences. BL showed larger N2 than ML. ML musicians showed larger P2 and reduced N2 than ML non musicians.
Kousaie and Phillips (2012)	25 ML (23.8y±4.7); 26 BL (24.5±3.4)	Simon, Flanker, Stroop	N2, P3, ERN	No	No behavioural differences. Stroop: larger N2/slower P3 in ML than in BL; Simon: larger P3 in ML than in BL. Flankers: larger ERN (compatible trials) and lower ERN (neutral/incompatible trials) in ML than in BL.
Coderre and Van Heuven (2014)	28 ML (22.2y ± 5.4) 25 BL (23.4y ± 4.0)	Stroop task (SOA manipulation)	N450	Yes. Faster RTsin control trials. No differentL1 conflict size	In conflict trials, no behavioural differences between groups. No ERP differences between groups. In no-conflict control trials, faster RTsand lower N450 in BL than in ML.
Heidlmayr et al (2015)	22 ML (25.5y ± 4.4) 22 BL (26.9y ± 5.5)	Stroop-negative priming task	N2, N450, LSN	No	No behavioural differences. Significant Stroop effects on N450 and LSN amplitudes in ML but not in BL
Morrison et al (2019)	23 ML (19.7y ± 2.3) 21 BL (19.7y ± 1.6)	n-back (0-back, 1-back, 2-back)	P2, N2, P3	No	No behavioural differences between ML and BL. P300 amplitude was smaller in ML than in BL
ELDERLY ADULTS					
Kousaie and Phillips (2017)	21 ML (71.7y ± 6.8) 22 BL (68.7y ± 5.2)	Simon, Flanker, Stroop	N2, P3	Yes (in Stroop but not in Simon and Flanker tasks)	Stroop: greater interference/slower N2 in ML than in BL. Larger P3 in BL than in ML for incompatible trials. Simon: No behavioural differences. Larger N2, lower and slower P3 in ML than in BL. Flanker: no behavioural differences. Earlier N2 in BL than in ML for incompatible trials. Earlier P3 in BL than in ML for compatible trials.
López-Zunini et al (2019)	23 ML (22.8y), 20 BL (22.7y); 18 ML (71.7y), 18 BL (71.4y)	Task-switching paradigm	N2, P3	Yes (in switching and mixing costs)	Smaller switch and mixing costs in bilinguals than in monolinguals (both, young and elderly). Larger N2 in bilinguals than in monolinguals. In elderly, smaller P3b amplitude in bilinguals than in monolinguals.

Table 2. This Table summarizes the existing ERP studies comparing monolinguals and bilinguals while performing executive functions tasks. Abbreviations: “y” (years old), “m”(months old);ML (monolinguals); BL (bilinguals);AX CPT (AX continuous performance task); SOA (Stimulus Onset asynchrony); RT (Reaction Times);P2 (P200); N2 (N200); P3: P300: ERN (Error-related negativity); LSN (Late sustained negative-going potential);LFP (late frontal positivity). The column “Bilingual advantage” informs about whether or not bilinguals outperformed monolinguals.



		Behavioural advantage	N200 latency	N200 amplitude	P300 latency	P300 amplitude	N450 amplitude	ERN amplitude
Inhibition	Go/No-Go	▲1 🔴2 🔴3 🟢4 🔴5	▲1 🔴2 🔴3 🔴4 🔴5	🔺1 🔴2 🔴3 🔴4 🔴5	▲1 🔴2 🔴4 🔴5	▲1 🔴2 🔴4 🔴5		🔴4
	Simon	🔴6 🟥10	🔴6 🟥10	🔴6 🟥10	🔴6 🟥10	🔴6 🟥10		🔴6
	Flankers	🔴6 🟥10	🔴6 🟩10	🔴6 🟥10	🔴6 🟥10	🔴6 🟥10		🔴6
	Stroop	🔴6 🔴7 🔴8 🟩10	🔴6 🔴8 🟥10	🔴6 🔴8 🟥10	🔴6 🟥10	🔴6 🟩10	🔴7 🔴8	🔴6
Working memory	n-back	🔴9	🔴9	🔴9	🔴9	🟢9		
Switching	Switching paradigm	🟢11 🟩11	🔴11 🟥11	🔴11 🟥11	🔴11 🟥11	🔴11 🟥11		

Table 3. Graphical representation of evidence for a bilingual advantage obtained on each studied ERP parameter, cognitive task, and group of participants (triangles: children; circles: young adults; squares: elderly). Green figures representdifferences between monolinguals and bilinguals that can beinterpreted as a bilingual advantage in executive functions. Red figures represent no differences or differences between monolinguals and bilinguals that cannot be interpreted as a bilingual advantage in executive functions. Studies: ***1***. *Barac et al., 2016;* ***2***. *Fernández et al., 2013;* ***3***. *Fernández et al., 2014;* ***4***. *Morales et al., 2015;* ***5***. *Moreno et al., 2014;* ***6***. *Kousaie and Phillips, 2012;* ***7***. *Coderre and Van Heuven 2014;* ***8***. *Heidlmayr et al., 2015;* ***9***. *Morrison et al., 2019;* ***10***. *Kousaie and Phillips, 2017;* ***11***. *López-Zunini et al., 2019*.