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The effect of bilingualism on cognitive control resources in younger and older adults

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The effect of bilingualism on cognitive control resources in younger and older adults.

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Declaration

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards. I confirm that I am submitting this work with the agreement of my Supervisor(s).

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy. Rwy'n cadarnhau fy mod yn cyflwyno'r gwaith hwn gyda chytundeb fy Ngoruchwyliwr (Goruchwylwyr).

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Thesis Abstract

Age-related cognitive decline is a common phenomenon characterised by changes in cognitive functions such as working memory capacity, attentional control, and inhibition. However, there is variability in the extent and impact of these declines between individuals. This variability may be attributed to differences in functional neuroplasticity, the ability to reorganise neural networks and recruit alternative brain regions to compensate for age-related changes. Bilingualism offers a unique lens through which to understand cognitive aging and functional neuroplasticity. Research suggests that bilingualism may modify the trajectory of cognitive changes in older adults, with bilingual older adults outperforming monolinguals on non-verbal executive function tasks related to inhibitory control, task switching and working memory. However, the specific role of functional neuroplasticity in driving these language group differences remain unclear. This thesis investigates how bilingualism may impact age-related changes in cognitive control and attentional processes using two non-verbal executive function tasks. Additionally, the influence of task demands on the observation of these differences is examined. Understanding how bilingualism may impact brain activity regulation can offer insight into the mechanisms behind experience-induced plasticity in older adulthood.

Experiment one employed a visual Go/NoGo paradigm to investigate the impact of bilingualism on age-related changes in conflict monitoring and attentional processes under low and high task demands. Results revealed that when conflict monitoring demands were low, both older adult monolinguals and bilinguals regulated conflict monitoring processes akin to younger adults, indexed by the presence of an N2-effect. However, under high task demands, older adult monolinguals over-recruited conflict monitoring processes, reflected in an attenuation of the N2-effect. Given the lack of behavioural differences between the two language groups, it is possible that this over-recruitment observed in older adult monolinguals reflected a compensatory process, and the absence of this over-recruitment in older adult bilinguals was reflective of more efficient cognitive control.

In Experiment two, the effect of bilingualism on age-related changes in the inhibition of interference from irrelevant information was investigated using a visual Simon task. Older adults exhibited increased interference to irrelevant stimuli relative to younger adults, indexed by larger Simon effects in reaction time. No behavioural differences were observed between monolinguals and bilinguals in either age group. However, at the neural level, older adult monolinguals exhibited greater interference from irrelevant stimuli than older adult bilinguals, indicated by a larger N2-effect, while the younger adult sample exhibited comparable N2 amplitudes between the language groups. These results suggest that language experience impacts the ability to inhibit irrelevant interference, but this effect may only be observable in older adulthood on this paradigm, possibly due to low task demands.

The third empirical chapter revealed no association between the Simon and Go/NoGo task on either behavioural or electrophysiological measures. This finding supports the lack of convergent validity between executive function tasks assumed to measure common EF constructs. This suggests that performance on these tasks could be underpinned by two different kinds of inhibitory control mechanisms.

Overall, this thesis contributes to our understanding of how bilingualism may impact functional changes in cognition during aging. It highlights how bilingual older adults are better able to adapt cognitive control processes to meet task demands especially under high task demands, and they experience less interference from irrelevant stimuli than monolinguals. Furthermore, the research presented here highlights the importance of considering the specificity of executive function tasks as performance may be underpinned by distinct aspects of inhibitory and monitoring processes.

Future work should employ extensive ladder design paradigms to further examine the impact of cognitive load on language group differences in cognitive control and attentional processes. Additionally, employing a multi-paradigm approach alongside latent variable analysis would enhance our understanding of executive function and the role of attention in explaining these differences.

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Chapter 1: General Introduction

1.1.THESIS AIMS AND OUTLINE

Bilingualism is undoubtedly a complex experience that places incredible demands on the human cognitive system. Such experiences have been shown to shape the brain through structural and functional neuroplasticity. Functional neuroplasticity can be defined as adaptive changes in existing neural networks that occur in response to behavioural or environmental changes (Puderbaugh & Emmady, 2022). These adaptations can facilitate stability, restoration, or compensation of functional processes in light of injury or pathology (Smith, 2022). Neuroplasticity is especially important in older adulthood as it plays a pivotal role in the brain’s ability to maintain cognitive function and adapt to age-related changes (Greenwood, 2007; Reuter-Lorenz & Cappell, 2008). Understanding the mechanisms behind functional neuroplasticity in older adulthood is important for promoting healthy aging, and recently, neuroimaging work has aimed to further understand the brain’s ability to maintain cognitive function in light of structural and functional age-related brain changes. Bilingualism offers us a unique lens through which to understand more about how experiential factors may contribute to changes in cognitive function in the aging brain. However, the mechanisms underpinning these changes remain unclear. The dearth of clear theoretical frameworks underpinning experience-based neuroplasticity contributes to our lack of understanding about how bilingualism may impact cognition. Moreover, investigating the impact of bilingualism on cognition using high performing younger adult samples performing easy, un-demanding tasks may be obscuring our ability to see the circumstances under which bilingualism may contribute to cognitive changes. The integration of aging and bilingualism literature alongside the utilisation of neuroimaging techniques will provide valuable insight into experience-dependant neuroplasticity in the aging brain.

In this thesis, the effects of bilingualism on inhibitory control and attentional processes in younger and older adults is investigated on two non-verbal tasks of executive function. Parallel to this, the impact of task demands on observable group differences in both behavioural and electrophysiological measures of attention and inhibition are also explored. The thesis aims to answer four distinct but related research questions:

RQ 1: Does bilingualism affect cognitive processing during inhibition of a pre-potent response in older adults?

RQ 2: Does bilingualism influence age-related changes in inhibition to interference?

RQ 3: Are there language group differences in non-inhibition processes such as attention and monitoring?

RQ 4: What is the functional significance of the N2 and P3 in non-verbal executive function tasks?

The thesis will firstly review behavioural evidence related to the investigation of bilingualisms' impact on cognitive processes. Following this, the event-related potential (ERP) technique will be introduced and evidence employing this technique to answer questions about the cognitive effects of bilingualism will be presented. Due to the often subjective nature of the ERP technique, a chapter is dedicated to methodological transparency of experimenter choices during the data collection, processing, and analysis procedures. After providing a comprehensive background to the thesis, a methodology chapter will present participant, paradigm and experiment related information. Then, three separate results sections will describe the findings from the exploration of the research questions. Finally, a general discussion chapter will aim to draw together the key findings across all three experiments to provide a clear interpretation and present ideas for future research.

1.2. HOW DOES BILINGUALISM SHAPE OUR BRAIN?

Bilingualism – proficiency in more than one language – has an integral place in the social, economic, and political domains of society. Bilingualism facilitates international trade, enables diplomacy and espionage, and enables the communication of cultural and political ideas across nations. On a more individual level, the impact of speaking more than one language has been the focus for cognitive and language scientists. Specifically, many researchers want to know: how does the knowledge of more than one language shape, sculpt and modify brain structure and function? And while global estimates are hard to acquire, it is generally assumed that more than half of the worlds' population is bilingual (Grosjean, 2021), so the answer to this question is pertinent to a large proportion of our global society.

Over the past 50 years, researchers have been aiming to answer just this. Attempts to understand the effect of bilingualism on cognition has been the focus of significant academic attention, as captured in the graph below (Figure 1). Even beyond the world of academia, the impact of knowing more than one language has captured the attention of audiences around the world (Figure 2).

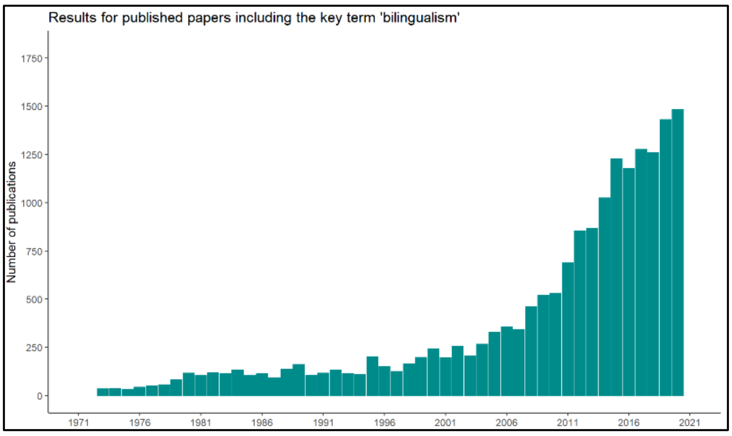
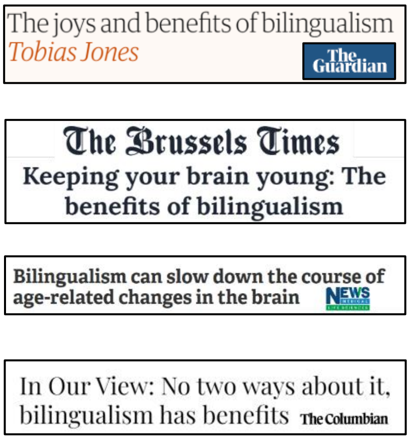


Figure 1. Dramatic rise in number of published papers with the term 'bilingualism' in the full text under the field of Psychology (Data source:dimensions.ai)


The joys and benefits of bilingualism
Tobias Jones
The Guardian

The Brussels Times
Keeping your brain young: The benefits of bilingualism

Bilingualism can slow down the course of age-related changes in the brain
NEWS

In Our View: No two ways about it, bilingualism has benefits
The Columbian

Figure 2. Newspaper headlines from around the world focusing on the effects of bilingualism.

Early literature reviews on bilingualism research concluded that learning two languages would have negative consequences for cognition, causing confusion and developmental delay (Hakuta, 1986). Contrary to this, in 1962, Peal and Lambert's seminal paper presented positive effects of bilingualism. The paper reported how a group of French-English bilingual children outperformed English monolingual children on a battery of verbal tests. Peal and Lambert (1962) also reported superior performance for the bilingual children on non-verbal tests - tests that did not require the use of language. Despite the findings of the landmark study now being called into question due to its reliance on intelligence tests and its dismissal of relevant sociolinguistic, cultural, and participant characteristics (Bialystok et al., 2022), this paper was the springboard for research focusing on the potential positive impact of bilingualism on behaviour and the brain.

This work continued to be extended, most notably by research from Ellen Bialystok, with a series of studies demonstrating that monolingual and bilingual children performed similarly on meta-linguistic tasks involving grammatical knowledge. However, in tasks requiring avoidance of interference from conflict, bilingual children consistently outperformed monolingual children (Bialystok, 1986, 1988). From here, the notion that benefits obtained from second language experience could be transferred to non-language domains was further explored and over the past 20 years there has been a dramatic rise in research focusing on the cognitive consequences of bilingualism (Kroll & Bialystok, 2013). Furthermore, with the advent of spatially and temporally sensitive neuroimaging techniques and more sophisticated statistical analyses, it is now possible to ask more complex and nuanced questions. To unravel the intricate influence of bilingualism on non-language domains, it is imperative to first grasp the fundamental underpinnings of bilingual language control.

1.2.1. Managing two languages and linguistic control in the brain

Two language systems exist in the bilingual brain so in turn bilingualism must involve the constant management of two competing linguistic representations (e.g., Marian & Spivey, 2003; Thierry & Wu, 2004). But how do these two languages co-exist and what are the consequences of juggling two languages in one brain?

It is widely accepted that the presence of two language systems results in competition for production as a result of cross-language activation (Whitford & Luk, 2019). Cross-language activation is the non-selective access of both the first language (L1) and second language (L2) representations. For example, imagine a bilingual individual fluent in both English and Welsh who encounters a sentence which contains a cognate – a word that is similar in form and meaning across two languages. For example, the sentence is “I like to drink coffee.” When the bilingual individual reads or hears the word "coffee" in English, it activates the corresponding concept and lexical representation in their mind. However, because Welsh is the individual's other language, the Welsh equivalent of "coffee" (which is "coffi") can also be automatically activated due to cross-language connections. This cross-language activation occurs because bilingual individuals have interconnected mental representations for words across their languages.

This notion has been supported by eye-tracking and event-related potential studies reporting parallel activation of both languages in bilinguals when speaking, reading, and hearing in only one language (e.g., Kroll, Gullifer & Rossi, 2013; Marian & Spivey, 2003; Thierry & Wu, 2004; Wu & Thierry, 2010). The competing L1 and L2 representations can occur at multiple levels such as the phonological, semantic, and syntactic level (e.g., Assche, Duyck & Hartsuiker, 2012; Whitford, Pivneva, Titone, 2016) and can have either facilitatory or inhibitory effects. Cognates are faciliatory as they map onto a common meaning. Cross-language activation can also interfere with language processing, for example interlingual homographs, words which share orthography but not semantics, can interfere as they map onto different meanings but compete for representation (e.g., De Groot, 2011).

The selection of language operates by selectively enhancing the processing of representations in one language and inhibiting those in the other language (Grainger & Dijkstra, 1992; van Heuven, Dijkstra & Grainger, 1998; Dijkstra & van Heuven, 2002). Without this, bilingualism and multilingualism would result in constantly competing languages with erroneous language production or loss of fluency occurring, yet this rarely occurs in bilingual individuals. Thus, a control system must be in place to manage the two (or more) competing languages. It is hypothesised that bilinguals employ domain-general higher-level cognitive processes in the continuous management of two languages (for review see Bialystok, et al., 2009).

One candidate for this control system is executive functions (EF). Executive functions refer to a set of high-level cognitive processes involved in cognitive control and self-regulation. The neuropsychological construct of executive function stemmed from deficits observed in planning and goal-oriented behaviour in patients with frontal lobe damage (e.g., Duncan, 1986; Shallice & Burgess, 1991). However, despite a wealth of studies investigating executive functioning, a formal definition and division of subcomponents remains absent. The understanding of EF has been shaped by the highly influential work of Miyake and colleagues, specifically their Unity and Diversity model proposed in 2000 which underwent further refinement in 2012 (Miyake et al., 2000; Miyake et al., 2012). In the 2000 model, Miyake and colleagues employed confirmatory factor analysis to delineate three distinct yet interrelated latent variables, forming the basis for performance on nine tasks purported to engage executive functions: updating, shifting, and inhibition. Shifting can be defined as an individual's ability to disengage from an irrelevant task and engage with a relevant task; updating is concerned with the updating of working memory representation; inhibition refers to an individual's ability to refrain from performing a dominant and prepotent response when necessary (Miyake et al., 2000).

Twelve years after the original model was proposed, a revised framework was developed introducing the concept of “common EF”, a broader and overarching ability that incorporates inhibition along with other cognitive functions. It is posited that this “common EF” manifests across both updating and shifting components. Meanwhile, the updating-specific and shifting-specific abilities were identified as distinct from one another, each accounting for unique variances associated with the tasks in the model.

In a 2013 review, Adele Diamond provided a comprehensive examination of executive functions and their role in various aspects of life including academic achievement, social interactions, and emotional regulation. Diamond (2013) also emphasized the interplay between different components of executive functions, highlighting their interconnected nature. Diamond emphasised that executive functions are not isolated abilities but function in a collaborative manner to facilitate goal-directed behaviour, problem-solving, and decision-making. This model proposed that core executive function components are inhibition and interference control, working memory and cognitive flexibility. Moreover, central to the tenets of this thesis, Diamond (2013) underscored the importance of considering the developmental trajectory of executive functions, discussing how executive functions undergo significant changes with age, and how these changes are influenced by factors such as genetics, environment, and experience.

But what is the link between executive functioning and language control? It is suggested that executive function processes could be employed to serve myriad functions in bilingual language control, including but not limited to: (a) switching from one language to another, (b) inhibiting the non-target language when utilising the target language, (c) monitoring the current environment regarding which individuals and/or contexts require the target language, (d) accessing and utilising language components such as grammar rules, pronunciation and semantics with reference to the target language (Moradzadeh, Blumenthal & Wiseheart, 2015). The extensive employment of these processes during language regulation is proposed to have consequences for cognitive and behavioural outcomes in non-language contexts (e.g., Bialystok et al., 2009; Kroll et al., 2015). Namely, bilinguals may experience better performance on tasks that tap into executive functioning. A wealth of empirical studies have investigated this idea by comparing the behavioural performance of bilinguals and monolinguals on tasks of executive function. Bilinguals are reported to outperform their monolingual counterparts on tasks of inhibition (e.g., Bialystok, Craik, Klein & Viswanathan, 2004; Blumenfeld & Marian, 2014), switching (e.g., Barbu, Orban, Gillet & Poncelet, 2018; Wiseheart, Viswanathan & Bialystok, 2016) and working memory (for review see Grundy & Timmer, 2017).

Moreover, the positive effects of bilingualism have been documented across the lifespan, from pre-verbal infants in a bilingual environment (Kovács & Mehler, 2009) and young children (for review see e.g., Bialystok, 2015), to adults (e.g., Costa, Hernández & Sebastián-Gallés, 2008; Henrard & Van Daele, 2017; Naeem et al., 2018) and into older adulthood (e.g., Houtzager et al., 2017; Gold et al., 2013). The experience of managing two languages may even contribute to cognitive reserve in the aging mind, offering neuroprotective properties and forestalling cognitive decline (Bialystok, 2021; Goral, Campanelli & Spiro, 2015; Guzmán-Vélez & Tranel, 2015). The pattern of amelioration of cognitive decline in bilinguals has also been suggested to extend to neurodegenerative diseases, wherein bilinguals experience a delay in the onset of dementia symptomatology of up to four years (Bialystok, Craik & Freedman, 2007; Ossher et al., 2013).

1.2.2. Inhibitory control

Inhibition, or inhibitory control, is the central tenet to several models of executive function. Diamond (2012) states that without inhibition we would be "at the mercy of impulses". For Miyake and colleagues, in their original model of executive function inhibition represented the ability to deliberately withhold dominant, automatic or prepotent responses. Evidence from lesion studies suggests that inhibition processes may be underpinned by the inferior frontal cortex, as damage to this area impairs performance on EF tasks by disrupting inhibition (e.g., Iversen & Mishkin, 1970). Moreover, structural MRI, functional MRI and EEG evidence supports this further, finding that damage to the right inferior frontal regions underlies inhibition performance deficits (for review see Aran et al., 2004). Empirical neuroimaging work has demonstrated that the prefrontal cortex (PFC) plays a role in inhibitory control (Aron, Robbins & Poldrack, 2004).

However, the notion of inhibition as a discrete process is challenged. The inhibition-specific component was later removed from the 2000 model of executive function developed by Miyake and colleagues, and in their updated model inhibition was replaced with an overarching "common EF" component (Miyake et al., 2012). Despite the removal of inhibition from Miyake and colleagues' model, much bilingualism research focuses on the role of inhibition in bilingual language control and investigates how the employment of inhibition may have consequences beyond language control (for review see Grundy, 2020). Such research was driven by the model proposed in 1998 by Green – the Inhibitory Control (IC) model. This framework details how the use of inhibition to suppress the non-target language and reduce interference from the non-target language results in positive cognitive outcomes for bilinguals. However, a notable distinction emerges between the inhibition component proposed by Miyake and colleagues and the one put forth by Green. Miyake's framework primarily emphasises inhibition in the context of motor responses, whereas Green's conceptualisation centres around inhibition as a cognitive control mechanism.

This absence of a clear cut and definitive conceptualisation of inhibition persists as a consistent theme in executive function and bilingualism research. This lack of clarity may in part be driven by the fact that inhibition is not a singular, unitary construct. Instead, different forms of inhibition seem quite distinct. One framework argues that there are two types of inhibition - inhibition of a motor response and inhibition of attention to task irrelevant stimuli (Bunge et al., 2002). This distinction is supported by the idea that the two disparate inhibition types have differential developmental trajectories (Bunge et al., 2002). Another framework proposed by Friedman and Miyake (2004) argues that there are *three* separable but related inhibition-related functions: Prepotent Response Inhibition (PRI), Resistance to Distractor Interference (RDI) and Resistance to Proactive Interference (RPI). Proactive Interference involves the ability to proactively suppress irrelevant information or prepotent responses before they become active. Reactive Inhibition refers to the ability to quickly and effectively inhibit a prepotent response that has already been initiated, i.e., stopping or changing an ongoing behaviour to meet task requirements. Thirdly, Resistance to Distractor Interference pertains to the capacity to resist interference from distracting stimuli or conflicting information to maintain attention on the current task. Importantly, a common agreement between the two frameworks presented by Bunge and colleagues (2002) and Friedman and Miyake (2004) is the distinction between *response inhibition* and *inhibition to interference*.

Given the distinction between different inhibition processes, how do these disparate processes link to bilingualism? The Inhibitory Control (IC) model posited by Green (1998) suggests that inhibition is required to suppress the non-target language in order to reduce interference from the non-target language. Evidence from brain imaging studies supports this, finding that the dorsal anterior cingulate cortex (ACC) is common to both domain-general and language control (Abutalebi at al., 2012). As a result, the constant employment of domain-general inhibition during language control results in better performances on non-linguistic tasks that recruit such processes (e.g., Hilchey & Klein, 2011). The presence of language group differences on tasks of inhibition has been investigated using an array of non-verbal tasks employing both response inhibition and interference suppression, including the Flanker task (e.g. Costa, Hernández & Sebastián-Gallés, 2008; Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009; Von Bastian, Souza & Gade, 2016), Simon task (e.g., Bialystok, Craik, Klein & Viswanathan, 2004; Bialystok, Craik & Luk, 2008), Stroop task (Bialystok, Craik & Luk, 2008; Coderre, Van Heuven & Conklin, 2013), Go/NoGo task (e.g., Moreno, Wodniecka, Tays, Alain & Bialystok, 2014), and Attention Network Task (ANT; Pelham & Abrams, 2014). However, language group effects on inhibition tasks are not uniform and researchers have proposed that bilingualism confers benefits to networks associated with *interference suppression* (inhibition of task irrelevant stimuli) but not *response suppression* (inhibition of a motor response) (Luk et al., 2010; Martin-Rhee & Bialystok, 2008). Neuroimaging evidence supports this, revealing how bilingualism selectively affects neural correlates for interference suppression but not response inhibition (Luk et al., 2010).

The selective influence of bilingualism on interference suppression but not response suppression can be attributed to bilingual language control. Bilingual individuals engage in the constant inhibition of one language while attending to another, this may enhance their ability to suppress interference from irrelevant stimuli. In contrast, response suppression primarily involves inhibiting a motor response, which may not be as heavily influenced by bilingual language processing. Secondly, brain imaging studies have shown that bilingualism selectively influences neural correlates associated with interference suppression, such as the prefrontal cortex and anterior cingulate cortex, while not significantly affecting regions associated with response inhibition (for review of behavioural and neuroimaging evidence see Bialystok, Craik & Luk, 2012). This suggests that the neural mechanisms supporting these two types of inhibition may be distinct and influenced differentially by bilingual language experience. However, despite this distinction, there is little work exploring how the bilingual language experience may impact inhibition processes differentially. Consequently, the current thesis will explore this through employing two non-verbal executive function paradigms used ubiquitously in cognitive control literature – the Simon task and the Go/NoGo task.

Simon Task

The Simon task is commonly used in research examining the impact of bilingualism on inhibition; in fact, over a third of all studies since 2008 use this paradigm (Privitera &

Weekes, 2022). In a standard version of the Simon task, participants learn a rule which maps two responses to a key press. For example, in a visual Simon task, a blue or red square is presented on a screen and participants must respond dependant on the colour (i.e., left for blue square, right for red square), irrespective of which side of the screen the shape was presented on. For congruent conditions, the position of the stimuli on the screen will correspond to the side of the required manual response. In incongruent conditions, the position of the stimuli will be opposite to the required manual response (See Figure 3). Measures of reaction time (RT) and accuracy (%) can be obtained for congruent and incongruent trials. Typically, incongruent trials reliably elicit longer response times and lower accuracy rates relative to congruent trials, this difference is the Simon effect (Simon, 1969). The Simon effect is not confined to one modality and can be obtained using visual, auditory, and somatosensory stimuli (e.g., Craft & Simon, 1970; D’Ascenzo et al., 2018; Salzer, et al., 2014). Moreover, it can occur when participants are required to respond using their hand, foot or with eye movements (Leuthold & Schröter, 2006).

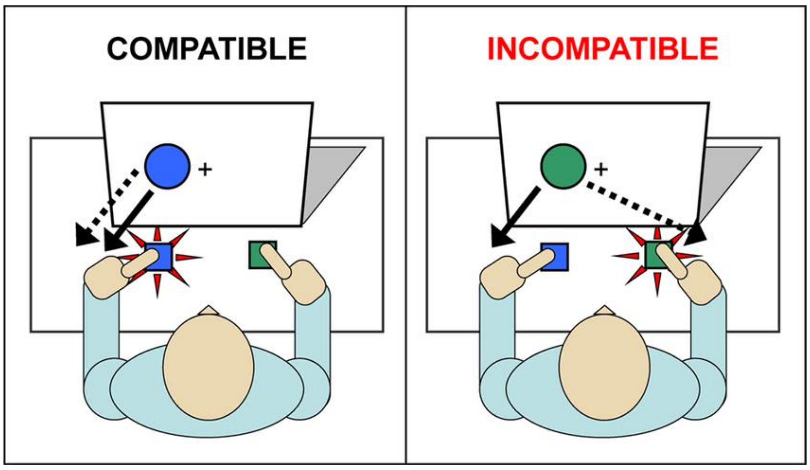


Figure 3. An example of a visual 2-way Simon Task taken from Van den Wildenberg et al., (2010). Participants press the left button when they see a blue circle and the right button when they see a green circle (dashed line). However, the spatial location of the circle can also influence the response (solid line). In congruent conditions, both the colour and spatial location activate the correct response, in incongruent conditions only the colour activates the correct response, and the spatial location activates the incorrect response route.

The Simon effect is posited to be the result of lack of correspondence between the spatial location of the stimuli and the spatial location of the required response i.e., stimulus-response (S-R) compatibility (e.g., Craft and Simon, 1970; Simon & Rudell, 1967) but the locus of the Simon effect remains controversial (for review see Hommel, 2011). One hypothesis is the dual-route model which attributes the Simon effect to a competition between two alternative responses (Kornblum, Hasbroucq & Osman, 1990). Dual route models argue that relevant and irrelevant stimulus attributes are processed in parallel through different routes. For example, in a visual Simon task, one route processes the relevant colour of the stimulus, and the other route processes the irrelevant spatial position. The model argues that the stimulus location is processed through a fast and automatic route, whereas the stimulus colour (or another relevant task feature) is processed through a slower, controlled route (Hommel, 2011). In instances where the stimulus-response pairing is congruent, the processing of the position is facilitatory as it activates the faster route. When the stimulus-response pairing is incongruent, the processing of the position is inhibitory as it activates both the stimulus location route and the slower, controlled stimulus colour route. The concurrent activation of the two routes generates conflict which must be resolved in order to execute a response, resulting in delayed reaction times and reduced accuracy. A review of neurophysiological studies found evidence to support the dual-route model, in that studies reported how stimulus location triggers one response while stimulus features trigger another response, and both compete to achieve the critical response threshold (for review see Cespón et al., 2020).

Increased age is typically associated with larger Simon effects in accuracy and reaction time (e.g., Kubo-Kawai & Kawai, 2010; Proctor, Vu & Pick, 2005), even after correcting for general slowing age (Van der Lubbe & Verleger, 2002). The increased Simon effect is argued to reflect increased interference from irrelevant spatial information relative to younger adults (Proctor, Vu & Pick, 2005). It is argued that the interference suppression used during bilingual language control is also employed during the Simon task, allowing bilinguals to outperform monolinguals (e.g., Bialystok, Craik, Green & Gollan 2009; Schroeder et al., 2016). Thus, it is commonly used as a measure to compare the abilities of monolinguals and bilinguals to inhibit interference from irrelevant information (for meta-analyses see Lehtonen et al., 2018; Ware, Kirkovski, Lum, 2020). The employment of the Simon task (as opposed to other spatial-response paradigms such as the Flanker) is beneficial, given how a meta-analysis determined that the effect sizes in the Simon task are typically larger than that of other non-verbal tasks used to measure EF such as the Stroop task, the Trail Making Test, and the Flanker task (Ware, Kirkovski & Lum, 2020).

In 2004, Bialystok and colleagues were the first to report the performance of monolinguals and bilinguals on a Simon task, finding that middle-aged and older adult bilinguals had smaller Simon effects in reaction times relative to their monolingual counterparts (Bialystok et al., 2004). The authors suggested that this was indicative of superior inhibitory processes in bilinguals due to their ability to resist interference to task-irrelevant information. From here, many studies have employed the Simon task to compare the inhibitory control of monolinguals and bilinguals, yielding mixed results. The superior performance of bilinguals in interference control on a Simon task has been replicated in some studies (Bialystok, Martin & Viswanathan, 2005; Woumans et al., 2015). However, a large sample study (*N* = 557) recruiting participants aged 2 to 90 years of age found no evidence for language group differences when looking at the Simon effect in reaction time or accuracy (Gathercole et al., 2014). Other studies have also failed to replicate these findings as highlighted in Figure 4, in which a sample of studies employing the Simon task to compare the inhibition abilities of monolinguals and bilinguals are plotted. The findings across studies are not consistent in terms of language group differences (also see Van den Noort et al., 2019 for a systematic overview of studies). However, it is important to note that the methodologies of the studies are also not consistent; different paradigms and age groups are often used.

Recently, research has turned away from single empirical studies and has turned to pooling data from several studies. For example, two large scale meta-analyses aimed to understand whether bilingualism is associated with enhanced executive functioning in adults (Lehtonen et al., 2018; Ware, Kirkovski, Lum, 2020). These reviews focused on behavioural comparisons of monolingual and bilingual adults on a range of executive functioning tasks. Lehtonen and colleagues (2018) reported how studies utilising the Simon task had a non-significant small effect (Hedges' *g* = 0.09, 95% CI [-.01, .20], *p* = .087) in favour of bilinguals (Lehtonen et al., 2018). It was reported that age did not modulate the outcome, however it should be noted that the authors did not report on the number of observations of older adult samples in the Simon task. In a subsequent large-scale meta-analysis of 170 studies, Ware and colleagues (2020) reported the effect size of comparisons between monolinguals and bilinguals on 48 observations of the Simon task (Ware, Kirkovski, Lum, 2020). It was reported that the two language groups had comparable Simon effects, but that bilingual samples were significantly quicker than monolinguals on both congruent and incongruent trials. Moreover, contrary to previous meta-analyses, the authors reported that the superior performance of bilinguals was larger for studies comprising samples aged 50 years and over (Hedges' g = 0.49), relative to those with samples aged between 18 and 29 years (Hedges' g = 0.12).

Based on the findings of these meta-analyses, it could be argued that bilinguals do not experience an advantage over monolinguals on behavioural measures of inhibition. However, one caveat of these meta-analyses is that different paradigms are grouped together under common umbrella terms. For example, Simon, Go/NoGo and Flanker measures are all grouped under inhibition measures and are assumed to measure the same executive functions components to the same extent. However, as discussed earlier in this section, inhibition is not a unitary construct that is employed similarly across all inhibition paradigms. Moreover, as will be discussed further in Section 3.6, this assumes cross-task validity amongst EF tasks, an assumption that has been called into question recently. Importantly however, these meta-analyses did highlight how participant characteristics such as socio-economic status, age of participants and differing definitions of bilingualism can modulate the effects of bilingualism, as can task-relevant characteristics such as choice of task and task difficulty. The effects of age and task difficulty on observing language group differences will be discussed in Section 1.4 and Section 1.5.

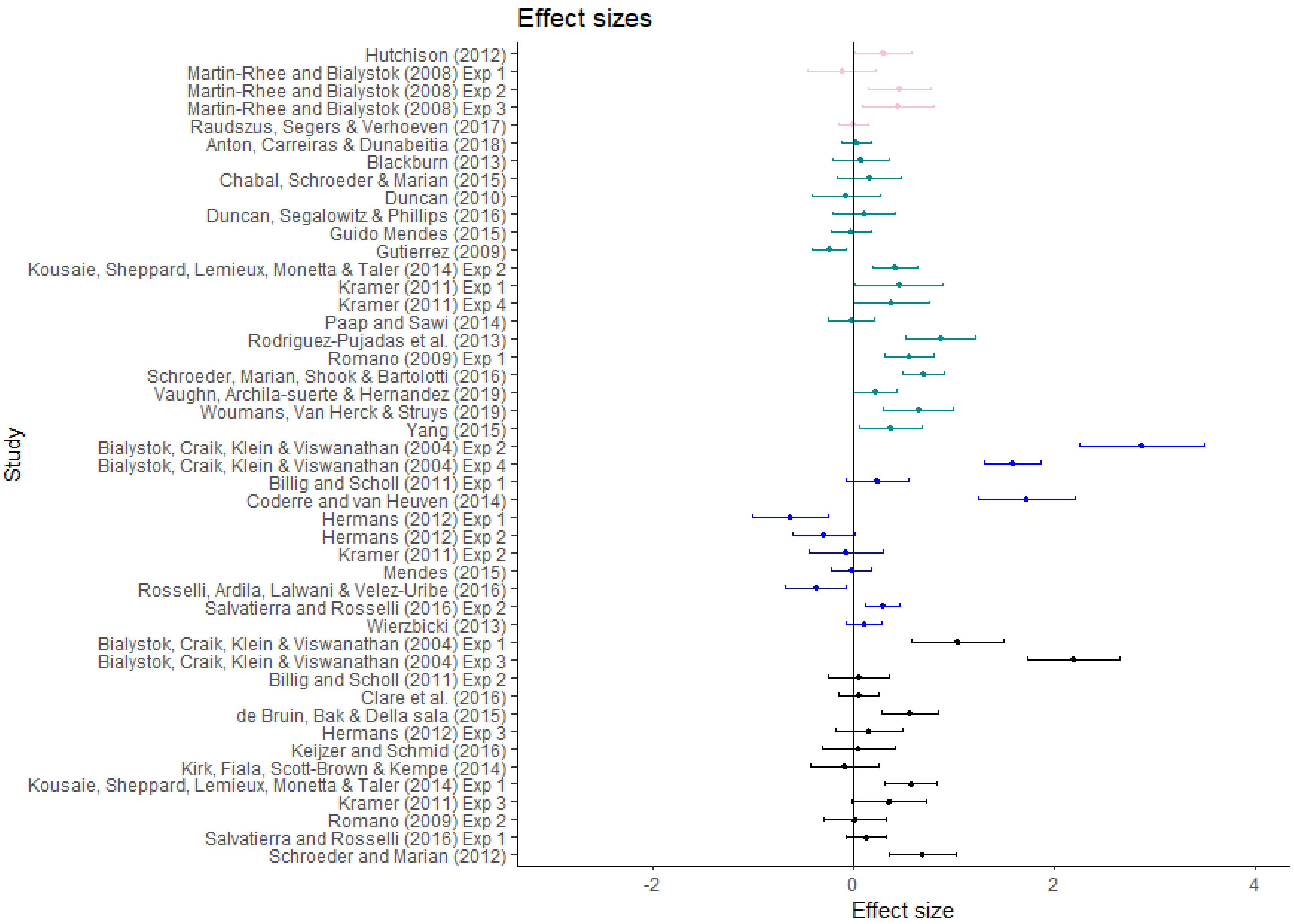


Figure 4. Reported effect sizes plotted using data calculated from Ware, Kirkovski & Lum, 2020. Positive effect sizes indicate better performance from bilinguals and negative effect sizes indicate a poorer performance by bilinguals on the Simon task.

Go/NoGo Paradigms

In addition to the Simon task, measures of inhibition can also be derived using the Go/NoGo paradigm (for reviews see Lehtonen et al., 2018; Cespón & Carreiras, 2020). In a typical Go/NoGo task, participants are instructed to respond to Go stimuli and withhold responses to NoGo stimuli. Behavioural measures of reaction time and accuracy can be obtained on the task. Accuracy on NoGo trials is typically used as a behavioural measure of inhibition (Lehtonen et al., 2018). The Go/NoGo effect is most consistently elicited in the visual modality but has been elicited using auditory stimuli (Nieuwenhuis, Yeung & Cohen, 2004). Research has utilised the Go/NoGo paradigm to compare bilinguals and monolinguals on inhibitory control processes (e.g., Festman, Rodriguez-Fornells & Münte, 2010; Javor, 2017; Moreno et al., 2014). Bilingual children are reported to perform the Go/NoGo with higher accuracy and have faster reaction times on Go trials relative to monolingual children (Barac, Moreno & Bialystok, 2016), and young adult bilinguals are reported to execute more correct responses while making fewer errors than monolinguals for Go and NoGo trials (Javor, 2017).

It could be argued that the Go/NoGo paradigm employs an inhibition process separable from the Simon task. While the Simon task requires *inhibition of interference* to task irrelevant stimuli, the Go/NoGo task requires *inhibition of a motor response*. Given the distinction of these two inhibition components, and the notion that bilingualism confers benefits to networks associated with interference suppression (inhibition of task irrelevant stimuli) but not response suppression (inhibition of a motor response) (Luk et al., 2010; Martin-Rhee & Bialystok, 2008), it could be argued that bilinguals will not experience a benefit on this task. And, in fact, work has reported a lack of behavioural differences between groups (Moreno et al., 2014), and a meta-analysis including 15 studies employing the Go/NoGo paradigm reported that monolinguals and bilinguals did not differ on the behavioural measures of inhibition on the Go/NoGo task (Hedges' $g = 0.14$, 95% CI [-.10, .38], $p = .252$) (Lehtonen et al., 2018). However, it is important to note that the Go/NoGo paradigm is most frequently used in conjunction with neuroimaging techniques such as event-related potentials (ERPs) (Cheng, Tsai & Cheng, 2019), and language group differences on the Go/NoGo task have been reported in electrophysiological data in the absence of behavioural differences (Fernandez et al., 2014; Fernandez et al., 2013; Moreno et al., 2-14). These differences are consistently manifested as larger N2 amplitudes – an ERP suggested to index inhibition[1]. However, the effects of age and task demands on bilingualism-induced changes on the inhibitory control processes employed in a Go/NoGo task are yet to be elucidated.

1.2.3. To inhibition... and beyond!

Research investigating the impact of bilingualism on cognition has focused on inhibition as the primary candidate for explaining language group differences. The inclusion of inhibition in Miyake's 2000 model and Green's IC model contributed to this approach. However, research has reported language group differences in the absence of conflict, in circumstances where inhibitory control is not required, such as bilinguals exhibiting faster reaction times on both congruent and incongruent trials (Hilchey & Klein, 2011). This pattern has been observed across the lifespan in work recruiting children (Martin-Rhee & Bialystok, 2008), adolescents (Chung-Fat-Yim, Himel & Bialystok, 2019), young adults (Costa et al., 2009) and older adults (Bialystok et al., 2004). Moreover, a recent meta-analysis across 61 studies examining reaction times on the Simon task further supports this, showing that bilinguals exhibit a speed advantage on both congruent and incongruent trials (Ware, Kirkovski & Lum, 2020). This challenges the idea that inhibition is the sole explanation for language group differences in executive function task performance. Moreover, the argument that inhibition is employed during language control to minimise interference from the non-target language is challenged by work demonstrating how the non-target language can influence task performance, even when the verbal stimuli are not relevant to the task (Wu & Thierry, 2013), and by work demonstrating language group differences in infants, for whom language inhibition is not necessary due to their rudimentary representations of language (e.g., Kovacs & Mehler, 2009; Singh et al., 2015).

To account for these non-inhibition specific language group differences, Hilchey and Klein (2011) proposed that bilinguals experience a general advantage in executive function performance that is not solely reliant on inhibition performance. These improvements may be linked to bilinguals' continuous monitoring of their environment in order to identify language conflicts (Costa et al., 2009). However, the account proposed by Hilchey and Klein (2011) posits that processing speed, as indexed by reaction time, would be an appropriate index to evidence this advantage, and while bilinguals do exhibit quicker reaction times on

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[1] The effects of bilingualism on neural measures of inhibitory control will be discussed in more depth in Chapter 2 (Introduction to event-related potentials).

some tasks (Hilchey & Klein, 2011), this approach does not account for instances of improved performance by bilinguals on tasks such as working memory tasks (e.g., Grundy & Timmer, 2017). Bialystok (2017) wrote an extensive review of behavioural and neuroimaging studies of non-verbal cognitive function tasks and bilingualism across the lifespan. Bialystok proposed that inhibition is an insufficient framework to account for language group differences on tasks of switching and monitoring. Instead, attentional control is posited as a mechanism that better explains cognitive performance differences between language groups. It is argued that bilingualism confers a domain-general benefit to attentional control as a result of adapting the attentional control system to meet environmental demands. Moreover, the paper argues that attention can be conceptualised as a continuum rather than a discrete process allowing us to more easily explain how disparate bilingual experiences (i.e., idiosyncrasies in proficiency, age of acquisition, usage), may result in different cognitive benefits.

The evidence supporting the role of attentional control in explaining bilingual task performance has been comprehensively reviewed in order to conceptualise attentional control more clearly (Bialystok & Craik, 2022). Bialystok and Craik (2022) argue that attentional control is a mechanism which can be applied to a wide range of non-verbal cognitive function tasks. It is noted that attentional control is a "broad, descriptive term" which is underpinned by several processes (Bialystok & Craik, 2022, *pg*. 1253), but it is conceptualised as a process which maintains current goals, facilitates cognitive operations, and suppresses interference as well as switching processing resources when required. It is important to note that inhibition comprises part of the proposed attentional control scheme proposed by Bialystok and Craik (2022). The paper notes how inhibition and attentional control are overlapping and are often recruited by the same tasks. However, the distinction is made in a hierarchical sense, in that attentional control is an overarching process which can be used to control many processes, including inhibition, meaning that inhibition, as defined by the Miyake model, may not be the only explanation for language group differences. The authors posit that bilinguals experience differences in the efficiency and utilisation of attentional control, and as a result bilinguals perform better on tasks that require attentional control and not just on tasks of inhibition. This account is supported by work finding quicker reaction times on congruent trials in Simon tasks (Bialystok et al., 2004; Costa et al., 2009) and greater facilitation effects in a Stroop task (Bialystok et al., 2008).

One way to empirically examine the contribution of attentional control in language group processing differences is to manipulate attentional control demands within a task. Research exploring the impact of task demands on behavioural outcomes between monolinguals and bilinguals is presented in Section 1.4, and neuroimaging evidence is reviewed in Section 3.5. A second complementary approach is to compare attentional control between monolinguals and bilinguals in circumstances in which attentional control abilities vary and one example of this is in variations that come with age. As described later in Section 1.5, the cognitive abilities of individuals change with age, including attentional control abilities that decline in older adulthood. Therefore, examining the role of bilingualism in modifying attentional control resources would be more easily observed in older adult samples. This thesis aims to further understand the role of task demands in modifying attentional demands and thus the ability to observe language group differences.

1.3. ABSENCE OF LANGUAGE GROUP DIFFERENCES

Despite decades of extensive empirical research highlighting the beneficial effects of bilingualism (Kroll & Bialystok, 2013), findings relating to language group differences are mixed. Primary research has reported no differences between monolingual and bilingual adults on their performance on tests of executive function including the Stroop Task, Simon Task, Sustained Attention Responses Tasks (e.g., Kousaie, et al., 2014; Mor, Yitzhaki-Amsalem & Prior, 2015; Paap & Greenberg, 2013; Paap, Johnson & Sawi, 2015; Paap & Sawi, 2014). Moreover, a meta-analysis conducted by Lehtonen and colleagues (2018) considered the results of over 150 studies comparing the performance of monolingual and bilingual adults in six executive function domains. Initial analysis revealed a small positive effect of bilingualism for inhibition, shifting and working memory but no group differences for monitoring or attention. After correcting for observed publication bias, no language group differences remained (Lehtonen et al., 2018). These inconsistencies have led some researchers to argue that any positive effects of bilingualism either do not exist or emerge only in restricted and undetermined circumstances (Paap, Johnson & Sawi, 2015).

On the other hand, a systematic review of research focusing on cognitive control performance in monolinguals and bilinguals reported that over half of the studies (54.3%) found beneficial effects of bilingualism, while 28.3% found mixed results and 17.4% found evidence against the presence of any language group differences (Van den Noort et al., 2019; Figure 5). Notably, no studies reported negative effects of bilingualism. Therefore, while cognitive effects of bilingualism can be measured, they are not consistently observed and the circumstances under which they may be observed remain unclear.

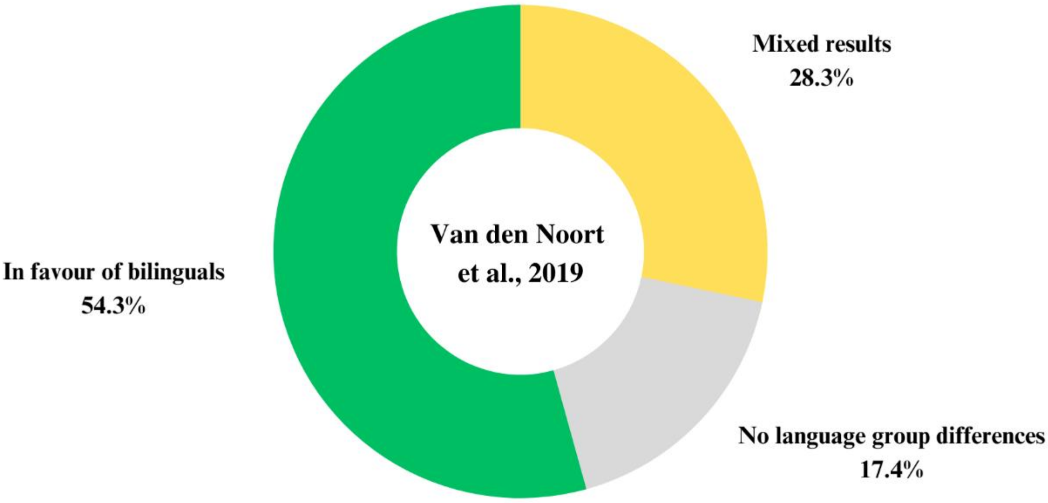

Figure 5. Meta-analysis of 46 original studies highlights the inconsistencies in the field of bilingualism research. Data taken from Van den Noort et al., 2019.

Importantly, the field of bilingualism is undergoing a significant shift in its research approach. Rather than adhering to a simplistic yes/no dichotomy regarding the impact of bilingualism on the brain, scholars are increasingly focused on investigating the specific conditions that give rise to observable brain plasticity associated with bilingualism (e.g., de Bruin, Dick & Carreiras, 2021; Bright & Fillippi, 2019; Poarch & Krott, 2019). Specifically, researchers are trying to understand under what circumstances language group differences can be more easily observed. Such investigations have given rise to two key factors which may be contributing significantly to our ability to measure and observe differences between monolinguals and bilinguals, (1) participant age and (2) task demands. However, the interplay between these two factors has received little attention, especially from a neuroimaging perspective. Elucidating how these factors can contribute to the presence of language group differences will provide insight into the circumstances under which bilingualism may benefit cognition. Put more simply, do participant age and task demands influence the ability to observe performance differences between monolinguals and bilinguals? If so, what does this tell us about how the bilingual language experience shapes the brain?

1.4. TASK DEMANDS AND LANGUAGE GROUP EFFECTS

One focal argument for a lack of behavioural differences between monolinguals and bilinguals pertains to the concept of a *ceiling effect*, which is attributed to the relatively low difficulty of some EF tasks (e.g., Zhang, 2018). Essentially, the ceiling effect assumes that participants are performing at peak cognitive function, thus limiting the potential for further improvement through individual experiences such as bilingualism. Consequently, this masking effect may hinder the detection of group differences (e.g., Czapka et al., 2020).

The effects of task difficulty have been explored by Bialystok, Craik, Klein and Viswananthan (2004), who manipulated task demands by comparing a two-colour Simon task with a four-colour Simon task. The two-colour Simon task was designed as per a typical Simon task, with two task relevant attributes and two possible manual responses. The four-colour Simon task mapped four relevant task attributes (four different colours) to two possible manual responses. The authors compared middle-aged and older adults separated into monolingual and bilingual groups. All participants experienced larger Simon effects on the four-colour task compared to the two-colour, and this increase was larger in older adults, but the age-related increase was smaller for bilinguals relative to monolinguals. This study demonstrated that while the effect of bilingualism on inhibition to interference is observable at lower levels, the effects are most evident when task demands increase.

Task difficulty has also been manipulated through varying the proportion of conflict and non-conflict trials. A study by Costa and colleagues employed a Flanker task with four different proportions of congruent and incongruent trials, whilst measuring reaction time on congruent and incongruent trials and the difference between these two trial types (RT-effect) and global reaction time (Global-RT) (Costa et al., 2009). In the low monitoring condition (92/8) with predominantly congruent trials, both language groups performance similarly. In the high monitoring condition (50% congruent, 50% incongruent), bilinguals exhibited faster overall response times (RTs), but comparable RT-effects relative to monolinguals. In the medium monitoring condition (75/25), bilinguals showed smaller RT-effects but comparable global-RTs to monolinguals. Interestingly, in the high monitoring condition, while overall RTs increased, the RT effect remained unaffected, indicating that bilingualism provided benefits to a mechanism underpinning performance on both congruent and incongruent trials. This suggests a dissociation between the processes underlying the two measures (global-RT and RT-effect). The authors argue that bilinguals have a behavioural advantage in tasks requiring conflict monitoring, but the expression of this advantage depends on the level of conflict: in medium conflict trials (75/25), bilinguals exhibited faster overall response times, reflecting superior conflict monitoring, however, in higher conflict trials (50/50), bilinguals showed an advantage in conflict resolution, resulting in smaller RT-effects.

However, the "low", "medium" and "high" conflict labels can be challenged by a review of behavioural and neural evidence of conflict monitoring and the anterior cingulate cortex (Botvinick, Cohen & Carter, 2004). While Costa et al. (2009) argue that conditions with 92% congruent trials require low monitoring from participants, Botvinick and colleagues (2004) argue that when incongruent stimuli are infrequent, more conflict is elicited when incongruent trials do occur. In contrast, when incongruent stimuli are more frequent, less conflict is elicited due to a higher rate of conflict monitoring, however Costa labelled this "medium" conflict. Following Botvinick's interpretation, Flanker tasks with a smaller proportion on incongruent trials are the most demanding for participant, and it was on this condition that no language groups were observed in the Costa et al. study (i.e., the low monitoring 92/8 condition in Costa et al., 2008). Despite potential alternative interpretations of the data, it is clear that task demands can impact language group differences, as on 50/50 and 75/25 splits language group differences were observed.

Interpretations of language group differences under different task demands is difficult given the dearth of research exploring the impact of task demands on language group differences. Meta-analyses often exclude studies using non-standard versions of tasks and only include standard versions of tasks (i.e., equal numbers of congruent and incongruent trials on Simon task) (e.g., Donnelly, Brooks & Homer, 2019; Lehtonen et al., 2018; Ware, Kirkovski, & Lum, 2020). Work from neuroimaging research produces promising results, reporting how language group differences are most easily observable on trials with high task demands (Barker & Bialystok, 2019; Bialystok & Comishen, 2021; Janus & Bialystok, 2018)[2]. However, more work is needed to understand how task demands influence our ability to observe language group differences, especially in different age groups. Understanding how bilingualism may impact cognition in older adulthood,

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[2] These studies will be presented and discussed in Chapter 3: *Using Neuroimaging to studying aging and bilingualism.*

especially under high task demands, would provide insight into how bilingualism may result in brain plasticity.

1.5. THE AGING BRAIN AND BILINGUALISM

Healthy aging is accompanied by changes in cognitive processes that are important for everyday functioning. The development of executive functions is argued to be bell-shaped, with acquisition and improvement in childhood and decline in later older adulthood (Zelazo, Craik & Booth, 2004). At the group level, older adulthood is associated with reduced efficiency in attentional control (Jennings & Jacoby, 1993), a decline in performance on word fluency and working memory tasks (Braver & West, 2008), and a reduced ability to inhibit unwanted responses and inputs, suggesting a decline in resistance to interference (Hasher, Zacks & May, 1999). It is argued that this decline is nearly linear, starting in early adulthood (Salthouse, 2010).

One theoretical model has posited that a decrease in inhibition contributes to age-related cognitive decline (Andres & Van der Linden, 2000). This is known as the Inhibition Deficit Theory which suggests that as an individual ages their inhibition processes are weakened. This inhibition process is utilised to suppress irrelevant information; thus, the weakened inhibition process allows for increased interference causing a decrease in performance on a range of tasks (Hasher & Zacks, 1988). The increased interference is indexed behaviourally by older adults requiring longer to select and execute an appropriate response (Anguera & Gazzaley, 2012), increased distractibility (Wascher et al, 2012) and difficultly ignoring distracting information in the visual field whilst reading (Duchek, Balota & Thessing, 1998). However, research has demonstrated how a decline in cognitive performance in older adulthood can be modulated at the individual level through lifestyle choices in social, mental, and physical domains (Fratiglioni, Paillard-Borg & Winblad, 2004; Scarmeas & Stern, 2003; Scarmeas et al., 2003). This modulation is driven by cognitive reserve, the ability to optimise or maximise normal performance in light of decline or pathology (Stern, 2002). The attenuation of age-related decline through experiential factors has been supported by neuroimaging methods reporting how complex mental activities across the lifespan can offer neuroprotective benefits against brain atrophy (Valenzuela, Sachdev, Wen, Chen & Brodaty, 2008).

Bilingualism is one mental activity that has been proposed as a contributor to cognitive reserve (for review see Bialystok, 2021), and this is supported by neuroimaging evidence reporting comparable behavioural results with monolinguals in light of more advanced neuroanatomical aging (Stevens et al., 2022). The idea that bilingualism can act as a factor ameliorating cognitive decline is supported by research reporting better performance by older adult bilinguals over their monolingual counterparts on tasks of inhibition (Bialystok et al., 2004; 2006; 2008), working memory (for review e.g., Grundy & Timmer, 2016) and switching (e.g., Houtzager, Lowie, Sprenger & De Bot, 2017). A small meta-analysis of 14 studies with 51 tasks revealed how bilingual individuals performed better than monolingual individuals, an effect which was more prominent in older adults with mild cognitive impairment (Chen et al., 2022). In fact, it is argued that superior performance in executive function tasks by bilinguals is age-dependant, with executive functioning advantages more likely to be observed in studies comprising samples of adults over age 50 (Ware, Kirkovski & Lum, 2020). The authors linked this age-dependant advantage back to the ceiling effect argument, which assumes that younger adults are at peak performance therefore cognitive advantages are between groups are difficult to see. In contrast, older adults experience changes in executive function performance, and aging is typically associated with a decline in executive function performance (Zelazo, Craik & Booth, 2004), therefore, the positive consequences of bilingualism are more easily observed.

However, there is empirical evidence reporting an absence of a language group effect in the older adult population. One study recruited adults aged between 60-80 years old, these participants had no history of neuropsychological disorders (Naeem, Filippi, Periche-Tomas, Papageorgiou & Bright, 2018). The bilingual participants were highly proficient, daily users of both languages and were matched by age, gender, and SES to monolinguals. A battery of tests was administered measuring a range of functions including non-verbal reasoning, working memory, inhibition as measured by the Simon task, Tower of London, and Digit Span task. Both the bilingual and monolingual older adult groups performed equivalently on all tasks, challenging the hypothesis that bilingualism can confer cognitive benefits and forestall cognitive decline in areas of executive function. This lack of language group difference is supported by other work, reporting sporadic benefits of bilingualism for older adult Welsh-English bilinguals (Hindle et al., 2015), no significant group differences on behavioural performance data for Card Sorting Task and Simon Task for Welsh-English older adult bilinguals and monolinguals (Gathercole et al., 2014), and no differences in measures of executive function derived from the Simon, Go/NoGo and Stroop task between older adult Welsh-English bilinguals and English monolinguals (Clare et al., 2016).

The inconsistencies in the aging and bilingualism research are possibly ascribed to the interaction between age-related changes in executive function processing and task demands. Previous work with younger adults has highlighted how task demands can modulate the observable difference between monolinguals and bilinguals (e.g., Comishen & Bialystok, 2021; Costa et al., 2009), wherein superior performance of bilinguals is most consistently observed on harder tasks. It is possible that the task demands in the research presented above did not exceed the resources available for older adults to recruit, therefore no language group differences were observed. This is supported by the fact that many EF tasks are eliciting over 90% accuracy, moreover when the average accuracy is lower (indicating a harder task) this is when we see language group differences (see Figure 6 for a sample of accuracy rates from EF tasks recruiting older adults).

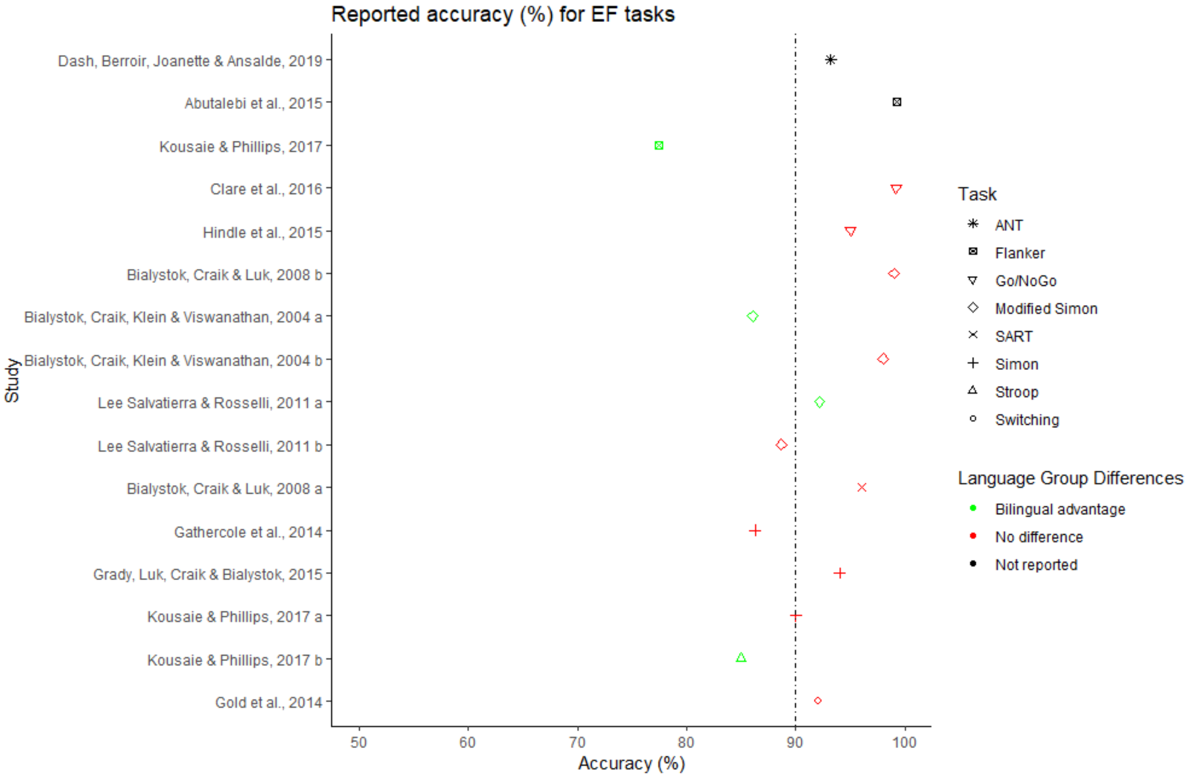

Figure 6. The reported accuracy of older adult participants on executive function tasks comparing the performance of monolinguals and bilinguals. A sample of 16 experiments as an example. Dotted line represents 90% accuracy. (a) and (b) represent experiment within the same paper.

The mechanism underpinning the presence of language group differences on harder tasks is linked to the notion that our cognitive resources are limited. As a result, there is competition for resources when performing an activity and so individuals must allocate these limited resources in order a achieve a goal (Qu et al., 2016). In younger adults, high processing demands are met with high processing resources, therefore allocation of resources is easy, and the task is achieved with ease. In older adults, high processing demands are met with lower processing resources, therefore harder tasks may exceed available resources. This hypothesis has been supported by a review of neuroimaging studies which highlighted how older adults meet a resource ceiling earlier than younger adults. According to the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008), older adults exhibit region-specific overactivation at lower task demands. This over-activation is compensatory and enables older adult participants to perform comparably with younger adults. However, as task demands increase, older adult aim to increase activation levels but they meet a resource ceiling due to over-activation at lower levels. This resource ceiling is accompanied with age-related decreases in behavioural performance. For easy tasks, there is minimal variability in behavioural responses at these lower levels even for older adults, meaning that a language group difference is not observable, however at these higher demand levels variability in brain activity regulation can be observed.

The notion of a resource ceiling that is modulated through bilingualism is supported by a review of neuroimaging studies suggesting that bilingualism is associated with more efficient brain recruitment relative to monolinguals (Grundy, Anderson & Bialystok, 2017). During tasks of non-verbal executive function, bilinguals rely less on the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) - two areas implicated in bilingual language and cognitive control (Abutalebi & Green, 2007) - and rely more on the basal ganglia and posterior regions - areas implicated in perceptual/motor functions- compared to monolinguals. This has been described as a 'bilingual anterior-to posterior and subcortical shift' (BAPSS; Grundy, Anderson & Bialystok, 2017) and is contrary to typical aging in which older adults show a posterior-to-anterior processing shift (Davis et al., 2007). In other words, younger adults recruit additional frontal regions when completing a difficult task, but for older adults all frontal resources are allocated due to the typical age-related posterior-to-anterior shift (Reuter-Lorenz & Cappell, 2008). However, if bilingualism is associated with a bilingual anterior-to posterior and subcortical shift then frontal resources will be available for bilinguals to recruit during difficult tasks. The authors of the BAPSS model argue that this neural recruitment shift may be the mechanism behind attenuated age-related cognitive decline in older adult bilinguals.

However, there is a dearth of empirical evidence investigating how the interaction between task demands and aging can result in comparable behavioural performances in monolinguals and bilingual older adults. The authors of the CRUNCH argue that the use of electrophysiological technique with high temporal resolution (such as event-related potentials) could help to elucidate the timing of age-related activation differences to understand the cognitive processes underpinning these over-activation difference (Reuter-Lorenz & Cappell, 2008). This thesis aims to tie together these hypotheses to highlight how monolinguals may exhibit age-related over-recruitment of neural resources whereas older adult bilinguals do not.

1.6. THE IMPACT OF BILINGUAL EXPERIENCE, SOCIO-ECONOMIC STATUS AND LIFESTYLE FACTORS ON LANGUAGE GROUP DIFFERENCES

1.6.1. Bilingual Experience

In 1998, Grosjean (1998) highlighted a myriad of factors contributing to the bilingual experience including, but not limited to, language history (age of acquisition, acquisition context), language stability (language acquisition/attrition), function of languages (context, frequency of use, purpose of use), language proficiency and language modes (duration and frequency of bilingual or monolingual mode). This concept remains of theoretical importance today and is crucial in explain contradictory evidence in the field of the bilingualism and cognition. One potential consequence of this diverse bilingual experience is varied demands on executive control in language management (Henrard & Van Daele, 2017). Kaushanskaya and Prior (2015) argued that the multi-dimensional nature of the bilingual experience should not necessarily be viewed as a variable that requires control, rather it should be the focus of the research question. Differences in the language experiences of a bilingual could help elucidate the mechanisms behind the tentative bilingualism-executive function link; distinct bilingual experiences could be compared to highlight the underpinnings of the executive function recruitment in bilinguals. As outlined by the Adaptive Control Hypothesis (Green & Abutalebi, 2013), differences in language experience will result in differential demands on control processes. In turn, these different demands may result in different effects of bilingualism.

Age of acquisition (AoA) refers to the age at which an individual began to acquire a second language. The influence of AoA on EF outcomes has been investigated by comparing the performance of young adult monolinguals, early bilinguals, and late bilinguals on the Flanker task. Age of onset was found to be correlated with the Flanker effect, with early bilinguals exhibiting a smaller Flanker cost, and thus experiencing smaller interference effects. Late bilinguals and monolinguals did not significantly differ with regards to Flanker cost (Luk, De Sa, & Bialystok, 2011). This differential performance for early and late bilinguals has been replicated in a study that subdivided bilinguals into early childhood bilinguals (ECB; AoA <4yrs old), late childhood bilinguals (LCB; AoA 4 -15yrs old) and early adulthood bilinguals (EAB; 15-19 yrs old). Tasks of attention switching were performed better by early childhood bilinguals whilst late childhood bilinguals and early adulthood bilinguals showed better performance on selective attention tasks (Bak, Vega-Mendoza, & Sorace, 2014). This suggests that early and late bilingual groups benefit from bilingualism, but in different ways. Disparate benefits as a result of different language experience have been supported by neuroimaging research which reported increased density of grey matter for bilinguals in the left inferior parietal cortex when compared to monolinguals, and how this increased density was more pronounced in early rather than late bilinguals (Mechelli et al., 2004).

The extent to which a bilingual is proficient in their second language may also impact on the extent to which cognitive control is recruited during language use. This has been supported by a recent study comparing 94 unbalanced Chinese-English bilinguals divided into three subsets: low, intermediate, and high L2 proficiency (Xie & Pisano, 2018). Highly proficient bilinguals were significantly faster than the other two subsets of bilinguals on neutral, congruent, and incongruent trials on a Flanker task. This result was mirrored with Hindi-English bilinguals which reported that highly proficient bilinguals exhibited faster reaction times than low proficient bilinguals, suggestive of increased efficiency in attentional disengagement (Mishra, Hilchey, Singh, & Klein, 2012). Such results may be due to the strong L2 eliciting higher interference when L1 is utilised, leading to higher control demands. Lehtonen et al., (2018) conjectured that bilinguals who are highly proficient in their L2 will experience larger interference to their L1 than individuals who are less proficient in their L2; this increased interference will lead to higher cognitive demands. However, this notion is challenged by the theory presented by Abutalebi and Green (2007) who argue that a higher L2 proficiency results in a shift from controlled language processing to automatic processing. Similarly, Goral, Campanalli & Spiro (2015) argue that if great effort is not exercised during language control, domain-general cognitive benefits may not be accrued. Both hypotheses offer logical theoretical arguments, however a review by Lehtonen et al., (2018) found no evidence to support either. It was reported in the recent review that proficiency did not moderate the effects of bilingualism on the behavioural performance across six executive function domains. It is possible that neither hypothesis offers an appropriate explanation of management demands with relation to proficiency, or it is possible that the L1 interference experienced by low L2 proficient bilinguals when speaking in their L2 is equivalent to the L2 interference experienced by high L2 proficient when speaking in their L1. The latter suggestion would mean result in equivalent bilingual management demands. A second explanation could lie in task demands, leading us back to the argument that if task demands do not exceed the available cognitive resources of one group, then group differences will not be observed.

1.6.2. Socio-economic status (SES) and immigration status

Socio-economic status (SES) is commonly measured using self-reported employment status, education, income, parental occupation, and parental education (for review see Rodríguez-Hernández, Cascallar & Kyndt, 2020). The role of SES in moderating academic performance (Lutz, 2007; Rodríguez-Hernández, Cascallar & Kyndt, 2020), IQ and vocabulary and memory (Meir & Armon-Lotem, 2017; Piccolo et al., 2016a;b). has been well established. Critically, SES has been shown to impact the development of executive function (EF) (e.g., Noble, Norman & Farah, 2005; Piccolo et al., 2016a;b). Further to this, in certain contexts, bilingualism coincides with immigration status. For example, in Canada bilingual children often come from immigrant Canadian families whose educational level is on average higher than that of monolingual Canadian families (PCEIP; Statistics Canada, 2003 as reported in Ladas, Carroll & Vivas, 2015). In British studies, low SES bilingual samples can be composed of first-generation immigrants, some of whom are refugee and/or asylum seekers (e.g., Naeem et al., 2018). As the effects of immigration status on executive functioning remains unclear it is pivotal to control for such factors.

Researchers have investigated socio-economic status as a possible alternative explanatory variable distinguishing monolingual and bilingual participants. For example, Paap, Johnson & Sawi (2015) argued that published findings reporting an advantage for bilinguals have yielded results due to confounding demographic variables such as socioeconomic status (SES). This conclusion is supported by evidence reporting how socioeconomic status, but not bilingualism contributed to EF performance - Morton and Harper (2007) reported that bilingualism had no impact on the performance of monolingual and bilingual children on a Simon task, but higher SES children performed better than low SES children. However, Calvo & Bialystok (2014) argue that the effects of socio-economic status and bilingualism are independent, wherein higher SES is associated with better performance on EF and language tasks, but bilingualism is associated with better performance on EF and worse performance on language tasks. The differential impact of SES and bilingualism has been replicated in a study of low and high SES monolinguals and bilinguals also employing the Simon task wherein superior performance of bilinguals was reported in the low SES individuals but had little impact in the high SES group (Naeem et al., 2018). Importantly, studies which have controlled for variables such as SES and intelligence have still reported better performance from bilingual groups (Tao et al., 2011). Despite conflicting evidence on how SES and bilingualism interact, it is clear that SES contributes to performance on EF tasks. Consequently, it is pivotal to control for SES when comparing groups of bilinguals and monolinguals to avoid erroneous conclusions.

1.6.3. Leisure activities and lifestyle factors

Beyond bilingualism, other lifestyle and leisure activities have been shown to have beneficial and detrimental associations with executive function performance. For example, short-term music training has been reported to enhance executive function in children (Moreno et al., 2011) and musical expertise in adulthood can modify measures of executive functioning (Bialystok & DePape, 2009; Moreno et al., 2014). Furthermore, video gaming has been shown to improve executive function in clinical and non-clinical populations (Stanmore, Stubbs, Vancampfort, de Bruin & Firth, 2017). This is supported by a meta-analysis reporting that video game training improved RT, attention, and memory (Toril, Reales & Ballesteros, 2014). Moreover, research in healthy adults highlighted how participants who participated in martial arts exhibited superior performance on an ANT task relative to participants who did not participate (Johnstone & Marí-Beffa, 2018). Moreover, a meta-analysis across 1,177 participants, 147 effect sizes and 28 studies reported that low, medium, and high-intensity exercise had a facilitating effect on executive function performance (Moreau & Chou, 2019). Even the use of simple brain training apps has been shown to modulate performance on EF tasks (Meltzer et al., 2023). In contrast, alcohol and recreational drug use are suggested to be associated with poorer performance on executive function tasks (Fernandez-Serrano et al., 2010; Heffernan et al.,2014).

It is clear that there are myriad lifestyle factors beyond just bilingualism that can influence performance on cognitive tasks. As such, it is important to properly understand participant samples in bilingualism and cognition research to ensure parity between monolingual and bilingual groups in domains outside of bilingualism.

1.7. PROBLEMATIC CONCEPTUALISATIONS OF EF

One issue that is important to raise in this thesis is the problematic conceptualisation of executive functions, even with the most influential models. The framework proposed by Miyake and colleagues (2000), which has been extensively relied upon in research investigating the relationship between cognition and bilingualism may not adequately represent the complexity of executive function. Specifically, the assumption that inhibition is a distinct and unified ability is challenged (e.g., Miyake et al., 2012; Bialystok & Craik, 2022). Furthermore, the role of inhibition in executive function, both within existing frameworks and as a differentiating factor between monolinguals and bilinguals, has been called into question (for extensive review see Bialystok & Craik, 2022).

Consequently, further exploration of inhibition and its implications in bilingualism research is needed. The research presented in this thesis will investigate the role of inhibition on non-verbal tasks of executive function and will aim to investigate under what circumstances language group differences in age-related changes on inhibition processes can be observed. This thesis also aims to understand the role of participant age and task difficulty on language group differences on neural indices of inhibition and attentional control, to be captured through the use of event-related potentials (ERPs) alongside behavioural data.

1.8. THE IMPORTANCE OF STUDYING AGING AND BILINGUALISM

Worldwide there is a demographic shift towards an aging population; in 2020, the number of adults aged 60 and above exceeded the number of children younger than 5 years (WHO, 2022). In the UK the proportion of adults aged over 65 is expected to grow to nearly a quarter of the population by 2046 (Randall, 2017). Globally, the world’s population over 60 will nearly double from 12% to 22% by 2050 (WHO, 2022). With healthy aging comes changes in cognitive function, such as changes in inhibitory control and speed of processing (e.g., Jennings & Jacoby, 1993; Salthouse, 2010). And, although age-related cognitive changes are inevitable, it is imperative to understand how the trajectory of this decline can be influenced by factors within our control. This is especially important when considering the personal, societal, and economic impact of aging (Lock, 2023). The potential for experiential factors to maintain cognitive health despite cognitive aging must be investigated and well understood, as such factors could be promoted as a healthy cognitive gaining initiative within government policy (for discussion see Mendis, Raymout & Tabet, 2021)

Evidence suggests that not all older adults experience the same rate of cognitive change (Reuter-Lorenz & Park, 2014). One purported mechanism behind this variability is ‘cognitive reserve’ (Stern, 2009), and models of cognitive aging suggest that engagement in physical, social, and cognitive can contribute to cognitive reserve through the idea of brain plasticity (e.g., Reuter-Lorenz & Park, 2014; Scarmeas & Stern, 2003). One definition of brain plasticity pertains to the ability to alter function processing networks in response reduced structural and function brain integrity (Greenwood, 2007). However, researchers are only just beginning to understand plasticity as a function of experience and training. Further research is required to develop a more comprehensive understanding of the neural mechanisms underpinning these plastic changes in older adulthood (Nguyen et al., 2019; Park & Bischof, 2022).

This brings us to bilingualism, as it offers a unique lens through which to investigate the impacts of experience-dependant brain plasticity on function in older adulthood. Across the globe, bilingualism is the rule rather than the exception, meaning that the majority of the world’s population can communicate in more than one language (Grosjean, 2021). Research has highlighted how bilingualism may contribute to brain plasticity, and how these brain changes may persist into older adulthood and manifest as protective factors such as an attenuation of age-related cognitive decline (Bialystok et al., 2016), a symptom-onset delay for Alzheimer's disease and dementia (Alladi et al., 2013; Bialystok, Craik & Freedman, 2007; Alladi et al., 2013) and mild cognitive impairment (Bialystok et al., 2014; Ossher et al., 2013). The delay affords individuals more time to live independently and reduces costs from personal, social, and economic perspectives. Despite this promising work, more research is required to understand the underlying neural mechanisms behind differences in functional processes in older adult monolinguals and bilinguals. In summary, bilingualism is a phenomenon which provides us with an opportunity to learn more about how experiential factors may contribute to functional changes in the aging brain.

1.9. CHAPTER SUMMARY

This section has provided an overview of behavioural research investigating the impact of bilingualism on cognition. Research has suggested that there are language group differences between monolinguals and bilinguals, including faster reaction times, smaller interference effects and better accuracy rates from bilinguals. However, the literature review also highlighted how age and task demands can play an important role in our ability to observe language group differences in behavioural measures.

Considering this, focus on purely behavioural measures of executive function provide us with a limited view of how bilingualism impacts cognition. Behavioural outcomes represent the final output of many cognitive processes. As a result, many researchers are advocating for the use of more sophisticated neuroimaging techniques to further elucidate the presence of language group differences (van Heuven & Coderre, 2015). The next section with explore the use of event-related potentials to measure executive functions and then the utility of this technique to measure the effects of bilingualism and aging on cognition will be discussed.

Chapter 2: Introduction to Event-Related Potentials (ERPs)

Many studies examining the impact of bilingualism on cognition rely solely on behavioural measures, such as reaction time and accuracy. However, these measures are influenced by various factors beyond the cognitive processes that they are argued to reflect. Factors such as motor control and practice effects contribute to manual responses, introducing individual variability and reducing the sensitivity of the measures (Nishikawa et al., 2007; Ghuntla et al., 2014). Consequently, researchers have advocated for the utilisation of more sensitive measures, including neuroimaging techniques (van Heuven & Coderre, 2015). One promising approach is the use of event-related potentials (ERPs), which can provide insights into the distinct mechanisms involved in executive function processes between monolinguals and bilinguals. Several ERP waveforms have been proposed as markers for executive function components such as inhibition and attention (Downes, Bathelt & De Haan, 2017), making them valuable tools for investigating bilingualism's effects on cognition. This section will highlight the utility of the event-related potential (ERP) technique by providing an overview of existing literature concerning ERPs in Go/NoGo and Simon paradigms, as well as examining studies that explore the influence of age and task difficulty on these measures.

2.1. ELECTROENCEPHALOGRAPHY AND EVENT-RELATED POTENTIALS

The advent and development of neuroimaging methods such as electroencephalography (EEG) has allowed researchers to measure and record cognitive processes in real-time. Previously, the speed of cognitive processes has been inferred from behavioural measures such as reaction times, but now precise neuroimaging methods can be employed alongside behavioural responses to measure the time course of cognitive processes (Incera, 2018). Among these methods, event-related potentials (ERPs) offer a valuable tool, providing rich datasets that can be used to identify multiple neurocognitive processes within a milli-second level temporal resolution (Luck, 2014). Importantly, ERPs serve as an online and covert measure of processing, eliminating the need for participants to execute a behavioural response to measure cognitive activity.

EEG measures electrical activity produced in the brain through electrodes that are placed on the scalp. The electrical activity in a neuron causes two types of potentials to occur: action potentials and postsynaptic potentials. Action potentials are positive voltage spikes, triggered when the membrane potential becomes sufficiently positive. These action potentials begin at the axon hillock and travel down the axon to the axon terminal where neurotransmitters are released to the following axon (Luck, 2014). These potentials rarely contribute to scalp ERPs because for them to be measurable action potentials need to fire at exactly the same time, in the same direction, to create summed activity large enough to be recorded at the scalp. However, neurons rarely fire at exactly the time, or in the same direction, and the noncorresponding orientation of axons can result in the action potentials cancelling each other out.

The second type of potential, postsynaptic potentials (PSPs), arises when the neurotransmitter binds with the receptors on the postsynaptic terminal at the end of an axon, resulting in the ion channels opening or closing. The opening or closing of the ion channels results in a change in potential across the cell membrane which either *excite* or *inhibit* action potentials. Excitatory potentials occur when positive charges move into the cell and inhibitory potentials occur when negative charges move into the cell. The term "electrical dipole" is used to describe a cortical pyramidal cell, where one end exhibits a positive charge and the other end a negative charge due to the postsynaptic potential. A dipole from a single neuron is too small to measure at the scalp, however under certain circumstances thousands (or even millions) of neurons will be simultaneously activated and when these neurons are lined up perpendicularly to the scalp it can be measured with scalp electrodes (Woodman, 2010). Summation of neurons is most likely to occur in groups of pyramidal neurons that are in the cerebral cortex. Thus, event-related potentials reflect the summation of postsynaptic potentials that occur simultaneously in large numbers of cortical pyramidal cells that are spatially aligned and perpendicular to the surface of the scalp (Peterson, Schroeder & Arezzo, 1995; Luck & Kappenman, 2012).

An event-related potential (ERP) refers to the neural response elicited by a specific sensory, cognitive, or motor event (Blackwood & Muir, 1990). While the ERPs are derived from continuous electroencephalography (EEG) recordings during the event, they are not typically discernible in a single-trial EEG recording. Instead, multiple trials are presented to participants, and their brain's neural responses to these trials are averaged to generate a waveform (Luck, 2014). The waveforms can be time-locked to specific events such as a stimulus presentation or the participants response, allowing for the analysis of voltage changes across trials, groups, or stimuli. This time-locked approach enables researchers to examine and interpret the patterns of neural activity associated with these events.

ERP waveforms are comprised of positive and negative deflections commonly referred to as 'components', 'waves' or 'peaks'. The naming conventions of components generally follows two rules. Firstly, a letter 'P' or 'N' is used to signify the direction of the wave (positive or negative) in relation to the baseline prior to the event. Secondly, a numerical value signifies the onset time of the component relative to the time-locked event. For instance, the P300 component is characterised by a positivity that peaks at around 300ms after stimulus onset (Luck, 2014). By following these conventions, researchers can systematically identify, and label, specific components based on their timing and polarity in relation to the event of interest. Such labelling facilitates comparisons across different tasks and participants, allowing for the investigation of task-specific and participant-specific features.

There are two salient features of a component that are commonly measured: amplitude and latency (Ibanez et al., 2012). Amplitude is quantified in microvolts (μV) and, traditionally, the maximum voltage change of a component (peak amplitude) was used to extract an amplitude measurement. However, a more prevalent approach now is to calculate the mean amplitude over a specific time window. A comprehensive review of over 400 studies utilising ERP found that over 75% employed mean amplitude measurement, while 42% used peak amplitude measurement, and less than 5% utilised an adaptive mean measurement method (Clayson, Baldwin & Larson, 2013). This shift in measurement preference is driven by the recognition that mean amplitude provides a more reliable measure, as peak amplitude can be influenced by noise levels and trial count (Luck, 2018).

The latency of a component refers to the relationship between the event of interest and the waveform (Coles & Rugg, 1995). Latency (in milliseconds) is considered relative to the onset of the stimulus or execution of the manual response by the participant. Two common measures are the peak latency and centroid latency. The peak latency measure quantifies the latency as the time of the most negative or positive going peak. This provides a clear and easily identifiable point in time where the component reaches its peak amplitude. In contrast, centroid latency represents the time at which the area under the curve is divided into equal halves. While centroid latency has the advantage of capturing the overall temporal pattern of the component, it can be subject to greater statistical bias in the presence of noise. Conversely, peak latency is often more robust and less sensitive to noise and variability in the data compared to centroid latency (Clayson, Baldwin & Larson, 2013), Most current research utilises the peak latency measure (> 80%; Clayson, Baldwin & Larson, 2013), meaning that the employment of peak latency facilitates comparisons across studies, providing a standardised measure that can be easily compared across different experimental conditions and populations.

The topographical distribution of the components across the scalp can also be measured and reported, and this distribution can be compared across groups and conditions. For example, Friedman, Kazmerski and Fabiani (1997) reported age-related topographical changes, wherein the P3b was frontally focussed for older adults yet parietally maximal in younger adults. Moreover, scalp distribution of the voltage for ERP components can also be utilised to estimate the neuroanatomical location of the cognitive processes, known as source localisation (e.g., Borchard, Barry & De Blasio, 2013; Vaughan, 1982). However, it should be noted that EEG has low spatial resolution due to electrodes recording electrical brain activity at the scalp. Consequently, the electrical activity must pass through several resistive layers (including the skull) to reach the scalp. This will distort the electrical signal and create a 'blurring effect' at the scalp meaning that the electrical activity a single electrode records is a mixture of activity from several underlying brain sources (Burle et al., 2015). It has been estimated that scalp EEG has a spatial resolution of only 5 to 9cm (Babiloni et al., 2001).

Research questions that focus on the timing of cognitive processes, as opposed to the spatial location of processes, are better answered by ERPs than other neuroimaging techniques such as fMRI (e.g., Corrigan et al., 2009). The benefits of utilising the event-related potential technique extends further than good temporal resolution. As ERPs are a covert measure of processing, they also allow researchers to measure cognitive processes even in instances where participants are not required to respond to a stimulus (Luck, 2014). For example, in paradigms which require participants to respond and attend to one stimulus whilst not responding to another, researchers can measure covert cognitive responses to the non-target stimuli on paradigms that do not require a response like Go/NoGo paradigms. This measure could be paired with behavioural measures such as reaction times and accuracy to measure and analyse both overt and covert responses by participants. Moreover, this allows for researchers to study the experimental effects across development, from infants, who are too young to be instructed to make a response, to older adults (Luck, 2014).

2.2. COGNITIVE PROCESSES AND ERP COMPONENTS

The event-related potential (ERP) technique is widely employed to study cognitive processing due to its high temporal resolution (Helfrich & Knight, 2019). Among the commonly measured ERPs association with executive function are the N200 and P300 (Cespón & Carreiras, 2020), which are also the focus of investigation in the experimental chapters of this thesis. In this chapter, evidence establishing these ERP components as indicators of specific cognitive processes will be examined. Subsequently, the utilisation of these ERPs in the context of the bilingualism and experience-dependent plasticity will be explored.

2.2.1. Inhibition and the N200

The ability to inhibit irrelevant thoughts, behaviours and stimuli are focal to everyday functioning, and the ability to disengage from one action and engage with another can be crucial to survival (e.g., when crossing a busy road) (Logan, Cowan & Davis, 1984; Pires, Leitão, Guerrini & Simões, 2014). It is posited that various cognitive domains including language, memory and attention are influenced by inhibition processes (MacLeod et al., 2003).

It is argued that cognitive inhibition has both an automatic and controlled component (Nigg, 2000; Shiffrin & Schneider, 1977). The automatic component refers to processes that occur without intention and/or conscious awareness. These processes are quick and can occur in parallel with other operations such a working memory. Contrastingly, controlled inhibition is conscious and intentional, and can be slow with limited capacity (Diamond, 2013; Pires et al., 2014). Many of the inhibition processes pivotal to everyday functioning occur within the first second of the stimuli or information being presented (Kok, 1999). This means that the high temporal resolution of the event-related potential technique is an ideal candidate for studying cognitive inhibition processes.

The N2 component, also known as the N200, is a well-established event-related potential (ERP) marker of automatic inhibition (Downes, Bathelt & De Haan, 2017). It is a negative-going component, peaking 200-350ms post stimulus with a frontal distribution (Falkenstein et al., 1999). Early research suggested that the N2 can be divided into several subcomponents, N2a, N2b, N2c and N2pc, dependant on manipulation of stimulus modality and attention (Pritchard, Shappell & Brandt, 1991). In this thesis, the focus will be on the N2b component, which is a fronto-centrally maximal negative going deflection seen only during conscious stimulus attention reflecting overriding of a prepotent response (Patel & Azzam, 2005). The N2b is suggested to reflect cognitive control necessary for successful inhibitory control and interference suppression (for review see Downes, Bathelt & De Haan, 2017).

N2 and Go/NoGo

The N2 has been predominantly studied in inhibitory control paradigms such as the Eriksen Flanker, Go/NoGo, Stop-signal and anti-saccade tasks (Pires, Leitão, Guerrini & Simões, 2014). In a Go/NoGo paradigm, the participant is required to execute a manual response to the Go stimuli and withhold the response for NoGo stimuli, there is a frontally maximal N2b component that is larger during NoGo trials, when a pre-potent response must be withheld (Jodo & Kayama, 1992; Gajewski & Falkenstein, 2013). However, it is important to emphasise that the N2b is not purely an index of motor response suppression. A study conducted by Nieuwenhuis and colleagues examined the N2 in three different conditions: high frequency of Go trials (20% NoGo), medium frequency (50% NoGo), and low Go frequency (80% NoGo). It was reported that the N2 was present for the infrequent stimuli regardless of whether the stimuli required the *execution* or *inhibition* of a response. This suggests that the N2 indexes a conflict monitoring process arising from competition between the pre-potent state and the required state, rather than solely motor inhibition (Nieuwenhuis et al., 2003).

The interpretation of the N2 as a measure of conflict monitoring, rather than motor inhibition, is further supported by research comparing its amplitude during Go/NoGo task, which requires *both* response inhibition and conflict monitoring, and a Go/GO task, which only requires conflict monitoring. In a study by Donkers and van Boxtel (2004) the Go/NoGo task was a typical Go/NoGo paradigm which required participants to withhold a response on NoGo and execute a response on Go trials. In the Go/GO task, participants were instructed to vary the forcefulness of their keypress, with "GO" representing a press of maximal force. Under the response inhibition hypothesis, a larger N2 relative to Go trials should be observed for NoGo trials but not for GO trials. Under the conflict monitoring hypothesis, a larger N2 will be observed for both NoGo trials and GO trials given how a pre-potent response (Go with nominal force) must be overridden. The results supported the conflict monitoring hypothesis, as a larger N2 was observed on both NoGo and GO trials, with larger amplitudes observed in the context of more frequent (80%) Go trials, relative to less frequent (50%). This provides evidence for the theory that the N2 is indicative of a process requiring the overriding of a pre-potent response, rather than a motor inhibition process.

Alongside measuring the absolute amplitude (in µV) of the N2 on Go and NoGo trials, subtractive logic can be applied to create a difference wave. By deducting the amplitude on Go trials from NoGo trials, a difference wave known as the N2-effect (ΔµV) can be computed. The use of difference waves allows us to isolate specific cognitive processes that are differentially active for two trial types. The subtraction means that only activity relevant to the condition remains while brain processes that are occurring on both trial types are eliminated (Luck, 2014) [3]. Research has shown that the amplitude of the N2 component in a Go/NoGo paradigm is influenced by both task difficulty and perceptual similarity. Specifically, the magnitude of the N2-effect (the difference between N2 amplitude on Go and NoGo trials) is modulated by task demands (Azizian et al., 2006). Put simply, when the NoGo stimuli are perceptually similar to the Go stimuli, the N2-effect is larger compared to NoGo trials where in stimuli are perceptually dissimilar. Paired with evidence that suggests that larger differences between the N2 amplitude for NoGo and for Go (N2-effect) are associated with better behavioural performance (e.g., Falkenstein, Hoormann & Hohnsbein, 1999), these results suggest that when there is increased perceptual overlap between the NoGo and Go stimuli, the N2 amplitude increases, indicating greater cognitive effort and greater need for conflict detection. These results provide support for the hypothesis that the N2 component in the Go/NoGo paradigm is associated with conflict monitoring.

N2 and Simon

In addition to the Go/NoGo paradigm, the Simon task has been utilised for studying inhibition through the lens of the N2 component. In a classic two-way visual Simon task, participants are instructed to execute a key press based to the physical attributes of a stimuli (i.e., shape or colour), while disregarding the spatial location of the stimuli. There are two possible trials; congruent trials (in which the spatial location of the stimuli and the side of the key press are matching) and incongruent trials (in which the spatial location of the stimuli

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[3] While difference waveforms can be an effective tool for isolating specific ERP components, there are several issues with the approach. Namely, when a difference wave varies in amplitude between groups or conditions, it can be difficulty to identify which of the two waveforms varied. Moreover, a difference waveform could also reflect differences in latency between the two original waveforms rather than differences in amplitude (for an in-depth discussion see Kappenman & Luck, 2012).

and key press do not correspond). Researchers have compared the N2 amplitude between congruent and incongruent trials to assess the level of inhibition employed in each trial type. The extant literature on the Simon task reports that the N2 is typically larger to incongruent relative to congruent stimuli, creating a Simon effect in the N2 amplitude (Chen & Melara, 2009; Melara et al., 2008; Scrivano & Kieffaber, 2022). It is suggested that the Simon effect in the N2 amplitude reflects the conflict caused by incompatible spatial-response (S-R) mapping (Melara et al., 2008).

Like with reaction time and accuracy effects in the Simon task, it is suggested that the larger Simon effects in the N2 amplitude are reflective of larger S-R conflict experienced by the participant (Millner et al., 2012). While smaller N2-effects in the Go/NoGo task are typically associated with poorer task performance (e.g., Falkenstein, Hoormann & Hohnsbein, 1999), the opposite pattern is observed for the Simon task. Millner and colleagues trained participants on a Simon task, recording both behavioural and ERP responses during congruent and incongruent trials. From these measures, RT-effects and N2-effects were derived and compared pre- and post- training. It was found that participants who displayed the largest reductions in RT-effects post-training also displayed the largest reductions in N2-effects (Millner et al., 2012). It is suggested that the training results in effortful control processes (responding to incongruent stimuli) becoming more automatic. Consequently, there is a reduced need for effortful control and a reduction in experienced conflict. Taken together, it is clear that there are contrasting relationships between N2-effects and task performance in Go/NoGo and Simon task. This highlights the complex nature of the N2 component and its interpretation. The exact mechanisms underlying the N2 component remains unclear due to its influence by task-specific factors. However, these results of Millner and colleagues' research provides support for two important notions. Firstly, that the Simon Task is indeed a task that requires cognitive inhibition, particularly during incongruent trials -the larger N2 amplitudes observed in incongruent trials indicate greater engagement of inhibitory processes to overcome the conflicting spatial information. Secondly, these findings support the idea that the N2 reflects cognitive inhibition rather than motor inhibition as, despite the presence of responses, participants observed increased N2 amplitudes for incongruent trials. Overall, the utilisation of the Simon task in investigating the N2 component provides valuable insights into the cognitive mechanisms underlying inhibition and conflict resolution.

Neural generator of the N2

Research employing source localisation techniques have attempted to identify the underlying neural generator of the N2. For example, one study collected ERP data and fMRI data whilst participants completed a Go/NoGo task (Mathalon, Whitfield & Ford, 2003). The Go/NoGo task contained pre-potent Go response (88%) and inhibition of responses on NoGo trials (12%). It was reported that the N2 to correctly identified NoGo stimuli correlated with activity in the anterior cingulate cortex (ACC). This is consistent with earlier findings from an ERP study using source localisation during a Go/NoGo task which reported how the ACC played a pivotal role in the generation of the NoGo N2 (Bokura, Yamaguchi & Kobayashi, 2001). The findings from these studies aligns with work identifying the role of the anterior cingulate cortex in motor control by facilitating the execution of appropriate responses and suppression the commission of inappropriate responses (Paus et al., 1993). The ACC has also been implicated in cognitive control; event-related fMRI has been utilised to report that the ACC is more active when responding to incongruent stimuli (MacDonald et al., 2000) suggesting that the ACC is involved in cognitive processes evaluating when control needs to be executed.

N2 and age

The N2 is sensitive to aging effects, with latency and amplitude changes from childhood into older adulthood. A meta-analysis highlighted how, compared to younger adults, older adults exhibit a reduction in NoGo-N2 amplitudes, particularly in high monitoring conditions (NoGo <50% of trials) (Cheng, Tsai & Cheng, 2019). This age-related decline in the NoGo-N2 may reflect difficulties in maintaining context information during aging as a result of faster information decay (Braver et al., 2011). Smaller Go-N2 and NoGo-N2 mean amplitudes are also reported for older adults with mild cognitive decline, indicating a smaller N2 amplitude is associated with a decline in executive function (Cid-Fernández, Lindín & Díaz, 2014). Alongside amplitude changes, later N2 peak latencies are reported for older adults relative to younger adults, indicating slower conflict detection processing (Falkenstein, et al., 2002; Hämmerer, et al., 2010). However, to date, there is no work investigating the effects of age on the N2 elicited by the Simon task. Thus, interpretations must be guided by previous work aiming to identify the functional significance of amplitude changes as a result of training (Millner et al., 2012).

Summary of the N2

In summation, much research has suggested that the N2 component reflects cognitive inhibition. Paradigms inducing cognitive inhibition, such as the Simon Task, Go/NoGo and Stop-Signal Task have been employed when measuring the N2 component. The results of such research support that notion that the N2 does reflect inhibition that is distinct from motor response suppression and that the N2 may reflect different processes across inhibition tasks. Research has shown that the N2 is subject to age and task related changes, specifically a reduced N2-effect with increasing age on Go/NoGo tasks, and changes in the magnitude of the N2-effect as a result of task demands and paradigm choice.

2.2.2. Attention allocation and the P300

The P300 is a component frequently measured during tasks of executive function (Downes et al., 2017). The P300, often referred to as the P3, is a positive going deflection occurring around 300-400ms post-stimulus (Polich, 2007) and can be divided into two subcomponents, the P3(a) and P3(b). The P3(a) is a stimulus-driven subcomponent with a frontal distribution. It appears after a novel stimulus and is associated with automatic attentional modulation. The P3(b) subcomponent is maximal at centroparietal sites (e.g., Picton, 1992) and is suggested to be reflective of attention mechanisms associated with memory (Polich, 2007). The work in this thesis will focus on the P3(b).

The functional significance of the P3b is widely investigated, and research has proposed that the magnitude of attentional resource allocation during a task is reflected in the amplitude and latency of the P3b, with smaller amplitudes and longer latencies elicited by more cognitively demanding tasks (Wickens et al., 1983). But like with the N2, the interpretation of the P3 is debated with some researchers arguing that the P3 reflects a response inhibition processes, especially in Go/NoGo paradigms. Go/NoGo tasks typically present a frequent target stimulus to which the participant must respond (Go), and an infrequent stimulus to which participants must withhold a response (NoGo). The NoGo stimuli typically elicit larger P3 amplitudes relative to Go stimuli (e.g., Donkers & Van Boxtel, 2004; Fernandez, et al., 2013; Eimer, 1993; Moreno, et al., 2014). This finding has led to some researchers to argue that the NoGo-P3 represents response inhibition. However, research has shown that the P3 amplitude can vary as a result of different stimulus probabilities, identifying how the P3b decreases in amplitude as target stimulus probability increases (Polich & Margala, 1997; Squires et al., 1976). Research using a Go/NoGo task which contains 20%, 50% and 80% NoGo probability conditions has further highlighted the impact of stimulus probability on the P3 amplitude (Hsieh, Wu, & Tang, 2016). If the NoGo-P3 simply reflects a response inhibition process, the amplitude of the P3 should be uniform across all three conditions. In contrast, a pattern of stimulus probability was observed wherein the NoGo-P3 was larger when NoGo trials were more infrequent, for instance the NoGo-P3 was smaller in the 20% NoGo condition relative to the 50 and 80% conditions. This effect has been found to be independent of stimulus modality, occurring in a comparable manner for auditory and visual oddball paradigms (Squires et al., 1977). From here, the interpretation of the P3 was dominated by the idea that the amplitude of the P3 represents attentional resource allocation. This is supported by work manipulating the perceptual similarity of nontargets to target trials. Research has highlighted how target trials elicit the largest P3 amplitudes, followed by similar nontargets and then finally dissimilar (Azizian et al., 2006). This further supports the idea that P3 amplitude can be interpreted as an index of the extent of cognitive processing needed for categorising stimuli varying in similarity to the target (Azizian et al., 2006). Stimuli which require more processing produces larger P3 amplitudes and dissimilar nontargets, or frequent stimuli, that are easily classified require less processing.

This idea is further supported by work observing P3 amplitude variations between trials in tasks that require no response inhibition, such as tasks that induce conflict between competing responses or in tasks that require a planned response to be changed. For example, on the Simon Task research typically finds that the P3 is larger for congruent than incongruent trials (Galashan et al., 2008; Cespón, Galdo-Álvarez & Díaz, 2013). On the Stroop task, Kousaie and Phillips (2012a) report smaller P3 amplitudes on incongruent conditions compared to congruent and neutral conditions. However, little work has been done to examine the amplitude and latency of the P3 in the Simon task, and so the functional significance of the P3 Simon-effect remains unclear. Some researchers suggest that the Simon-effect in P3 amplitude suggests that the locus of the Simon effect is at the stimulus evaluation and not response selection stage (for review see Cespón et al., 2020).

The functional significance of a second facet of the P300, latency, has also been investigated. The peak latency of the P300 is argued to be an index of stimulus categorisation time (Polich & Donchin, 1988) as shorter latencies are elicited by less demanding tasks. Age-related changes are also reported for latency, with the P300 peaking later for older adults relative to younger adults (Freidman, 2012; Polich, 1996; for meta-analysis see: Cheng et al., 2019). Taken together, these findings support the idea that shorter P3 latencies represent faster stimulus classification and superior cognitive performance (Magliero et al., 1984).

Neural generators of the P3b

Evidence from intracranial recordings, lesion studies and functional neuroimaging studies have contributed to our understanding of the neural generators of the P300. A review of such studies reported that target related P3 responses are associated with activity in the parietal and cingulate cortex (Linden, 2005). Moreover, a review of ERP focussed research supported this, arguing that the P3b is generated by temporal and parietal lobes (Polich, 2007). However, Linden’s 2005 review highlighted the presence of conflicting findings about the neural origins of the P3 when integrating evidence from different localisation techniques. Despite this, Linden argued that there is strong evidence to support that the inferior parietal lobe and temporo-parietal junction in particular are responsible for the generation of the P3b. The involvement of these areas in its generation align with the interpretation of the P3b as an index of stimulus-drive attentional allocation as these areas are also implicated in goal-directed attention and visuomotor integration (e.g., Corbetta &Shulman, 2002).

P3 and age

Like the N2, the P3 amplitude and latency changes as a function of age. In older adults, the P3 is smaller in amplitude and peaks later relative to younger adults (Freidman, 2012; Polich, 1996; for meta-analysis see: Cheng, Tsai & Cheng, 2019). A meta-analysis of 32 studies focusing on age-related variations of the P3 concluded that a robust relationship exists between P3 latency prolongation and aging (Polich, 1996; van Dinteren, et al., 2014). This delay is suggested to be an index of reduced information processing speed as a result of less efficient neurocognitive processes (Salthouse, 2000), supporting behavioural studies reporting slower reaction times for older adults (e.g., Anguera & Gazzaley, 2012; Salthouse, 1991; Verhaeghen & Cerella, 2002). Moreover, the amplitude reduction in older adults is linked to poorer performance on IQ and neuropsychological tests (Riis et al., 2008).

One of the most consistent findings reported in the aging and ERP literature is how the P3b in older adult is much more frontally distributed compared to young adults (Kopp et al., 2014). A comparison of younger and older adults on a visual oddball task utilised fMRI and EEG simultaneously to measure the amplitudes and topography of the P3b component (O'Connell et al., 2012), which is typically accompanied with a parietal topography (Polich, 2007). Older adults were reported to have significantly reduced P3b amplitudes in parietal electrodes and larger amplitudes over frontal electrode sites. This topographical shift was characterised by an increased activation in the right dorsolateral prefrontal cortex and left temporal regions in older adults (O'Connell et al., 2012). The age-related variation reported in the study aligns with previous models describing the changes in brain area recruitment with age. Specifically, the results align with the posterior-anterior shift (PASA) model which suggests older adults recruit frontal regions more due to degraded functioning in posterior regions (Davis et al, 2007). The consequences of this increased frontalisation have been examined, and such shifts have been associated with poorer performance in neuropsychological tests (Fabiani, Friedman & Cheng, 1998).

Due to this frontally focused shift, amplitude differences between older and young adults for the P3b component have been a well-replicated finding. Smaller P3b amplitudes for older adults compared to younger adults has been reported in a wide variety of tasks including the oddball paradigm and task switching (Stige et al., 2007; Friedman et al., 2007). This age-related amplitude reduction is a methodological consequence of recording the P3b at parietal sites; older adults have significantly larger P3b amplitude in frontal sites than younger adults, whereas younger adults have larger P3b amplitudes at centro-parietal sites (Freidman et al. 2007).

For the Simon Task, age-related differences for the P3 component have been reported, with smaller P3 peak amplitudes for older relative to younger participants (Van der Lubbe & Verlege, 2002). For younger adults, the P3 amplitude was larger for incongruent trials than congruent trials, however for older adults the P3 amplitude was larger for congruent trials, and this P3 component was delayed in older adults. This demonstrates how the Simon Task can elicit age-related differences in the amplitude of the P3 component, in line with research on other paradigms that also report this delay and amplitude modulation.

Work with the Go/NoGo paradigm has examined the interplay with task demands and age by manipulating the relevance of the NoGo information to create three conditions; irrelevant NoGo, conflict NoGo and Go (Hsieh, Wu & Tang, 2014). As a reminder, past work has suggested that the amplitude of the P3 increases as task difficulty decreases (e.g., Pratt, Willoughby & Swick, 2011; Watter, Geffen & Geffen, 2001). In the research by Hsieh and colleagues, analysis of event-related potential data indicated that older adults exhibited larger P3 amplitudes for the irrelevant-NoGo trials relative to the conflict-NoGo trials suggesting that irrelevant-NoGo trials were harder. However, behavioural performance followed the opposite pattern with more commission errors on the conflict-NoGo trials. In younger adults, larger P3 amplitudes for conflict trials were paired with more commission errors on this trial type, suggesting that this trial type had the highest difficulty for this age group. These findings suggests that older adults are recruiting more resources in order to overcome the pre-potent response plan in the NoGo trials, especially during the irrelevant-NoGo. It may be that this age group find these trials more cognitively challenging, possibly due to increasing vulnerability to distracting information with age (Grady et al., 2006). This is in line with the interpretation of the P3 amplitude as a stimulus classification index in the Go/NoGo paradigm (Azizian et al., 2006).

2.3. CHAPTER SUMMARY

In summary, the N2 and P3 are both frequently used to measure executive function performance and are shown to be elicited by both Go/NoGo and Simon Tasks. These components have been shown to be modulated by age and task difficulty, making them ideal candidates to measure when investigating the effects of bilingualism on age-related changes in older adulthood.

Chapter 3: Using neuroimaging techniques to study aging and bilingualism

It is well-reported that increasing age can be accompanied with a decline in cognitive processes such as working memory, executive function, and suppression of distracting information (Salthouse, 2010; Wascher et al, 2012). However, models of aging argue that lifestyle factors including mental, physical, and social activities can influence structural and functional age-related changes (Reuter-Lorenz & Park, 2014). Reviews of neuroimaging evidence suggest that bilingualism is one such factor that can influence age-related neurocognitive changes (e.g., Anderson et al., 2021; Bialystok, Craik & Luk, 2012; Zhang & Thierry, 2020). Such reviews also highlighted how limited work investigated the link between bilingualism and aging in older adult samples, especially using the event-related potential technique (Zhang & Thierry, 2020).

This chapter will outline extant evidence employing the event-related potential technique to elucidate differences in the cognitive processing of monolinguals and bilinguals and will highlight the gaps in current knowledge when examining the effects of age and task design.

3.1. EVIDENCE FROM EVENT-RELATED POTENTIALS (ERPs)

Event-related potentials can offer valuable insight into age-related cognitive changes and the influence of experience on these changes. Firstly, the temporally sensitive nature of event-related potentials is well suited to measuring the time course of cognitive processes underlying executive function and thus may detect subtle group differences that are not measurable in behavioural data (Incera, 2018). Further to this, there is a wealth of research measuring event-related potentials during tasks of executive function such as working memory (Fabiani & Wee, 2001), conflict monitoring (e.g., Larson, Clayson & Clawson, 2014) and task switching (Eppinger et al., 2007). The profile of common components (such as the N2 and P3) are well documented in relation to executive function tasks, therefore clear a priori hypotheses can be made concerning the ERP results related to specific paradigms. This is further aided by research reporting consistent and robust age-related topography, amplitude, and latency changes in older adults (for review see Cheng, Tsai & Cheng, 2019). However, there is limited research employing the ERP technique to investigate cognitive processing differences between monolinguals and bilinguals - a meta-analysis has highlighted only 11 studies from childhood to older adulthood investigating the effects of bilingualism on executive functions (Cespón & Carreiras, 2020).

Before reviewing literature exploring the impact of bilingualism on cognition through the use of event-related potentials, it is first important to briefly discuss how modulation of ERP components related to executive functions can be interpreted. It has been argued that there is ambiguity in neural measures wherein modulations of the amplitude or latency in an ERP component are interpreted differentially by different researchers and labs (see Paap et al., 2014). Consequently, it is important to outline how latency and amplitude modulations can be interpreted when comparing language groups.

3.2. N2 AMPLITUDE AND LATENCY MODULATIONS

Depending on the paradigm, the N2 is suggested to reflect a host of different cognitive processes, such as conflict monitoring and inhibition (for review Larson, Clayson & Clawson, 2014). It is important to note the modulation of the amplitude of the N2 can only be interpreted within the confines of specific paradigms. Therefore, caution should be taken when comparing N2 findings between different paradigms.

As previously discussed, the N2 amplitude is consistently elicited in Go/NoGo paradigms, with larger N2 amplitudes to NoGo relative to Go trials, known as the N2-effect. On Go/NoGo tasks, the N2 is suggested to be an index of conflict monitoring (e.g., Donkers and van Boxtel, 2004). Smaller N2-effects are associated with poorer behavioural performance (increased false alarm rates) (e.g., Falkenstein, Hoormann & Hohnsbein, 1999) and smaller N2-effects are also reported for older adults (Cheng, Tsai & Cheng, 2019). As a result, reduced N2 amplitude effects in Go/NoGo are suggested to reflect decreased ability to detect conflict information (Clawson et al., 2017).

The amplitude of the N2 has also been studied during performance of spatial-response conflict (SRC) tasks such as the Simon. In this paradigm, the N2 is larger for incongruent trials than for congruent trials (Chen & Melara, 2009; Melara, Wang, Vu & Proctor, 2008; Scrivano & Kieffaber, 2022). In contrast to the Go/NoGo, larger N2-effects are associated with *poorer* behavioural performance (Millner, et al., 2012). Larger N2-effects in SRC paradigms are suggested to reflect increased processing of the irrelevant spatial stimuli and thus increased interference from irrelevant information (Larson, Clayson & Clawson, 2014). The latency of the N2 in Go/NoGo paradigms peaks later for older adults relative to younger adults indicating slower conflict detection processing (Falkenstein, Hoormann & Hohnsbein, 2002; Horvarth et al., 2009). This finding is supported by a meta-analysis of Go/NoGo studies with younger and older adults (Cheng, Tsai & Cheng, 2019).

Given this, shorter N2 latencies in trials of conflict (i.e., NoGo or incongruent trials) for one group compared to another would support a superior speed of processes associated with inhibition and monitoring. For N2 amplitude modulation, superior conflict monitoring processes in the Go/NoGo would be manifested as larger N2-effects, but in the Simon task it is manifested as smaller N2-effects.

3.3. P3 AMPLITUDE AND LATENCY MODULATIONS

For Go/NoGo tasks, the NoGo stimuli typically elicit larger P3 amplitudes relative to Go stimuli (e.g., Donkers & van Boxtel, 2004; Fernandez et al., 2013; Eimer, 1993; Moreno, Wodniecka et al., 2014). Additionally, the magnitude of the P3 amplitude is modulated by perceptual similarity of the nontarget to the target, with similar nontargets eliciting larger P3 amplitude than dissimilar nontargets (Azizian et al., 2006). This suggests that the P3 amplitude can be interpreted as an index of the extent of cognitive processing required for categorising stimuli that vary in similarity to the target (Azizian et al., 2006). Stimuli which demand more processing, such as trials perceptually similar to Go, evoke larger P3 amplitudes, while dissimilar nontargets that are easily classified as nontargets require less processing. Moreover, there is an age-related reduction in the NoGo-P3 amplitudes (Cheng, Tsai & Cheng, 2019), suggesting that, compared to younger adults, older adults experience inefficient processing of stimuli.

In Simon tasks, the P3 is larger for congruent than incongruent trials (Galashan et al., 2008; Leuthold, 2011). Moreover, larger P3 amplitudes are correlated with better performance on cognitive functioning tasks (Amin et al., 2015). Thus, in the Simon task, the P3 is larger for less demanding experimental conditions, therefore, larger P3 amplitudes for one group over another would indicate an advantage for processes related to categorising information.

The latency of the P3 is suggested to reflect speed of cognitive processes involved in updating working memory (Polich, 2007; Leuthold, 2011). Shorter P3 latency is argued to represent faster stimulus classification and thus superior cognitive performance (Magliero, et al., 1984). In Go/NoGo tasks, the latency of the P3 is delayed for NoGo trials (Bokura, Yamaguchi & Kobayashi, 2001). The latency of the P3 is delayed in older adults in Go/NoGo tasks (Cheng, Tsai & Cheng, 2019). Similarly, in Simon tasks, the latency of the P3 is delayed for incongruent trials (Leuthold, 2011). Therefore, larger P3 amplitudes and earlier P3 may be indicative of superior efficiency and speed of processes related to updating working memory contexts (Cespón & Carreiras, 2020).

3.4. EXAMINING BILINGUALISM AND COGNITION USING ERPs

A meta-analysis has highlighted how only 11 studies from childhood to older adulthood investigate the effects of bilingualism on executive functions (Cespón & Carreiras, 2020). Surprisingly, only *two* of these focus on older adult populations. Whilst one of these papers is relevant to the topic of this thesis and thus is discussed below (Kousaie & Phillips, 2017), the second paper focuses on task-switching, which is not the primary focus of this thesis (Zunini et al., 2019). Due to the paucity of research focusing on the cognitive benefits of bilingualism in older adults, as measured by ERPs, this section will also review research recruiting samples of children and younger adults.

To investigate these effects of bilingualism on executive control in children, a study employed a Go/NoGo paradigm with 62 children aged 5 years old (Barac, Moreno & Bialystok, 2016). Bilingual children were faster and more accurate compared to monolingual children. Moreover, bilingual children exhibited shorter N2 and P3 latencies, suggesting faster conflict monitoring and attentional resource allocation processes. Bilingual children also exhibited larger P3 amplitudes, suggestive of more efficient attentional resource allocation. One key caveat to such interpretations is the lack of clear functional significance of these components, and the argument that overall differences in amplitudes between groups is uninformative due to inter-individual variability. Further to this, there were no significant language group differences in the N2 amplitude. It is important to note that the authors focused on the absolute N2 amplitude, rather than the N2-effect, and no classic Go/NoGo effect was reported for the N2 amplitude, so it remains unclear whether the paradigm evoked such an effect. Visual inspection of the N2-effect in the reported ERP waveforms suggests that such analysis may reveal language group distinctions. Despite this, these findings highlight the potential benefits of bilingualism on cognitive processes, particularly in attentional control. Further investigation using the N2-effect analysis and with other age populations could offer valuable insights into the specific mechanisms underpinning language group differences in cognitive processing.

Evidence from younger adult populations has also reported the presence of language group differences on neural measures. Using visual Go/NoGo task, Moreno and colleagues highlighted how younger adult bilinguals exhibited larger N2 amplitudes relative to monolinguals, specifically larger N2-effects (Moreno, et al., 2014). Work from an auditory Go/NoGo task revealed similar results, with larger N2-effects for bilinguals driven by larger N2 amplitudes on NoGo trials (Fernandez, Tartar, Padron & Acosta, 2013). Interestingly, these neural differences were observed in the absence of behavioural differences. This differentiation highlights how monolinguals and bilinguals are processing conflict differently in order to reach the same behavioural outcome. This suggests that bilinguals may be utilising processes more efficiently as they are adapting cognitive processes to meet task demands.

Language group differences also extend beyond Go/NoGo paradigms, with research demonstrating language group differences at the neural level on the Stroop task (Coderre & Van Heuven, 2014; Heidlmayr et al., 2015; Kousaie & Phillips, 2012b), and Flanker and Simon task (Kousaie & Phillips, 2012b). To date, only one paper has investigated the effects of bilingualism on electrophysiological indices of executive function in older adults (Kousaie & Phillips, 2017). This key piece of research compared the electro-cortical and behavioural responses of older adult monolinguals and bilinguals aged between 60 and 83 years of age on three tasks of executive control: Flanker, Simon, and Stroop (Kousaie & Phillips, 2017). Bilinguals were highly proficient, daily users of English and French who had learned their second language before the age of 18, and monolinguals had minimal exposure to a second language. The amplitude of latency of the N2 and P3 were measured alongside reaction time and accuracy.

The results from both behavioural and electrophysiological measures revealed how language group differences were not consistent across the Stroop, Flanker and Simon task. In the Stroop task, bilinguals were faster and more accurate relative to monolinguals, but this pattern was only observed on incongruent trials. Similarly, in the Flanker task, bilinguals showed increased accuracy not only on the incongruent trials but also on congruent trials, but there were no differences in reaction time between the two language groups. Conversely, in the Simon task, there was no language group effect for behavioural measures, with monolinguals and bilinguals achieving comparable reaction times and accuracy rates. The differential pattern of results across the Stroop, Flanker and Simon tasks suggests that the influence of bilingualism on executive function may vary as a result of the specific cognitive demands of each task. For example, bilinguals appear to exhibit enhanced inhibitory control as evidenced by their improved behavioural performance on the incongruent trials in the

Stroop and Flanker tasks, but these benefits did not extend to the Simon task, suggesting that the effects of bilingualism are not uniform across tasks.

This lack of uniformity is further exemplified when reviewing the event-related potential results. For the Stroop task, analysis of the electrophysiological data revealed an earlier N2 peak for bilinguals than monolinguals during the incongruent trials, but no amplitude differences were observed between the two language groups. This suggests conflict detection processes may occur earlier for bilinguals relative to monolinguals, an interpretation which converges with the faster reaction time and higher accuracy rates reported for bilinguals on this task. For the Simon task, the electrophysiological data revealed that monolinguals overall had larger N2 amplitudes relative to bilinguals. However, the N2 amplitudes of monolinguals did not differ between congruent and incongruent trials, suggesting that monolinguals were monitoring for conflict to an equal extent for both trial types. Conversely, for bilinguals, larger N2 amplitudes were exhibited for incongruent trials. This suggests that bilinguals were monitoring for conflict more efficiently and adapting cognitive processes to meet task demands. However, this adaptation did not result in improvements in behavioural performance as RT and accuracy were comparable between the two language groups. In the Flanker task, analysis of the N2 amplitudes yielded distinct results for the two language groups. Monolinguals exhibited larger N2 amplitudes for incongruent relative to congruent trials. In contrast, statistically, bilingual individuals had comparable N2 amplitudes across both trial types. However, visual inspection of the waveforms indicates that the incongruent and congruent trials were not processed comparably, as the N2 amplitudes do appear to differ quantitatively, but this difference was not borne out in the statistics. The results of the Flanker task are difficult to interpret given the increased accuracy on incongruent trials for bilinguals over monolinguals. It is possible that the task demands of the Flanker task were not high enough for bilinguals resulting in non-significant trial type N2 amplitude difference.

The amplitude and latency of the P3 was also measured during the Stroop, Flanker and Simon task. During the Stroop task, larger P3 amplitudes were observed for congruent stimuli in both monolingual and bilingual groups. Direct comparison of the P3 amplitudes on incongruent trials revealed that the amplitude on this trial type was larger for bilinguals than monolinguals. When paired with the faster and more accurate responses for bilinguals on incongruent trials, this may suggest that bilinguals allocate resources to the more difficult incongruent trials to produce quicker and more accurate responses than monolinguals.

For the Simon task, language group differences were observed on both congruent and incongruent trials. Specifically, larger P3 amplitudes and earlier peaks were reported for bilinguals relative to monolinguals for both trial types (Kousaie & Phillips, 2017). The larger P3 amplitudes indicate greater resource allocation devoted to stimulus evaluation and categorisation. The earlier latencies indicate faster stimulus categorisation. As these language group differences were observed on both congruent and incongruent trials, these findings provide support for the notion that influence of bilingualism extends beyond conflict-specific trials, as suggested previously (e.g., Bialystok et al., 2004; Costa et al., 2008; Hilchey & Klein, 2011). However, it should be noted that this was not reflected in the behavioural data as both language groups performed comparably. Finally, for the Flanker, language group differences were again observed for the P3. Namely, earlier P3 peak latencies were observed for bilinguals compared to monolinguals, but this effect was observed on congruent trials only. This indicates earlier stimulus categorisation similar to the Simon Task. Despite this latency difference on both the Flanker and Simon Task, no significant reaction time differences were observed between the two language groups suggests that both groups were equally effective in executing a response under these task demands.

It is clear that the findings of this paper are complex and difficult to interpret without a clear theoretical framework. The absence of a direct comparison with a younger adult sample contributes to the complexity of the interpretations. While insights from past literature can contribute to our understanding of predicted patterns of results in younger adults, a direct comparison with a younger adult sample would have aided interpretation of the data. Interestingly, the authors have also collected data using the same three paradigms and with a younger adult sample of monolinguals and bilinguals (Kousaie & Phillips, 2012), a paper which produced equally complex results with several methodological flaws[4]. However, the pattern of results was not the same as with the older adults and the data from the younger and older adult samples have not been directly compared. A direct comparison would have contributed to our understanding about the potential trajectory of these observed effects, allowing us to gain further insight into the role of bilingualism and age in shaping cognition.

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[4] The N2 and P3 components were measured at two electrode sites despite recording with a 64-electrode montage, time-windows were decided using visual inspection of the ERP (a practice heavily advised against due to its ability to bias results), large number of trials may have induced practice effects and participants were required to achieve at least 80% accuracy so a ceiling effect may have been artificially induced.

The findings of the 2017 paper with older adults provide several key insights, from both a methodological and theoretical perspective (Kousaie & Phillips, 2017). Firstly, the pattern of language group differences was not consistent across the three tasks aligning with previous work suggesting that the three tasks show little convergent validity (Paap & Sawi, 2014). Secondly, it is important to consider why the verbal Stroop task was the paradigm that elicited the most consistent superior behavioural performance from bilinguals, while the behavioural measures on the Simon task did not distinguish between the two groups. The lack of convergence may be driven by differential task demands. In the Stroop task, bilinguals were quicker and more accurate than monolinguals. During this task, a singular stimulus provides both the target information (colour) and the distraction information (word). The cognitive control system experiences high demands as it must suppress the automatic pre-potent response of reading the word in order to respond to its colour. This high cognitive demand may allow for clear, language group differences in the behavioural data to be observed. However, this interpretation is disputed by the results of the Simon task which also utilised a singular stimulus to deliver target information (colour) and distracting information (spatial location) yet elicited comparable reaction times and accuracy for both language groups. Alternatively, language group differences on the Stroop may be driven by the linguistic nature of the task, but this is challenged by well-established research highlighting how bilinguals often have worse performance than monolinguals on linguistic tasks (e.g., Bialystok, 2009; Grundy, 2020). It is clear that the language group differences were variable across tasks, and there is not a clear, parsimonious explanation for these differences. Future work should aim to understand how robust the observed effects are, and also future work should endeavour to utilise clear theoretical frameworks of bilingualism and aging to interpret results.

Further to work focusing purely on non-verbal tasks, research has highlighted how non-linguistic conflict resolution may be influenced by language context, even when this is irrelevant to the task. Wu and Thierry (2013) employed a modified version of the Flanker task wherein Welsh-English bilingual participants were instructed to respond to the direction of the central arrow, ignoring the direction of surrounding arrows, which may be congruent or incongruent. Interspersed between these trials were words which participants were instructed to ignore; these words could either be presented in Welsh or English. Analysis of the behavioural results revealed how error rates for incongruent trials were lower in the mixed-language block compared to the single-language monolingual block. That is, when both Welsh and English words were interspersed between Flanker trials, participants found responding to incongruent trials easier than when just English or just Welsh words were presented. This pattern is supported by analysis of electrophysiological measures which showed that the P3 amplitude was reduced for incongruent trials in the mixed block compared to the single-language block. As the P3 amplitude was taken to be a measure of inhibition in this paradigm, the reduction of amplitude indicates that participants experienced less interference in the mixed-language context. The authors interpreted the results to reflect that the mixed language context 'heightened' participants conflict resolution system, so that the system was more alert to conflict, in turn conferring better performance on incongruent trials. However, while this interpretation provides a convincing account, behavioural results contrast to what is expected. It would be predicted that individuals would perform more poorly in the mixed-language content due to the demands on the cognitive control system. It should be noted that performance was high in all conditions (>85%) and individual variability is not reported, thus the impact of outliers cannot be established. Nevertheless, this research further highlights the link between language control and cognitive control in bilinguals and highlights how electrophysiological measures can be successfully utilised to investigate how domain-general executive function may be influenced by language experience.

The review of these studies makes it clear that the effects of bilingualism on cognition across tasks purported to measures executive function are not clear, and the effect of task demands, and age, remain to be clearly elucidated.

3.5. TASK DEMANDS AND ERPs

The influence of task demands has been explored through behavioural evidence in Section 1.5., wherein research was presented supporting the idea that on easy tasks language group differences are less likely to be observed, whereas on harder tasks bilinguals outperform monolinguals, specifically in the Simon task (Bialystok,2006) and Flanker task (Costa et al., 2009; Grundy et al., 2017). These behavioural investigations have been extended to electrophysiological work. Barker and Bialystok (2019) instructed younger adults to complete a N-back task while behavioural and EEG measures were taken. Behaviourally, the bilinguals were slower but more accurate relative to monolinguals during 2-back trials, while performance was comparable on 1-back trials. With focus on the P3, bilinguals exhibited a decrease in amplitude from the 1 to the 2-back, an expected trial effect as a result of task demands. Monolinguals, however, did not show this pattern, exhibiting comparable P3 amplitudes for both trial types. Paired with the more accurate responses, this suggests that bilinguals adapted their attentional control mechanisms to meet task demands. These results are at odds with earlier work reporting that both monolinguals and bilinguals experienced a decrease in P3 amplitude as a result of increases task demands, but overall, the P3 amplitudes of bilinguals were larger, but it is important to note that behaviourally the two groups were comparable in this study (Morrison et al., 2019).

Comishen and Bialystok (2021) offer the explanation that when bilinguals outperform monolinguals (like in the Barker & Bialystok paper), bilinguals employ their attentional resources more effectively, resulting in the trial effect in the P3 amplitude, especially when task demands increased (on the 2-back). This explanation was supported by their data which compared younger monolingual and bilingual adults on an n-back task which comprised of increasing task demands. Participants completed 0-, 1-, 2-, and 3-back conditions while behavioural and electrophysiological data was recorded. Analysis of the behavioural results indicated that bilinguals had higher accuracy relative to monolinguals, particularly in the most difficult conditions (2- and 3- back). However, commission of false alarms and reaction time did not differ between language groups. Analysis of the electrophysiological data revealed three key results; (1) the P2 amplitude was larger for bilinguals than monolinguals overall, but there was no interaction with condition, (2) the N2 amplitude reduced with increasing task difficulty but did not differ by language group, (3) the P3 amplitude reduced with increasing task difficulty and the mean amplitude of the P3 was larger for bilinguals overall. The P2 can be considered an index of working memory capacity, wherein larger amplitude reflects greater capacity (e.g., Lijffift et la., 2009). Consequently, these results may indicate that bilinguals had increased working memory capacity, an interpretation which aligns with the superior accuracy performance on harder trials. However, it should be noted that the functional significance of the P2 on the n-back task is not reliably established and there is limited evidence exploring the influence of bilingualism on this measure (Cespón & Carreiras, 2020). While previous work has reported larger P2 amplitudes for older adult bilinguals over monolingual counterparts (Morrison & Taler, 2020), other work comparing the amplitude of the P2 on a Go/NoGo task found no language group differences on this measure (Moreno et al.,2014). Therefore, further work is required to definitively establish the functional significance of the P2.

No language group differences were found for the analysis of N2 amplitudes, contrasting with work employing Go/NoGo paradigms (Moreno et al., 2014; Fernandez., 2013). One interpretation could be that the cognitive processes indexed by the N2 on the n-back task is sensitive to task demands, but this cognitive process is not influenced by bilingualism. The function significance of the N2 on Go/NoGo paradigms is well established as is suggested to reflect inhibitory control, a process posited to be influenced by bilingualism (e.g., Green, 1998). However, it is possible that the N2 in n-back tasks reflect a different process entirely. A review posed a strong case that the N2 may represent ability to discriminate between the presented stimulus and one held in memory (Folkstein & Van Petten, 2008). However, the functional significance of the N2 is not reliably established in n-back paradigms. The interpretation of these findings could be bolstered through the inclusion of a behavioural measure of discrimination such as d-prime for two reasons. Firstly, correlating this measure with N2 amplitude would help to elucidate the functional significance of the N2 in this paradigm (although arguably d-prime may lack granularity). Secondly, comparisons of language groups on this measure would help to inform interpretation concerning cognitive processes on which bilinguals may outperform monolinguals.

In a similar fashion to the N2, the P3 was sensitive to task demands, and was larger for bilinguals overall, however there was no interaction between language group and task demands. This suggests that both monolinguals and bilinguals adapted attentional resource allocation as a function of task demands similarly, but that there are language group differences in the overall deployment of these resources. However, it could be argued that absolute differences between groups is not informative given the inter-individual variability in amplitudes of ERP measures. It is argued that interactions are required to interpret group differences.

Research investigating the interplay between task demands and the effects of bilingualism could be extended through the employment of paradigms for which functional significance of electrophysiological measures are well established. Moreover, the recruitment of older adult samples would be informative to our understanding of how task demands may interact with any observable language group differences.

3.6. CONVERGENT VALIDITY IN EXECUTIVE FUNCTION TASKS

A focal issue for research aiming to explore the impact of bilingualism on executive function is the choice of paradigm. A wide range of tasks have been used to measure executive function (see Valian, 2015). In one meta-analysis, Ware and colleagues (2020) included 7 different paradigms that were identified as valid measures of executive functioning (Simon, Stroop, ANT, Flanker, Trail Making Test, Task switching and Card sort tasks). Similarly, a meta-analysis of executive function comparisons in monolingual and bilingual children identified over 20 different paradigms across 136 peer-reviewed articles, 11 doctoral thesis and two unpublished data sets (Lowe, et al., 2021). These reviews considered studies focusing on all aspects of executive function. However, a review by Van den Noort and colleagues (2019) highlighted the use of 21 different paradigms to examine the effects of bilingualism on cognitive control. Another review highlighted how inhibitory control has been measured through at least three different tasks including Simon, Stroop and Go/NoGo (Gunnerud et al., 2020).

Moreover, previous meta-analyses have grouped the results from different paradigms together under the assumption that the paradigms measure comparable constructs. For example, one meta-analysis included behavioural measures from three different tasks (Simon task, Stroop and Go/NoGo task) when assessing the effects of bilingualism on inhibition and analyses of these studies revealed a small mean effect size for superior performance from bilinguals on inhibition (Gunnerud et al., 2020).

The variability in paradigm choice between studies aiming to examine the same cognitive process is problematic as it is linked to a multitude of issues including the presence of task-specific effects. Previous attempts to understand the convergent validity of executive function tasks report a low or a lack of correlation in behavioural indices of inhibition (RT effects and accuracy effects) (e.g., Paap & Greenberg, 2013; Poarch & Van Hell, 2019). In Figure 1, the results of 37 investigations of convergent validity have been synthesised. Only around 16% of the studies presented here found a significant correlation between the interference scores of executive function tasks (see Appendix I for more information on these tasks). It also clear that there is no consistent pattern within the 6 studies that did find a correlation, whilst they all included younger adult participants, they did not all test associations with the same paradigms.

The lack of convergence between tasks of inhibition can be explained by the argument made by Friedman and Miyake (2004) that inhibition is not a unitary construct.

The authors argue that inhibition can be separated into three distinct processes: prepotent response inhibition, resistance to distractor interference and resistance to proactive interference. This distinction is supported by a recent meta-analysis which reported how the presence of language group differences is dependent on the type of task used to measure executive function (Ware, Kirkovski & Lum, 2020). Given this distinction, it is not surprising that the measures do not correlate as performance on inhibition tasks is not underpinned by a single, unitary inhibition component.

Two paradigms which are commonly grouped together as comparable indices of the same underlying inhibition processes are the Go/NoGo and the Simon task (e.g., Lehtonen et al., 2018). However, there is a theoretical distinction between the inhibitory control processes utilised in these tasks as per the taxonomy presented by Friedman and Miyake (2004). The Go/NoGo tasks requires participants to execute a speeded manual response to some stimuli (Go) and withhold this response to other stimuli (NoGo), requiring *prepotent response inhibition*. In contrast, the Simon task requires participants to respond to one task-relevant attribute (such as colour) while ignoring another task-irrelevant attribute (such as position), requiring *resistance to distractor interference*. It is important to note that pre-potent response inhibition is not constrained to NoGo trials, that is pre-potent response inhibition does not reflect the inhibiting of a motor response but the overriding of a bias of a response (which could be either Go or NoGo). This has also been labelled response conflict monitoring (Donkers & van Boxtel, 2004).

In order to understand whether bilingualism provides benefits to inhibitory control, firstly the construct of inhibitory control must be well understood. Is there a domain-general mechanism that influences performance across inhibitory control tasks, such as the attentional control component posited by Bialystok and Craik (2022), or, as Friedman and Miyake (2004) suggested, are different sub-components of inhibition employed during tasks? After establishing this, it is possible to begin investigating whether bilingualism enhances domain-general processes underpinning inhibitory control, or if language group differences are specific to certain sub-components of inhibition.

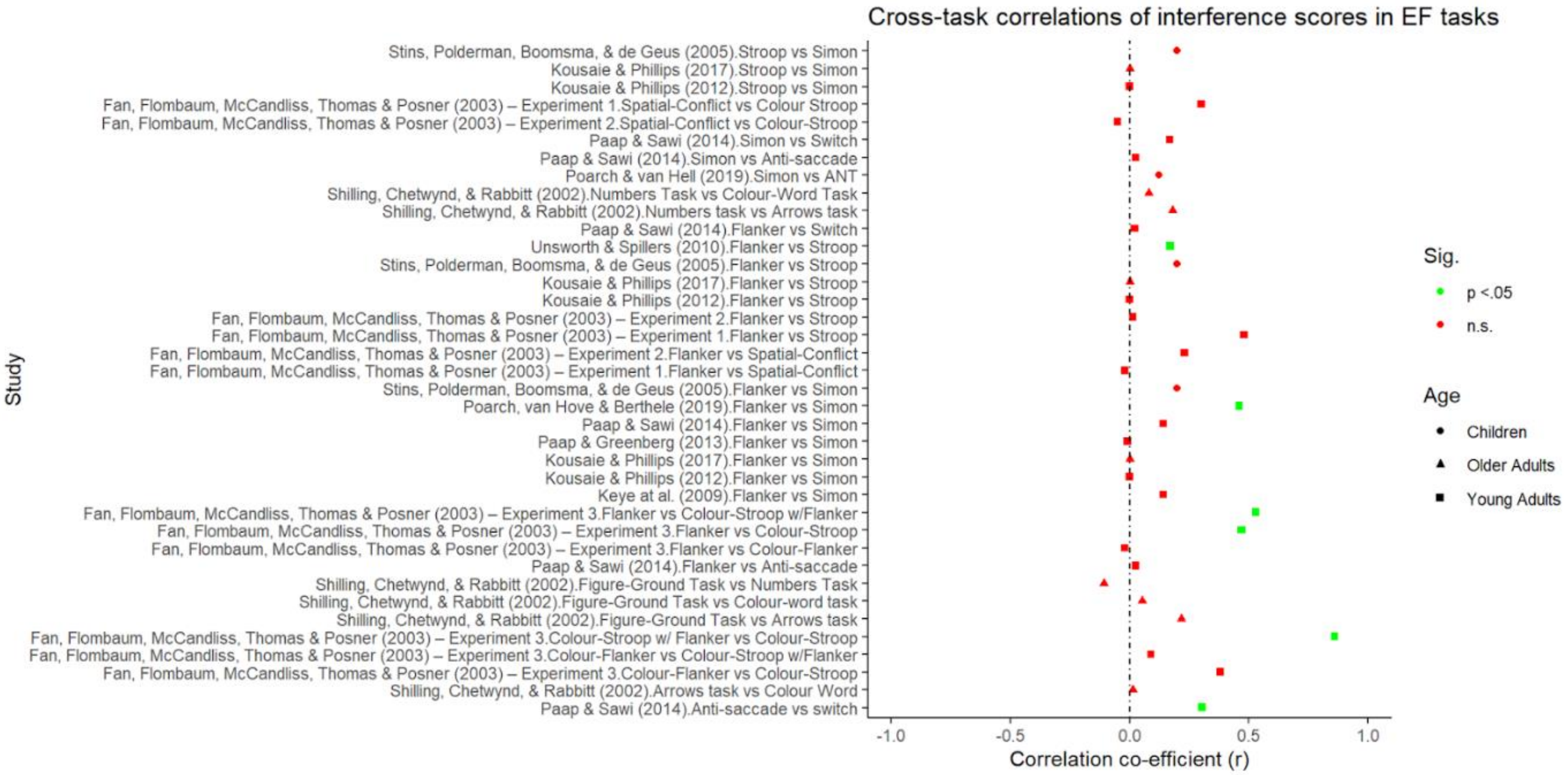

Figure 1. Cross-task correlations between interference scores on executive function tasks. Green symbols represent studies that reported a significant correlation. Note that Kousaie & Phillips (2012b; 2017) did not report a correlation co-efficient but stated that the cross-task correlations were non-significant, so here the co-efficient is reported at 0 for these missing values.

To date, no research has investigated the convergent validity of the neurobiological underpinnings of the Go/NoGo and Simon Task, and previous investigations into the convergent validity of EF tasks have focused on behavioural measures such as reaction time and accuracy effects. When correlations between tasks are reported, this is usually found when correlating measures of monitoring, rather than measures on inhibition (e.g., Keye at al., 2009; Paap & Sawi, 2014; Ross & Melinger, 2017; Stins et al., 2005). Monitoring is most frequently measured using global-RT or RT on congruent trials (see Lehtonen et al., 2018)[5]. However, using cross-task correlations of 'monitoring' (i.e., global-RT) to support the notion that executive function tasks employ the same underlying EF construct is problematic. Global-RT is a measure of processing speed alongside other factors such as motor control (e.g., Nishikawa et al., 2007) and practice effects (Ghuntla et al., 2014). Put simply, if a participant is quick in one task, they will likely be quick in another, and the impure nature of response times does not allow researchers to draw reliable conclusions about processing speed.

The use of neuroimaging methods, such as event-related potentials (ERPs) can help elucidate which cognitive processes are employed on tasks and can allow for group comparisons independent of motor responses. Two main electrophysiological components are associated with executive functioning: N2 and P3. The amplitude and latency of these components have been compared between monolinguals and bilinguals to establish the presence of a language group differences in the processes the N2 and P3 are thought to index (for meta-analysis see Cespón and Carreiras, 2020). Despite this promising approach, often, event-related potential modulations do not align with behavioural modulations, and in the absence of behavioural modulations authors reach different interpretations of whether an amplitude increase, or decrease, is associated with more efficient cognitive processes (de Bruin, Dick & Carreiras, 2021). Paap and colleagues have argued that this 'valence ambiguity' means that neural measures provide a limited role in highlighting executive function processing differences in bilinguals (Paap et al., 2014). One meta-analysis has attempted to outline recommendations on the way increases and decreases in amplitudes should be interpreted with respect to language group differences (Cespón and Carreiras, 2020). However, these recommendations are again problematic as the proposed framework

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[5] It is hypothesised that bilinguals may experience superior domain-general executive function tasks exhibited by better performance on congruent and incongruent trials relative to monolinguals. One way of empirically testing this is by comparing the Global-RTs of monolinguals and bilinguals on tasks of executive function, and there is evidence to support this notion (for review see Hilchey & Klein, 2011).

assume that the N2 and P3 reflect the same underlying cognitive processes across all paradigms. Here, it is important to note that the amplitude and latency of the N2 is a dependent measure. That is, the functional significance of the N2 is likely to change as a function of task conditions and the paradigm on which it is elicited. This is supported by work reporting how the amplitude of the N2 across three executive function tasks (two oddball tasks and one spatial-response compatibility task) were not correlated (Morand-Beaulieu, Perrault & Lavoie, 2021).

Moreover, the amplitude of the N2 in a Go/NoGo task is thought to reflect conflict monitoring (for review see Folstein & Van Petten, 2008) and it is reliably established that older adults typically exhibit a reduced N2-effect (difference between NoGo-N2 and Go-N2) (for meta-analysis see Cheng, Tsai, & Cheng, 2019). This reduction is suggested to reflect poorer conflict monitoring processes resulting in increased false alarm rates (e.g., Falkenstein, Hoormann & Hohnsbein, 1999). In contrast, little work has been done to investigate the effects of age on the N2 in the Simon task, but behaviourally older adults are reported to exhibit larger Simon effects for reaction time and accuracy (e.g., Kubo-Kawai & Kawai, 2010; for review see Proctor, Vu & Pick, 2005). In younger adults, larger Simon effects in RT and accuracy are associated with larger N2-effects (Millner et al., 2012). Larger Simon effects are indicative of increased interference from irrelevant spatial information (for a review on the origins of the Simon effect see Hommel, 2011). Therefore, it is possible that older adults would experience larger N2-effects reflective of increased interference by irrelevant stimuli on the incongruent trials.

Neuroimaging evidence supports that activity in the ACC is observed during the performance of both the Simon and Go/NoGo tasks (Nee, Wager & Jonides, 2007). Moreover, a review of ERP and fMRI studies has proposed that the amplitude of the N2 reflects activity in the anterior cingulate cortex (ACC) (Van Veen & Carter, 2002). While it is suggested that ACC activity is reflective of engagement of control processes and is an area implicated in tasks that require cognitive control (for meta-analysis see Ridderinkhof et al., 2004), the ACC is also modulated by many different factors such as performance monitoring and decision making (for review see Shenhav, Botvinick & Cohen, 2013). One model of ACC function argues that the ACC does not represent a unitary function but actually integrates three key streams of information through a diversity of functions: the reward from a controlled process, the cost of cognitive effort and the magnitude of control required (Shenhav, Botvinick & Cohen, 2013). Based on this model, the N2 in Simon and

Go/NoGo may both be generated by the ACC but again, this activation may reflect different processes. This assumption is supported by brain imaging evidence reporting distinct neural correlates for interference suppression and response inhibition in bilinguals (Luk et al., 2010).

Secondly, the amplitude of the P3 has been associated with intensity of processing (Kok, 2001) and resource allocation (Polich, 1996) and is posited to index updating of working memory (Polich, 2007). Smaller P3 amplitudes are reported for more difficult trials (Gajewski & Falkenstein, 2013). In line with this, on the Go/NoGo task the P3 is reported to be smaller on NoGo trials relative to Go trials (Azizian et al., 2006). On the Simon task, the P3 is smallest for incongruent trials relative to congruent trials (Galashan et al., 2008; Cespón, Galdo-Álvarez & Díaz, 2013). For both the Go/NoGo and Simon task, the amplitude of the P3 is attenuated in older adults (Cheng, Tsai, & Cheng, 2019; Van der Lubbe & Verleger, 2002). This suggests that a common cognitive process which is indexed by the P3 underpins performance in the Go/NoGo and Simon task.

It is tempting to assume that the N2 and P3 in the Go/NoGo paradigm and Simon paradigm reflect the same underlying cognitive processes. However, there is no empirical evidence to support this as to date no single study has investigated how the two tasks are correlated using behavioural or electrophysiological methods. Chapter 8 in this thesis will investigate whether measures from a sample of younger and older adults who completed both the Simon and Go/NoGo task are associated. The findings of this study will provide key insights into the functional significance of the N2 on these tasks, as while both paradigms share a common element of inhibition, it is argued that the Go/NoGo task requires pre-potent response inhibition/conflict monitoring, and the Simon task requires inhibition to distractor interference. In contrast, if the inhibition processes engaged in these two tasks are underpinned by the same cognitive construct, it is expected that the amplitude effects will be negatively correlated (Figure 2).

Moreover, the findings also have implications for the literature aiming to understand whether monolinguals and bilinguals engage different cognitive processes on non-verbal cognitive processing tasks. While some researchers are calling for more papers utilising neuroimaging techniques such as ERPs (van Heuven & Coderre, 2015), other researchers are arguing that the interpretation of neural differences between language groups is risky due to valence ambiguity, i.e., lack of clarity on whether larger amplitudes represent better or worse performance (Paap, Johnson & Sawi, 2015). It will also help to differentiate between different components of inhibition and in turn may help explain inconsistencies between the comparisons of monolinguals and bilinguals on inhibition tasks. It may be that bilinguals experience an advantage in specific inhibition processes or domain-general inhibition advantage as reported in other neuroimaging techniques (Luk et al, 2010).

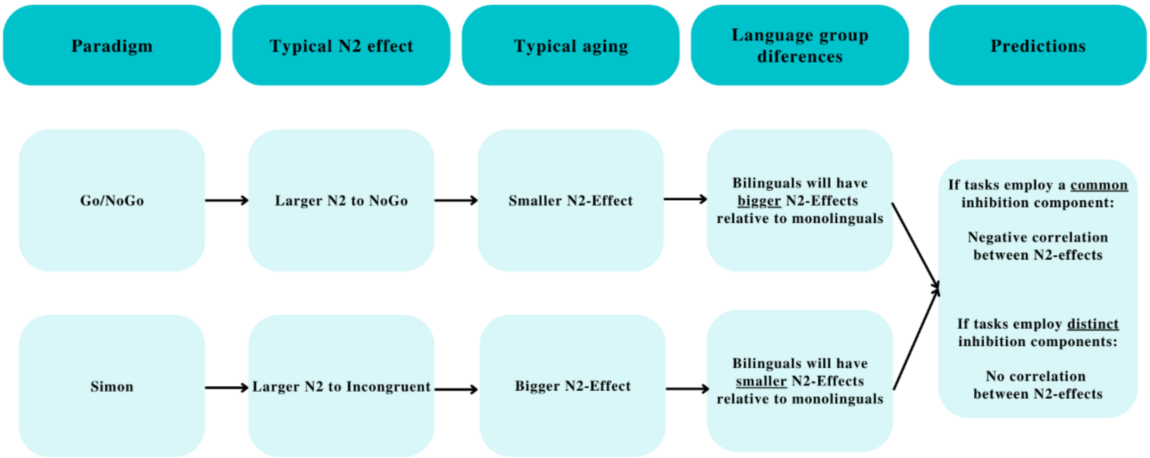

Figure 2. Diagram outlining how past literature has guided potential language group differences, and predictions for associations between paradigms.

3.7. SUMMARY OF INTRODUCTORY CHAPTERS

Bilingualism leads to a myriad of cognitive changes; these changes are complex and interact with factors such as participant age and task demands. This introductory chapter has provided a broad overview of how knowing more than one language may have positive consequences for cognition, but that these changes are not always easily observable. Chapter 1 reviewed the wealth of literature employing behavioural measures to outline how the cognitive demands of bilingualism can confer benefits to executive function processes, and how these cognitive changes are most consistently observed in older adults and under high task demands.

In Chapter 2, the benefits of using event-related potentials to investigate the consequences of bilingualism on executive function processes were highlighted. High temporal resolution along with the sensitive, covert measuring properties of ERPs can provide key insight. Research using ERPs to measure cognitive processing differences in monolingual and bilinguals younger and older adults is sparse, and the results across the small collection of extant literature are not underpinned by a clear theoretical framework. It is clear that differences between language groups manifest differently across tasks and across ages. However, the mechanisms underpinning these language group differences remain unclear. To move forward, research needs to focus on understanding the processes underlying language group differences on executive function tasks while employing clear theories to interpret language group differences.

The current thesis aims to investigate how bilingualism is an experiential factor which may affect age-related changes in executive function under low and high task demands, specifically it aimed to answer four research questions.:

RQ 1: Does bilingualism affect cognitive processing during inhibition of a pre-potent response in older adults?
RQ 2: Does bilingualism influence age-related changes in inhibition to interference?
RQ 3: Are there language group differences in non-inhibition processes such as attention and monitoring?
RQ 4: What is the functional significance of the N2 and P3 in non-verbal executive function tasks?

Chapter 6: Experiment 1 investigates the effects of bilingualism on age-related changes on cognitive control and attentional resource allocation through the use of a Go/NoGo paradigm with an older adult sample. This chapter also aimed to understand how task demands may impact observable cognitive control processing differences between the two language groups by manipulating perceptual similarity of the NoGo to the Go. Behavioural and electrophysiological measures were taken. The amplitude and latency of the N2 was recorded as an index of cognitive control allocation and conflict monitoring processing speed. Attentional resource allocation and stimuli classification speed was index through amplitude and latency of the P3.

It is hypothesised that as a result of extensive employment of domain-general inhibition processes during language control, older adult bilinguals will exhibit increased ability to regulate cognitive control resources to meet task demands relative to older adult monolinguals. Additionally, it is hypothesised that bilingualism will result in the adaptation of attentional resources in that bilinguals are better able to regulate attention. It is predicted that while older adult monolinguals will exhibit typical age-related attenuation of the N2-effect, older adult bilinguals will display larger N2-effects, especially when task demands are high, akin to younger adults. Moreover, it is predicted that bilinguals will exhibit larger P3 amplitude effects relative to monolinguals, reflecting increased ability to regulate attention.

Chapter 7: Experiment 2 employs a visual two-way Simon task to explore the effects of bilingualism on inhibition to interference in a group of younger and older adults. Reaction time and accuracy Simon effects are recorded and compared between age groups and language groups. At the neural level, increased interference to irrelevant stimuli will be indexed by differences in the amplitude of the N2 between congruent and incongruent stimuli. Amplitude and latency of the P3 will be recorded as an index of magnitude of attention devoted to a stimuli and speed of processing stimuli as a target or non-target.

It is hypothesised that the bilingual language experience will confer the ability to better inhibit interference to irrelevant stimuli relative to monolinguals. Moreover, it is hypothesised that age will interact with the ability to observe language group differences. Thus, it is predicted that while older adult monolinguals will exhibit larger Simon effects in RT, accuracy and N2 amplitude relative to younger adults, this pattern will not be observed in older adult bilinguals.

The effects of age on the slowing of inhibitory control and attentional processes will also be assessed using N2 and P3 latencies as indexes. It is hypothesised that increasing age will be associated with later latencies in both the N2 and P3, indexing slowing of both inhibitory control and attentional mechanisms. It is hypothesised that bilingualism will attenuate this slowing due to behavioural evidence suggesting that language experience can influence the trajectory of age-related slowing.

Chapter 8: Experiment 3 will address the issue of convergent validity between tasks proposed to measure common constructs of inhibitory control. Correlational analysis will be used to assess associations between behavioural and electrophysiological measures of inhibition, monitoring, and attention on the Simon and Go/NoGo task. It is hypothesised that inhibitory control performance on these tasks may be underpinned by inhibition constructs with shared variance, as a result it is predicted that there will be an association between the N2-effects on these paradigms.

Chapter 4: Methods

In 2000, Picton and colleagues developed guidelines for research employing the event-related potential (ERP) technique (Picton et al., 2000). These guidelines promoted methodological transparency through the clear reporting of key parameters in ERP studies. Given the advent of new methodological and statistical techniques, these were then updated in 2014 (Keil et al., 2014). The guidelines were developed to encourage researchers to clearly document and effectively communicate methodological choices in EEG/ERP research. Such transparency is integral to research given that research focusing on the effects of bilingualism on cognition - and the field of Psychology as a whole (Wiggins & Christopherson, 2019) - is argued to be suffering from a replication crisis (Paap, Johnson & Sawi, 2015).

Throughout the data processing and data analysis pipeline, the researcher must make choices that could potentially influence the latency, amplitude, and morphology of the final ERP waveform. The flexibility of choice with regards to the way researchers collect and analyse data has been referred to as *experimenter degrees of freedom* (Simmons, Nelson & Simonsohn, 2011). In ERP studies, common experimenter degrees of freedom include, but are not limited to, choice of reference electrodes, online/offline filtering, software packages and measurement time windows (for a comprehensive list see reporting guidelines; Keil et al., 2014).

Methodological transparency is pivotal to the production of replication studies as replication failures are increased when experimenter degrees of freedom are increased and when methodologies are not clearly reported (Forstmeier, Wagenmakers & Parker, 2017). Without clearly stating which reference electrode, filtering and software were used, a researcher intending to replicate a study may choose different parameters which may lead to different results and conclusions. For example, as discussed later in the section on filtering, a P600 ERP waveform, unfiltered and with 0.01Hz high-pass filter will show a standard P600 profile, but more aggressive high-pass filters, with cut-offs at 0.3Hz and above, distort the P600 waveform by reducing the amplitude of the component and introducing artefactual negative peaks either side of the positive peak.

However, despite the clear reporting guidelines for ERP studies (Picton et al., 2000; Keil et al., 2014), a review of 150 randomly selected ERP studies found that on average only 63% of guideline parameters were reported (Clayson et al., 2019). Underreporting of these parameters will contribute to the low replicability of ERP studies. Moreover, clear justification for parameters that are reported is good practice to ensure that certain steps have been decided a priori rather than due to exploratory analysis which could lead to potentially erroneous conclusions. This chapter will explain and justify methodological choices made during the data collection and data processing pipeline for the studies presented in this thesis.

4.1. CHOICE OF REFERENCE SITE

Voltages of scalp electrodes are measured relative to the chosen reference site, wherein the voltage is the difference in electrical potential between the scalp electrode and the reference electrode. The choice of an appropriate reference has long been debated since the first report of human EEG (Berger, 1929). As scalp electrodes are measured relative to the reference, different references will result in different measured effects (Yao et al., 2005). The differences are most stark in frontal sites, in contrast to the high convergent validity which is reported for different reference sites when measuring at posterior regions (Hagemann, Naumann & Thayer, 2001). Measured effects can differ in terms of amplitude, spatial distribution (Tian & Yao, 2013) and latency of the ERP (Tian et al., 2018). Differences in such measurements can lead to very different interpretations of the data thus it is important to clearly justify your choice of reference site.

Two commonly used references are the digitally linked mastoids (both bones behind the ear) and the average reference (average of all scalp electrodes) (Yang, Fan, Wang & Li, 2017). The selection of a reference site is a hotly debated topic within event-related potential research, as each option offers distinct advantages, but it is important to note that no reference site is without drawbacks. For example, the average reference assumes that the activity across all the scalp electrodes represents all the electrical activity generated in the brain. However, in reality there is inadequate spatial sampling as only the top of the participants head is covered in electrodes, leading to spatial distortions. Conversely, the mastoid reference assumes that the average potentials recorded over the two mastoids is close to zero, but there is not a genuinely electrically inactive reference site on the head (Katznelson, 1981 as cited in Hagemann, Naumann & Thayer, 2001). Despite this, it can be assumed that some sites on the head will be less active than others. This issue is especially pertinent for research recording and measuring activity at channels near the ears. It is recommended to avoid using a reference near the scalp location where the effect of interest is expected to be largest. If this is done, the reference will record the component of interest and subtract it from the data causing spatial distortion. This distortion will manifest as a counterintuitive pattern wherein the component of interest appears smallest at the region of the scalp where the absolute voltage is in fact largest, while also producing a large positive voltage at distant sites (Luck, 2014). Despite these drawbacks, one key benefit of the mastoid reference is its independence from electrode montages, meaning that results from different electrode caps and laboratories can be compared.

The studies in this thesis employed a mastoid reference as (1) the components of interest in these studies are not largest at areas near the mastoid, and (2) mastoid reference allows for comparison of ERPs with other labs with differing electrode montages.

4.2. FILTERING

Electroencephalography (EEG) recordings taken from electrodes on the scalp include both signal of interest and non-neural signal, such as environmental, instrumental, and physiological noise. It is important to remove non-neural signal as the presence of noise can mask the signal of interest. Filtering techniques can be used to selectively remove frequency bands that contain artefacts and noise, increasing the signal-to-noise ratio.

Slow drifts and skin potentials can create low frequency noise signals, but high pass filtering can be used to remove this low frequency noise from the data. High frequency noise signals can be generated by line noise (when recording data in an unshielded environment) and muscular activity. For example, wrinkling of the brow by the frontalis muscle generates activity at 30-40Hz and the masseter muscle, involved in chewing, is around 50-60Hz (O'Donnell, Berkhout, & Adey, 1974). Low pass filtering can be used to remove such noise from the raw data.

Although filtering can improve the signal-to-noise ratio, it is important to note that some filter settings can distort waveforms and lead to erroneous conclusions. Moreover, filter choices can vary greatly depending on the paradigm, recording environment and the participant population. For example, aggressive filters can distort the amplitude and timing of the signal of interest (Duncan-Johnson & Donchin, 1979). The effects of different filters on ERP waveforms have been demonstrated by Tanner and colleagues, who compared the effects of .01Hz, .1Hz, .3Hz, .7Hz and 1Hz high-pass filter on a simulated P600 component (see Figure 1; Tanner, Morgan-Short & Luck, 2015). As the high-pass filter increased to .3Hz and above, the peak amplitude of the component decreased and artefactual negative peaks either side of the positive peak were also induced by the aggressive filters.

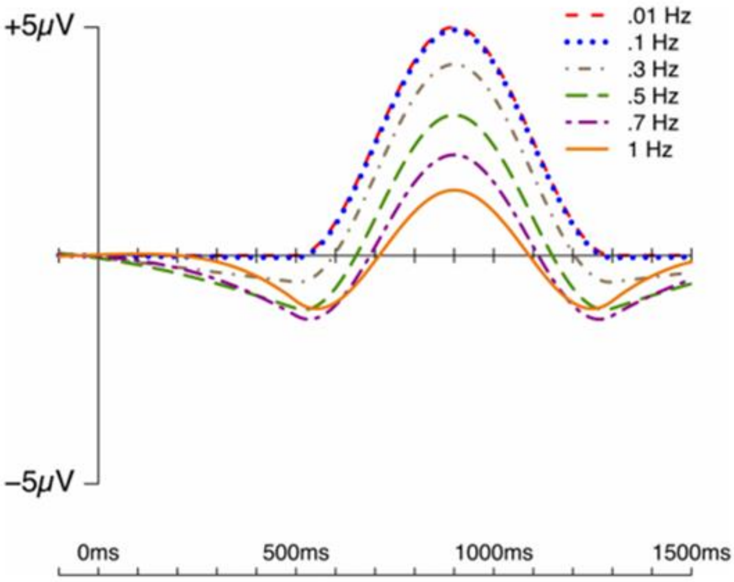

Figure 1. Effects of different high-pass filter settings (24dB/octave roll-off) on the simulated P600 component. Taken from Tanner, Morgan-Short & Luck, 2015.

Contrastingly, it has been reported that a .01Hz high-pass filter and a 30Hz low-pass filter produces almost no distortion into the ERP waveform whilst still removing low-frequency noise that could influence the waveforms. The use of 0.01Hz high-pass filter for adult and older adult population to successfully clean data without distortion is reiterated by several other researchers (Luck, 2014; Acunzo, MacKenzie & van Rossum, 2012).

Half-amplitude cut-off frequency refers to the frequency at which the amplitude is reduced by 50%. The rate at which this cut-off declines is called the roll-off. The studies presented in this thesis use a half-amplitude cut-off frequency of 30Hz to minimise the distortion to the data which can be induced by narrow frequency range. A relatively gradual slope of 12dB/octave roll-off was applied. Steeper slopes can produce distortion of the waveform through artefactual oscillations (Bénar et al., 2010; Luck, 2014).

The data in these studies were filtered offline with a band-pass filter of 0.01Hz to 30Hz. Moreover, as suggested by Acunzo, MacKenzie & van Rossum (2012), a grand average waveform was generated for the data presented in this thesis both with and without the selected filter applied to ensure that the overall morphology of the waveforms was not affected.

4.3. ARTEFACT DETECTION

Whilst filtering may attenuate some sources of artefacts (e.g., electrical activity), other artefacts which are smaller and more constant cannot be eliminated because they are typically present on many trials (Luck, 2014). Such artefacts can be problematic as they decrease the signal-to-noise (SNR) ratio of the averaged ERP waveform, reducing the experimenter's ability to detect true differences in the data. Moreover, if these artefacts are systematic, it is possible they may be mistaken for true effects leading the experiments to erroneous conclusions about their manipulation.

One possible source of such artefacts is blinks and eye movements. In visual ERP paradigms, participants are advised to maintain their gaze on a central fixation point and minimise eyeblinks as best they can. However, it is impossible for participants to avoid blinking entirely, and lateralised stimuli may induce horizontal eye movements. Such ocular artefacts are problematic, given that they are much larger than the signal of interest (see Figure 2).

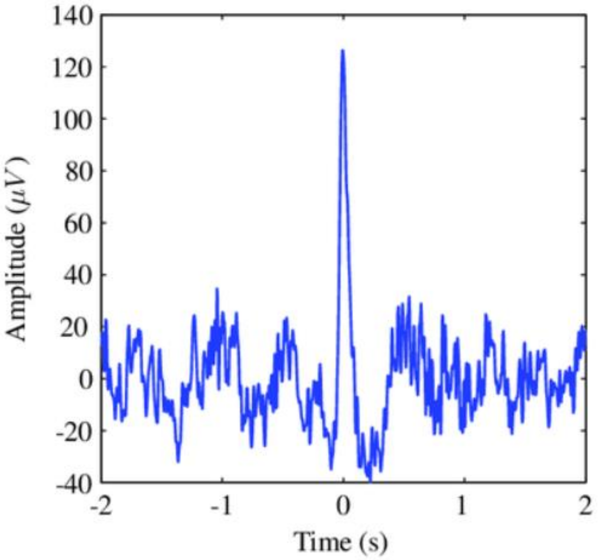

Figure 2. An example of an eye-blink evoked potential. Taken from Erkens & Molin (2008).

There are two approaches to managing ocular artefacts and artefacts from other sources; one approach is removing trials containing blinks and eye movements (artefact rejection), and the second approach is to correct for them (artefact correction). Firstly, artefact rejection refers to the procedure of identifying trials with excessive artefacts, induced by blinks, muscular movements, or drift, and rejecting these trials for inclusion in the final event-related potential waveform that is generated from the participants data. The simplest method for this is to determine a fixed amplitude threshold, such as 50μV, and selectively remove any epochs which exceed this threshold. However, one paper suggests that this method suffers from several caveats, namely that EOG rejection also results in rejection of EEG activity that correlates highly with EOG activity (Verleger, Gasser, & Möcks, 1982), and that adequate rejection criteria can be hard to establish (Verleger, 1993). Another drawback of using the artefact rejection approach is that if many trials need to be rejected then the number of trials remaining for the averaged ERP waveform will be reduced (Luck, 2012).

A second approach, artefact correction, estimates the artefactual activity and subtracts it out of the participants data, leaving artefact-free EEG that can be included in the averaged ERP waveforms. One of these artefact correction procedures is Independent Component Analysis (ICA). Briefly, ICA determines what spatially fixed and temporally independent components compose an observed waveform and can been used as a tool to separate artefactual data, such as blinks and eye movements, from the signal of interest (for discussion see Mennes et al., 2010). However, there are three main caveats to artefact correction techniques. Firstly, some of these artefact correction techniques are prone to systematic errors in estimating and removing the artefactual activity (Lins et al., 1993). Secondly, artefact correction may not be effective on data which contains eye movements (Croft & Barry, 2000), and while there are several possible algorithms for ICA, it is not always possible to apply ICA effectively (Mennes et al., 2010). Thirdly, the computation time and computer memory required to perform artefact correction procedures (including but not limited to ICA) can exceed available resources. Despite these two approaches being hotly debated, there is limited literature comparing the outcomes of artefact rejection to artefact correction. However, due to the drawbacks of artefact correction procedures, an artefact rejection approach was used in this thesis[6]. This method will be described below.

Before artefact detection procedures were undertaken, average waveforms were generated in ERPLab Toolbox (Lopez-Calderon & Luck, 2014), within EEGLab Toolbox (Delorme & Makeig, 2004) on version R2015b of MATLAB (The Mathworks, Inc., Natick, MA, USA) for each participant. Visual inspection of these waveforms was carried out to

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[6] To ensure that the artefact rejection approach did not influence or bias the data, both artefact correction and artefact rejection procedures computed on a subset of the data from the Go/NoGo paradigm. It was determined that for this subset, the two artefact detection approaches did not differ. That is, waveforms were visually comparable and patterns of significance regarding trial type differences remained the same.

identify any artefacts affecting the data and/or any individual electrode issues. This resulted in two waveforms generated for each participant: one waveform with and one without artefact detection. This facilitated a comparison between the waveforms to ensure that the overall morphology of the waveform had not changed and that only noise had been removed.

Ocular artefacts such as blinks and eye movements were detected using the ERPLab Toolbox (Lopez-Calderon & Luck, 2014), within EEGLab Toolbox (Delorme & Makeig, 2004) on version R2015b of MATLAB (The Mathworks, Inc., Natick, MA, USA). The moving window peak-to-peak procedure was used, wherein voltages exceeding a set threshold within that window are flagged. For the components measured in this thesis (N2 and P3), a period of -200 to 800ms was selected. In the chosen time window, any voltage change that exceeded a certain threshold within a 200ms time frame on channels VEOG (vertical eye channel), EOG1 (under left eye), EOG2 (to the side of right eye) and A2 (right mastoid) was identified as a blink. Activity identified as characteristic of oculomotor were removed from analysis. A time window of 200ms was chosen, as this is the average time of a blink, but blinks can last up to 400ms and can have a magnitude more than 10 times that of cortical signals (Joyce, Gorodnitsky & Kutas, 2004).

To avoid selecting and removing data that was not oculomotor and was in fact true data, firstly a voltage threshold of +/-200µv was selected for each individual. A threshold of +/-200µv was initially chosen as a typical blink is over 100µv (Woodman, 2010) and eye movements are 20µv per degree of eye movement (Navarro, Vázquez & Guillén, 2018). Average waveforms were generated using data with artefact rejection procedures at +/-200µv and were visually inspected to ensure all blinks and eye movements had been removed from the data. This threshold was then decreased until all eye movements were removed without removing the signal of interest. An individual threshold was found for each participant as there is individual variability in the amplitude of ocular activity (Jervis, Ifeachor & Allen, 1988).

4.4. QUANTIFICATION OF EVENT-RELATED POTENTIALS

When employing the event-related potential technique, measurement procedures must be undertaken to facilitate the comparison of the amplitude and latency of waveforms between groups and/or conditions. There are several possible ways of quantifying amplitude and latency: a review of 446 published articles from three leading event-related potential journals (Psychophysiology, International Journal of Psychophysiology, and Neuropsychologia) reported that for measurement of ERP amplitude, the majority of articles employed a mean amplitude measurement (75.6%) and/or used a peak amplitude measurement (42.4%) and only a small number used an adaptive mean measurement approach (4.9%). For latency measures, the majority of articles utilised a peak latency approach (80.9%) and only one paper used a centroid latency approach (0.5%) (Clayson, Baldwin & Larson, 2013).

Measures of event-related potentials can be biased by background noise from artefact sources such as muscular activity, electrocardiographic activity, skin potentials and electrical noise in the environment. Averaging ERPs across many trials should minimise non-systematic noise, however, residual noise can still remain. The accuracy of ERP measurements will decrease as noise in the ERP increases, so it is important to choose an extraction method that reduces the bias imposed by noise thus increasing the reliability of ERP measurements.

With regards to measuring the amplitude of an event-related potential, it is argued that peak amplitude is heavily influenced by high-frequency noise which can exaggerate the amplitude of the peak (Luck, 2014). Moreover, peak amplitude can still be biased by noise even after low-pass filtering has taken place (Woodman, 2010). In contrast, it is suggested that any non-systematic noise will be averaged out across many trials when using the mean amplitude approach (Luck, 2014). When directly comparing the mean and peak approaches of measuring amplitude, mean amplitude is reported to be a more robust measurement against increases in background noise, whilst peak amplitude consistently overestimated the true measurement of the ERP waveform (Clayson, Baldwin & Larson, 2013). When measuring the latency of a component, two common measures are peak latency (time at which the component reaches its maximum or minimum point) and centroid latency (an area-based approach analogous to mean latency) (Woodman, 2010). Peak latency is less susceptible to bias as noise increases but is more variable compared to the centroid latency measure (Clayson, Baldwin & Larson, 2013).

Different measurement techniques can result in different results and conclusions, so the comparison of findings between ERP papers can be facilitated through the use of comparable quantification approaches. A review reported that over 80% of studies employed a peak latency approach and over 75% of articles reported a mean amplitude measurement approach (Clayson, Baldwin & Larson, 2013). Thus, alongside the advantages described above, the use of mean amplitude and peak latency measures in this thesis will be most conducive to allowing comparisons of results between the current studies and previous studies.

4.5. MEASUREMENT PARAMETERS

One of the best ways to reduce experimenter bias despite the large experimenter degrees of freedom within event-related potential research is to define measurement windows and electrode sites a priori before seeing the data (Luck & Gaspelin, 2017). Past research using similar paradigms can be used to guide these analysis parameters. However, despite the latest publication guidelines stating that measurement windows and electrode site choices must be well justified (Keil et al., 2014), only a very small number of articles report whether a priori temporal windows (3%) and electrode sites (5%) were used (Clayson, Carbine, Baldwin & Larson, 2019).

For the ERP components measured in the current studies, previous research was used to help identify appropriate time windows. Papers employing both the Go/NoGo and Simon task were reviewed in order the understand common time windows and electrode site choices for the components of interest. Additionally, the electrode site choices have been guided by past research reporting the spatial distribution of the component outside of these paradigms. Across all three studies, two event-related potentials were measured: the N2 and P3, and the same time windows were used to measure mean amplitude and peak latency for all three studies. The review of this literature is outlined below.

4.5.1. N2

Electrode site choice

The N2 is a stimulus-locked ERP that appears 200-400s post stimulus (for review see: Pires et al., 2014). There is a wealth of research supporting how the N2 has a fronto-central distribution in Go/NoGo paradigms (for review see Folstein & Van Petten, 2008), especially the NoGo-N2 which has a well-established fronto-central distribution (e.g., Folstein & Van Petten, 2008; Nieuwenhuis et al., 2003). Moreover, in older adults, the N2 in Go/NoGo studies is most commonly measured at fronto-central sites (Cheng, Tsai & Cheng, 2019).

Compared to the Go/NoGo literature, the literature examining the N2 during the Simon task is much more limited. One meta-analysis has highlighted how the N2 in spatial-response congruency tasks is commonly measured at fronto-central sites (Cespón, & Carreiras, 2020), but there is a dearth of research focusing on the distribution of the N2 in

Simon tasks. The limited literature that is available on the N2 in the Simon task has employed frontal sites to measure the N2 in the Simon task (Kousaie & Phillips, 2012; Kousaie & Phillips, 2017). Based on this literature, the N2 was measured at nine fronto-central electrode sites: FP1, AF3, F1, FPz, FP2, AF4, AFz, Fz, and F2 (Figure 3).

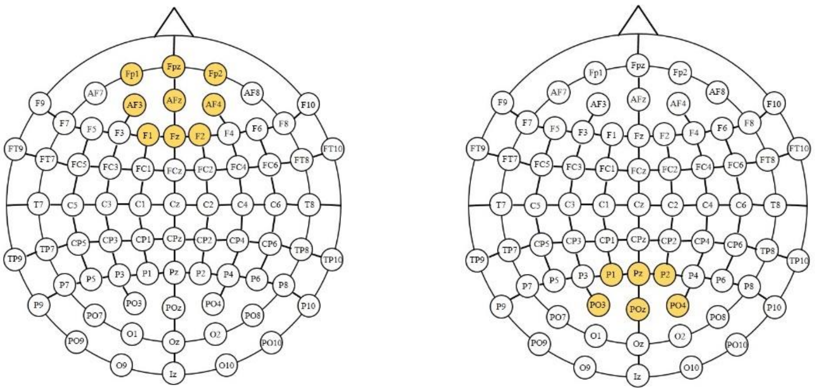

Figure 3. Electrode site choice for the N2 (left) and the P3 (right).

Time window choice

Appropriate time-windows for analysis were determined using three complementary approaches: (1) reviewing past research, (2) visual inspection and (3) 50ms bin-based analysis. The literature presented above was also used to guide time-window choices. This literature suggests that the N2 should be measured in 200-400ms time-window (for review see Falkenstein, Hoorman & Hohnsbein, 1999). In support of this, a more recent literature review revealed how the N2 peaking between 200 and 400ms post-stimulus is consistently hypothesised to reflect inhibitory control (Pires et al., 2014). Negative deflections outside of this 200-400ms window reflect may different cognitive processes. For example, negative deflections earlier such as in a 0-200ms time window (reflecting the N1 component) reflect automatic orientation of attention, and negative deflections later, such as in a 400-800ms time window (reflecting the N400 or N450 components), are more related to slower inhibition processes (such as semantic inhibition interference). Further to this, the N2 in Go/NoGo (e.g., Fernandez et al., 2013, 2014; Moreno et al., 2014) and Simon tasks (e.g., Kousaie & Phillips, 2012) is commonly measured in a time window starting 200-250ms post stimulus and ending 300-400ms post stimulus.

Further to the literature review, visual inspection of a grand average waveform was conducted. A grand average waveform was computed which included all participants in each paradigm, with one grand average for the Go/NoGo task and one for the Simon task. These grand average ERPs were visually inspected to determine if the literature-driven time window was appropriate. Visual inspection supported the time-window choice, as the window adequately captured the component of interest. Visual inspection is key at this stage as event-related potentials can vary from task to task, visual inspection is important to ensure that the ERP components were fully captured by the selected time window, and that the time window does not overlap with preceding or subsequent components. However, it is important to note that determining time windows based on visual inspection alone results in one key issue - the inflation of Type I error rates (Keil, 2013). When observed waveforms are used to determine how data are quantified and analysed, the likelihood that the difference will be significant increases, even if this difference represents noise rather than a robust and reliable effect.

This brings us to the third approach used to determine time windows – a 50ms bin-based analysis. This approach has been suggested by several researchers as unbiased, useful way to help capture differences in an ERP (e.g., Kappenman & Luck, 2016; Keil, 2013). To conduct this analysis, the mean amplitude of the N2 was measured over every consecutive 50ms time bin with a 10ms overlap with the previous bin (i.e., 0-50, 40-90, 80-120), from 200 - 800ms. A repeated measure ANOVA was computed with time and condition (Go/NoGo) as independent factors and amplitude as a dependent factor, multiple comparisons were adjusted for using Greenhouse Geisser epsilon correction. This 100ms bin-based analysis revealed that the difference between the conditions began at bin 280-330ms and ended at 400-450ms bin.

Using the three approaches described above, a 250-400ms post-stimulus time window was chosen. Thus, the mean amplitude (μV) of the N2 was calculated as the average amplitude during a 250 – 400ms post-stimulus time window, relative to a -200 – 0ms pre-stimulus baseline period, relative to a -200 - 0ms pre-stimulus baseline period. Peak latency (in milliseconds) was calculated as the time at which the most negative peak occurred between 250 - 400ms post-stimulus.

4.5.2. P3

The P3 is an exogenous, time-locked component that appears 300-600ms post-stimulus onset with a parietal topographical distribution (e.g., Gajewski & Falkenstein, 2011, Polich, 2007). As with the N2, the electrode sites were determined through reviewing past literature. Previous research has documented the centro-parietal distribution of the P3b in tasks involving inhibition (Falkenstein et al., 2000; Gajewski & Falkenstein, 2011; Polich, 2007), including in the Go/NoGo task (Bruin & Wijers, 2002; Fallgatter & Strik, 1999) and the Simon task (Frühholz, et al., 2011). In light of this research, the P3 component was analysed at electrode sites P1, Pz, P2, PO3, POz, PO4 (Figure 1 above).

For the determination of time windows, this was done through the three-method approach described for the N2: (1) a literature review, (2) visual inspection and (3) 50-ms bin-based analysis. A review of the same literature used to guide electrode site choice highlighted how past working measuring the P300 in cognitive control paradigms has utilised a 300-600ms time-window analysis, as the P300 tends to peak in this timeframe (Bruin & Wijers, 2002; Falkenstein et al., 2000; Fallgatter & Strik, 1999; Frühholz, et al., 2011; Gajewski & Falkenstein, 2011; Polich, 2007). Secondly, a visual inspection of a grand average ERP generated from all participants supported the literature-driven time window choice as the time-window adequately captured the P300 without including overlap from preceding or subsequent components. Thirdly, the mean amplitude of the P3 was measured over every consecutive 50ms time bin, from 300 - 1000ms at electrode sites P1, Pz, P2, PO3, POz, PO4. A repeated measures ANOVA was computed with time (bin) and condition (Go/NoGo) as independent factors and amplitude as a dependent factor, multiple comparisons were adjusted for using Greenhouse Geisser epsilon correction. This 50ms bin-based analysis confirmed the 300-600ms time window choice. This approach has been suggested by several researchers as unbiased, useful was to help capture differences in an ERP (e.g., Kappenman & Luck, 2016; Keil, 2013).

Using the three complementary approaches, a time-window of 300-600 post stimulus was chose. Thus, the mean amplitude (in μV) of the P3 was calculated as the average amplitude in a time window of 300 - 600ms post-stimulus onset, relative to a -200 – 0ms pre-stimulus baseline period. The peak latency (ms) of the P3 was calculated as the most positive peak in a 300-600ms time window.

4.6. BASELINE CORRECTION

After extracting epochs from the continuous EEG, which includes a baseline period prior to the event of interest (typically 100-200ms) and a period after the event (500ms-1500ms depending on the component of interest), a baseline correction procedure will be undertaken.

Put simply, baseline correction subtracts the voltage measured during the pre-stimulus window from the voltage measured in the post-stimulus window. Baseline correction minimises the effects of vertical offsets and drifts that can be caused by skin hydration and static changes in the electrodes - factors which may vary across participants and impact greatly on the ERP amplitude measures (Woodman, 2010).

Luck (2014) recommends using a baseline that is at least 20% of the overall epoch duration. It is also important to note that the pre-stimulus baseline period should be a multiple of 100 because this will cancel out any alpha-frequency (10Hz) EEG oscillations. The initial epochs in this study were -200 to 1500ms[7], and the epoch duration in these studies for artefact detection were 1000ms (-200 to 800ms; 20% = 200ms). The data presented in this thesis were baseline corrected to an epoch -200 – 0ms relative to stimulus onset. A 200ms reflect the benefits of a longer baseline whilst reducing the costs of a longer baseline. A baseline of 100ms may be too short and will not provide an accurate estimate of the true voltage offset and in turn a less precise measure of post stimulus amplitudes. However, 300ms baseline may be too long, and a baseline that is too long may contain ERP activity from the previous trial which will contaminate the baseline. Moreover, a baseline of -200 to 0ms has been shown to be associated with better internal consistency than other baseline line correction time windows (Klawohn et al., 2020).

4.7. SAMPLE SIZE

Studies utilising small sample sizes can suffer from a myriad of negative effects, such as low statistical power, low reproducibility of effects and reduction in the likelihood that statistically significant results reflect true effects (Button et al., 2013). In line with this, Paap and colleagues argue that research comparing the performance of monolinguals and bilinguals on cognitive processing paradigms are often underpowered due to "risky small numbers" of participants (Paap, Johnson & Sawi, 2014). Moreover, disclosure on how sample sizes were determined reduces the possibility of biased flexibility in data collection i.e., ending data collection as soon as data yields a significant result (Simmons, Nelson & Simonsohn, 2011). For these reasons, in 2014, the Psychological Science Journal amended its methods section requirements to encourage researchers to report more methodological

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[7] It should be noted that artefact detections procedures were performed on a -200 to 800ms epoch. Creating initial epochs longer than the artefact detection window (-200 to 1500ms in this case) can be useful for looking for artefacts which may occur just before or after the window of interest (-200 to 800ms). For example, it is possible to spot any blinks or artefacts pre- or post-800ms which may influence the data.

details on factors such as how sample size was determined (Eich, 2014). To preclude claims concerning underpowered studies and biased flexibility about the work presented here, this thesis utilised power analysis calculations in order to determine an appropriate sample size.

A power analysis was computed using G*Power 3.1 software (Faul et al., 2007). To do so, effect size (η_p^2) estimates for the power analysis calculation were guided by effect sizes previously reported in comparable research papers. Specifically, effect sizes for interactions between language group and condition on the amplitude of the N2 amplitude on a Go/NoGo task with younger adults (η_p^2 = .16; Moreno et al., 2014). G*Power indicated that for the Go/NoGo task in this thesis, in order to detect an effect of partial eta squared = .16, with 80% power in a repeated measures 2 x 2 Mixed ANOVA (two groups, alpha = .05, non-sphericity correction = 1), a minimum sample of size 50 was required (25 per group). This aligns with papers suggesting that for a medium effect size, 52 participants are required to reach 80% power when investigating the main effects of one variable in a 2x2 repeated measures ANOVA (Brysbaert, 2019). A total of 69 participants were recruited for this study.

It is important to note that final participant numbers exceeded the sample size suggested by G*Power for a multitude of reasons. Firstly, a more conservative sample was recruited in order to account for potential participant attrition as a result of poor data quality or omission of participants as a result of Montreal Cognitive Assessment Scores (MoCA). Secondly, as Albers and Lakens (2018) demonstrate, using previously observed sample effect sizes (effect sizes reported in individual studies) as estimates when determining power can result in interesting effects being overlooked. Sample effect size overestimates the true population effect size, often leading to underpowered studies.

For the Simon task, previous research has only reported main effects of language group for the P3 for younger adults (η_p^2 = .11; Kousaie and Phillips, 2012), and the N2 for older adults (η_p^2 = .11; Kousaie and Phillips, 2017). Given the similarity to the Go/NoGo effect sizes, similar power calculations were concluded for the Simon task in this thesis. With an alpha of .05 and power of 80%, the projected sample size needed with this effect size is approximately 51 for the simplest between group comparison. As a result, we intended to investigate both the effects of age (younger vs older adults) and language (monolingual vs bilinguals), we aimed to get a minimum 25 participants in each of our four samples (younger adult monolingual; younger adult bilingual; older adult monolingual; older adult bilingual), allowing for at least 50 participants in each of our between-group comparisons. However, due to COVID-19 inducing complete cessation of data collection, only 24 younger adults and 42 older adults were collected. Despite not reaching the power estimates proposed by G*Power, it is reported that with robust effect sizes (>1.5 µV), 20 subjects per group and 30 trials per individual is sufficient to reach 80% power (Gibney et al., 2020), a criterion that was met in our data.

Chapter 5: Experimental Methodology

The methodologies of the three experimental chapters comprising this thesis share commonalities in areas such as participant recruitment, language group definitions and EEG methodologies. For that reason, the common methodologies for the three experiments will be presented together here for brevity. However, while the experimental chapters share some common participants, there are differences in sample sizes and distinct paradigms are used. As a result, information regarding demographics, language information and task-specific methodology is then presented separately for each chapter.

5.1. PARTICIPANTS

Participants were recruited via flyers or word-of-mouth and given either £20 or course credits as reimbursement (see Appendix A). Information sheets were provided before the start of the experiments and all participants provided voluntary informed consent, and at the end of the experiments, participants were verbally debriefed. All procedures were approved by the School of Psychology Ethics Committee. All data were kept in secure locations and identifiable information remained separate from anonymised questionnaires and EEG data in accordance with General Data Protection Regulation (GDPR) guidelines. All participants reported normal or corrected-to-normal vision and hearing, and no participants reported any psychiatric or neurological disorders.

5.2. LANGUAGE GROUP OPERATIONALISATION

Participants were asked to self-report languages spoken, age of acquisition (AoA), and percentage of daily usage for first (L1) and second language (L2) (Table 1). Proficiency was self-reported for speaking, comprehension, reading and writing on a 7-point Likert scale. For instance, the Likert scale for speaking proficiency was as follows: 1 = “I have no proficiency in this language”, 2 = “Only know some words and expressions”, 4 = “Can carry out basic conversations”, 6 = “Can carry out extended conversations”, 7 = “I have native-like proficiency in this language”.

Self-reported L2 proficiency is an accurate predictor of second-language performance and is strongly correlated with behavioural proficiency measures (Marian et al., 2007). Moreover, second language proficiency in speaking and comprehension have been identified as two important factors for describing degree of bilingualism (Anderson et al., 2018). Based on this, an average score was calculated from self-reported L2 speaking and comprehension proficiency.

Average scores of L2 understanding and speaking proficiency have previously been used to categorise individuals into language groups (e.g., Paap & Greenberg, 2013; Pelham & Abrams, 2014). Pelham and Abrams (2014) required monolinguals to score 3 or below (out of 10), indicating "fair" proficiency. Paap and Greenberg (2013) classified participants as monolinguals if they scored a 3 out of 7 or below, referring to "intermediate" proficiency in their scale. Given that research has identified that how second language proficiency modulates executive control in bilinguals (e.g., Singh & Mishra, 2013), we wanted to ensure we included low L2 proficiency bilinguals in the sample. Individuals who scored 3/7 or below were categorised as monolingual, and individuals who scored above 3/7 (can at least carry out basic conversations) were categorised as bilingual. Participants were asked to report the percentage of time spent using each language. All monolinguals reported speaking 0% L2 at home. All participants were born inside the UK.

It is important to note that *how* bilingualism is operationalised can change the statistical pattern of results (Champoux-Larsson & Dylman, 2021). Therefore, I wanted to understand whether changing the operationalisation of bilingualism in this thesis would change the pattern of results. To do so, a short analysis was performed to determine whether changing the cut-off point of 3/7 would affect the statistical pattern of results in the data. The pattern remained the same when decreasing the cut off (to 2) or increasing to (to 4). Moreover, when only extreme responses were used to created groups (true monolinguals[8] vs highly proficient bilinguals[9]), the pattern of statistical significance remained the same for all experimental chapters (see Appendix C and E).

5.3. DEMOGRAPHIC VARIABLES

As described earlier in the introductory chapters, participant-related characteristics outside of bilingualism can potentially confound language group effects. For this reason, several demographic factors were self-reported by participants to ensure parity between groups.

5.3.1. Handedness

Handedness (either being left dominant, right dominant, or mixed dominance in hand use) has been shown to influence brain imaging results. Namely, differences in patterns of hemispheric asymmetry for language between left and right handers. That is, language

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[8] Individuals with an L2 composite proficiency of 1 or 2 were included in the monolingual group.
[9] Individuals with an L2 composite proficiency of 5, 6, or 7 were included in the bilingual group.

lateralisation is more common in right-handers (~90% of the population) relative to left-handers in whom the lateralisation is less extreme (for meta-analysis see Carey & Johnstone, 2014). This reduction in lateralisation is also extended to other domains such as face perception and body perception (Johnstone et al., 2021). Brain activity differences between left and right handers are also pronounced on studies employing event-related potentials, even on tasks which do not involve language. For example, the amplitude and latency of the N2 and the P3 has been shown to differ between left and right handers (Alexander & Polich, 2007; Polich & Hoffman, 1998).

For these reasons, it was important to ensure parity between groups in terms of the distribution of left, mixed and right handers in our sample, to minimise possible artefactual topographical distribution effects. To do so, the Edinburgh Handedness Inventory (Oldfield, 1971) was completed by participants. This categorised individuals as left, mixed or right handers.

5.3.2. Cognitive Decline

Cognitive decline, defined as non-pathological loss in cognitive function, is common in older adults (Nilson, 2003; Salthouse, 1996). However, cognitive decline beyond healthy aging may be indicative of pathologies such as Mild Cognitive Impairment (MCI) or Alzheimer's Disease (AD) (Albert et al., 2001; Kirova et al., 2015). Individuals with diagnoses of MCI or AD are reported to experience a decline in executive function performance (Albert et al., 2001; Kirova et al., 2015). Therefore, it is important to measure for the presence of cognitive decline to eliminate the possibility of confounds on the results of the executive function tests in this thesis. To do so, the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) was administered to all older adult participants. The MoCA has been shown to be one of the best tools to discriminate between individuals who no cognitive impairment and those with MCI, with over 90% sensitivity (Nasreddine et al., 2005). It is also shown to be an accurate detector of AD (Nasreddine et al., 2005; Pinto et al., 2019).

5.3.3. Socio-economic status (SES)

As described in the introductory chapter, socio-economic status (SES) has been shown to influence executive function (EF) (e.g., Noble et al., 2005; Piccolo et al., 2016a,b). However, it is unclear how socio-economic status and bilingualism may interact. Therefore, it is imperative to measure socio-economic status within the sample of participants in this thesis to circumvent the argument that any possible language group differences are driven by SES differences. To do so, the Barratt Simplified Measure of Social Status (BSMSS; Barratt, 2006) was employed. Participants were required to self-report level of education and occupation for themselves, parents, and any spouse. The summed score is a weighted total with a 2:1 ratio for education to occupation. For individuals in families headed by a single parent, or those without a spouse, scores were adjusted accordingly. From these responses, a total composite score was calculated which ranged from 8 (low SES) to 66 (high SES).

5.3.4. Lifestyle factors

Alongside engagement in cognitive leisure activities (such as bilingualism), it is well established that engagement in physical exercise can influence cognitive and brain plasticity across adulthood (Kramer et al., 2004), possibly even leading to a reduction in memory impairment in older adults (Erickson et al., 2012). More specifically, exercise has a beneficial effect on outcomes of executive function tasks in older adults (for meta-analysis see Chen et al., 2020). Such findings extend to research employing the electrophysiological technique, with findings that older adults who engaged in regular physical activity exhibited improved attentional resource allocation processes - as indexed by larger P3 amplitudes - compared to older adults who had a sedentary lifestyle (Fong et al., 2014) or engaged in irregular physical activity (Dai, et al., 2013). Conversely, factors such as cigarette smoking and higher alcohol consumption have been shown to impair cognitive control in Go/NoGo paradigms as indexed by attenuated N2 and P3 components (Buzzell, et al., 2014; Oddy & Barry, 2009).

Due to the potential impact of such lifestyle factors on the amplitude and latency of the N2 and the P3, and executive function more generally, participants were asked to self-report their engagement with several lifestyle factors. Participants were asked to report the volume and frequency of alcohol intake, frequency of cigarette smoking, frequency of prohibited drug use, frequency of vigorous and moderate physical activity, frequency of muscle-strengthening exercise and sleep quality (see Appendix B for questionnaire). All 9 questions were phrased on a 5-point Likert Scale. For example, for the question “How often do you have a drink containing alcohol?” participants had the choice of responding 0 = “Never”, 1 = “Monthly or less”, 2 = “2-4 times a month”, 3 = “2-4 times a week”, 4 = “5 or more times a week”. A composite lifestyle score was generated from the responses to the nine questions, all responses with equal weight. This created a score from 0 – 36 points, with a lower score indicating a healthier lifestyle.

5.4. PARTICIPANT CHARACTERISTICS FOR EACH SAMPLE

5.4.1. Experiment 1: Go/NoGo

The sample for Experiment 1 (Go/NoGo task) was comprised of 69 older adults; twenty-eight monolinguals and 41 bilinguals, aged between 61 and 87 years (*M* = 72.22, *SD* = 6.41). All monolinguals reported their first language as English. In the bilingual group, individuals reported their first language as either English (*n* = 28) or Welsh (*n* = 13) and reported their second language as Welsh (*n* = 26), English (*n* = 13), French (*n* = 1) or German (*n* = 1). All bilinguals reported using the L2 at least some of the time, save for four individuals who reported 100% L1 use. Two of these four bilinguals scored 7/7 on proficiency and the remaining two scored 4/7. See Table 1 for a breakdown of self-reported L1 and L2 language proficiency. Participants also completed the demographic questionnaires as described earlier[10]. Monolingual and bilingual participants did not differ on demographic measures (Table 2).

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[10] Only a subset of participants completed the lifestyle questionnaire (monolinguals = 22/28, bilinguals = 38/41).

Table 1. Self-reported L1 and L2 proficiency for Experiment 1 (Go/NoGo).

	Speaking		Comprehending		Reading		Writing		Composite	
Language	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2
Monolinguals (*n* = 28)	7.00 (.00)	1.41 (.69)	7.00 (.00)	1.86 (.97)	7.00 (.00)	1.46 (.87)	6.96 (.18)	1.23 (.58)	7.00 (.00)	1.63 (.70)
Bilinguals (*n* = 41)	6.94 (.28)	5.97 (1.32)	6.97 (.15)	5.96 (1.21)	6.97 (.15)	5.44 (1.88)	6.83 (.47)	5.36 (1.73)	6.96 (.16)	5.96 (1.21)
Sig.	.168	**<.001***	.413	**<.001***	.413	**<.001***	.103	**<.001***	.090	**<.001***

Note: Standard deviations are in parenthesis. Scores are from 1 to 7, with a higher score indicating a higher proficiency. Composite was created from Speaking and Comprehending proficiencies only. Groups were compared with an independent t-test. A * indicates a significant result.

Table 2. Demographic information across language groups for Experiment 1 (Go/NoGo).

	Gender *Females (Males)*	EHI *Left, Mixed, Right*	Age (years)	MoCA	SES	Lifestyle
Monolingual (*n* = 28)	13(15)	0, 10, 16	72.50 (*6.68*)	26.44 (*1.88*)	43.84 (*11.77*)	19.04 (*5.22*)
Bilinguals (*n* = 41)	24(17)	3, 12, 28	72.02 (*6.29*)	27.05 (*2.27*)	43.73 (*9.03*)	18.16 (*5.29*)
Sig.	.108	.101	.765	.384	.965	.532

Note: Mean (SD) are reported. The two language groups did not differ on these demographic measures.

5.4.2. Experiment 2: Visual two-way Simon.

The sample for Experiment 2 (Simon Task) included both younger and older adults. Twenty-four younger adults participated, aged between 18 and 29 years (*M* = 20.04, *SD* = 2.22), and forty-two older adults participated, aged between 61 and 87 years (*M* = 72.62, *SD* = 7.18). Using the pre-determined language group categorisation procedure as described in Section 5.2. *Language Group Operationalisation*, participants were categorised as monolingual or bilingual. This created four groups; younger adult monolingual (YAM; *n* = 9), younger adult bilingual (YAB; *n* = 15), older adult monolingual (OAM; *n* = 15) and older adult bilingual (OAB; *n* = 27).

In the younger adult sample, *n* = 15 participants were born in the UK, the remaining *n* = 9 participants were born in Afghanistan (*n* = 1), Bulgaria (*n* = 1), Burma/Myanmar (*n* = 1), China (*n* = 1), Cyprus (*n* = 1), Hungary (*n* = 1), Poland (*n* = 1), Romania (*n* = 1), and Spain (*n* = 1). Monolingual participants all reported their first language was English (*n* = 9). Younger adult bilingual participants reported their first language as either English (*n* = 7), Bulgarian (*n* =1), Finnish (*n* =1), Polish (*n* =1), Hungarian (*n* = 1), Greek (*n* = 1), Romanian (*n* = 1), Persian (*n* = 1) or Chinese (*n* = 1) and their second language as either English (*n* = 8), Welsh (*n* = 4), Spanish (*n* =1), Tulu (*n* = 1) and one participant did not report their L2 (see Table 3 for self-reported language proficiencies).

In the older adult sample, all older adult participants were born in the UK. All monolinguals reported their first language as English. Two monolinguals reported having a second language, which was reported as either Welsh (*n* = 1) or Spanish (*n* =1) but did not have a basic level of proficiency. In the bilingual older adult group, individuals reported their first language as either English (*n* = 16) or Welsh (*n* =11) and reported their second language as Welsh (*n* =15), English (*n* = 11) or French (*n* = 1).

Neither in the younger nor the older adult group did monolinguals and bilinguals differ on demographic variables (Table 4)[11].

5.4.3. Experiment 3: Cross-task convergence.

The sample comprised of 61 participants; 19 younger adults aged between 18 and 29 years (*M* = 20.05, *SD* = 2.41) and 42 older adults aged between 61 and 87 years (*M* = 72.55, *SD* = 7.09). For this chapter, participants were not categorised by language group.

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[11] All younger and older adult participants completed the questionnaire.

Table 3. Self-reported L1 and L2 proficiency for Experiment 2 (Simon task).

	Speaking		**Comprehending**		**Reading**		**Writing**		**Composite**	
Younger	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2
Monolinguals	7.00	1.22	7.00	1.44	7.00	1.11	7.00	1.11	7.00	1.22
(*n* = 9)	(0.00)	(0.44)	(0.00)	(0.53)	(0.00)	(0.33)	(0.00)	(0.33)	(0.00)	(0.34)
Bilinguals	6.93	5.46	6.93	6.00	6.60	5.46	6.53	5.20	6.75	5.53
(*n* = 15)	(0.25)	(1.41)	(0.93)	(0.92)	(0.83)	(1.92)	(0.63)	(1.74)	(0.38)	(1.38)
Sig.	.451	**.000***	.451	**.000***	.165	**.000***	**.041***	**.000***	.070	**.000***
Older	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2
Monolinguals	7.00	1.50	7.00	1.93	7.00	1.70	6.93	1.23	6.93	1.59
(*n* = 15)	(0.00)	(0.68)	(0.00)	(0.92)	(0.00)	(1.06)	(0.25)	(0.62)	(0.13)	(0.61)
Bilinguals	6.96	5.83	6.96	5.93	6.96	5.51	6.85	5.46	6.93	5.68
(*n* = 27)	(0.19)	(1.41)	(0.19)	(1.28)	(0.19)	(1.83)	(0.43)	(1.57)	(0.13)	(1.44)
Sig.	.463	**.000***	.463	**.000***	.463	**.000***	.512	**.000***	.178	**.000***

Note: Standard deviations are in parenthesis. Scores are from 0 to 7, with a higher score indicating a higher proficiency. Composite was created from Speaking and Comprehending proficiencies only. Groups were compared with an independent t-test. A * indicates a significant result.

Table 4. Demographic information across language groups for Experiment 2: Simon Task.

Younger Adults						
	Monolinguals (*n* = 9)	Bilinguals (*n* = 15)				
	M *(SD)*	M *(SD)*	*df*	*t*	*p*	Cohen's d
Age	19.67 *(1.12)*	20.27 *(2.68)*	22	-.634	.533	0.292
SES*	45.66 *(10.24)*	41.03 *(17.00)*	21.98	.833	.414	0.329
Lifestyle	14.12 *(2.53)*	13.53 *(4.76)*	21	.325	.748	0.154
Older Adults						
	Monolinguals (*n* = 15)	Bilinguals (*n* = 27)				
	M *(SD)*	M *(SD)*	*df*	*t*	*p*	Cohen's d
Age	74.27 *(7.86)*	72.07 *(6.77)*	40	.949	.328	0.299
SES*	42.52 *(13.88)*	45.19 *(8.16)*	40	-.787	.436	0.234
Lifestyle	18.86 *(5.05)*	18.15 *(5.81)*	39	.396	.694	0.130
MoCA	26.00 *(1.88)*	27.07 *(2.30)*	40	-1.54	.132	0.509

Note: There were no differences between the language groups on demographic measures. An asterisk (*) indicates equal variances not assumed. In these cases, values were adjusted for.

5.5. ELECTROENCEPHALOGORAPHY (EEG) METHODOLOGY

The three experiments constituting this thesis share commonalities in terms of the electroencephalography (EEG) procedures used for recording and pre-processing. To reduce redundancies, these common methodologies are presented here. In instances where the experiments differ, the methods are presented separately in each respective section.

5.5.1. EEG Recording

The experiments were conducted in a sound-attenuated room with participants 120cm away from the presentation screen. Stimuli were presented on a 1920 x 1080 Samsung HD LCD TV. A simulation PC running Presentation by Neuroal Systems (NBS; version 14.5) controlled the presentation of the stimuli for all paradigms. The data acquisition PC utilised ActiView605, BioSemi. The EEG was recorded continuously using a 64-channel pin type Ag-AgCl BioSemi Active 2 (Version 6.05, 2007) active electrode system. The electrodes were positioned according to the International 10/20 configuration system affixed to a BioSemi head cap. A sampling rate of 2048Hz and were amplified by a factor of 20,000. Reference electrodes comprised of electrodes over the left and right mastoid sites; ocular movements were recorded through a left infraorbital electrode and a right lateral canthus. Offsets for all electrodes were reduced and maintained at 25μv or below, this is conceptually related to the impendence. The acquisition of the EEG was recorded reference and filter-free.

5.5.2. EEG Pre-processing

EEG analysis was performed offline using the ERPLab Toolbox (Lopez-Calderon & Luck, 2014), within EEGLab Toolbox (Delorme & Makeig, 2004) on version R2015b of MATLAB (The Mathworks, Inc., Natick, MA, USA). Data were re-referenced offline to average of the left and right mastoid electrodes and filtered offline with an IIR Butterworth bandpass filter of 0.01Hz to 30Hz. A cut-off frequency of 30Hz and a 12dB/octave roll-off. Baseline correction was applied to all EEG data using a 200ms pre-stimulus epoch. Epochs of -200 – 1500ms were created[12].

A moving peak-to-peak amplitude method was used to identify activity characteristic of oculomotor, electromyographic or cardiac artefacts. A moving peak-to-peak window of 100ms in a -200-800ms time window was used. Trials were rejected if signal amplitude exceeded a threshold set for each individual participant in any EOG channel. Individual

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[12] This epoch is software dependant, and the length of the initial epoch (-200 to 1500ms) is independent of the epoch for artefact detection and rejection (-200 to 800ms).

thresholds were set as there is often significant variability across subjects in the size and shape of the voltage deflections produced by artefacts and EEG (Luck, 2014). Only trials that contained responses 200-1000ms after the stimulus onset were included for analysis.

5.6. BEHAVIOURAL DATA PROCESSING

Reaction times (ms) and accuracy (%) were extracted using ERPLab Toolbox (Lopez-Calderon & Luck, 2014), within EEGLab Toolbox (Delorme & Makeig, 2004) on version R2015b of MATLAB (The Mathworks, Inc., Natick, MA, USA).

5.6.1. Experiment 1: Go/NoGo

Mean reaction time (RT; ms) to Go stimuli was calculated. Accuracy for Go trials (% of correct hits) and NoGo trials (% of correctly withheld responses) was calculated. An overall accuracy score was also calculated (Go Accuracy + NoGo Accuracy / 2). A d prime (d') score was calculated for each participant (Z(hits) – Z(misses)). The d' score is a sensitivity index for signal detection and a larger d' indicates better signal discrimination (i.e., hitting Go trials and not responding to NoGo).

5.6.2. Experiment 2: Visual two-way Simon task

Reaction times (RT;ms) and accuracy (in %) were calculated using ERPLab Toolbox for each of the two conditions: congruent and incongruent. Accuracy was defined as the percentage of trials correctly responded to within the time frame (200 – 1500ms). The Simon effect was calculated for reaction time by deducting the reaction time for congruent trials from the reaction time incongruent trials. A larger, positive Simon effect in RT indicates a larger RT for incongruent trials. The Simon effect for accuracy was calculated by deducting the accuracy for congruent trials from incongruent trials. A larger, negative Simon effect in accuracy indicates a better accuracy for congruent trials. Trials with no registered responses were discarded from the analysis rather than categorising them as errors, as all trials required a response.

5.6.3. Experiment 3: Cross-task convergence: Measures of inhibition and monitoring

The Go/NoGo task is assumed to require conflict control to overcome the pre-potent Go response during NoGo trials, whilst still accurately detecting and responding to the Go trials. By deducting accuracy on NoGo trials from that of Go trials, we acquire the Go/NoGo-effect. This is used as a measure of inhibition (e.g., Gunnerud et al., 2020). Here, we will also utilise d prime (d') as a measure of effective inhibition.

In the Simon task, conflict is induced as a result of spatial-response incompatibility during incongruent trials. This conflict is reflected in larger RTs and poorer accuracy on incongruent trials, a pattern observed in the data in Experiment 2. The difference between RT and accuracy on incongruent and congruent trials (RT effect and accuracy effect) is commonly used as a measure of inhibition (for review see Lehtonen et al., 2018). For general task monitoring, reaction times on congruent (Simon) and Go trials (Go/NoGo) are commonly used as indices (see Lehtonen et al., 2018).

5.7. DATA EXCLUSION AND TECHNICAL ISSUES

5.7.1. Data exclusion procedure

Typically, in studies employing the event-related potential technique trials containing blinks, eye movements and other artifacts are removed from the averaged ERP waveform (Luck, 2012). As described in Chapter 4, this thesis has taken a rejection rather than correction approach to these artefacts.

As described in Chapter 4, for each participant, trials with excessive artefacts were removed from the data. The N2 component can require ~250 trials per condition and the large, late P3 component can be measured with only 35-60 trials per condition per subject (Woodman, 2010). Therefore, when deciding what the minimum trial count should be, I wanted to balance having clean data whilst still having sufficient power to measure the components of interest. Consequently, participants were required to have at least 30 trials remaining after artefact rejection for each relevant condition to be included in the analysis. This is based on reports that when averages comprise of 30 or more trials, the temporal sequence of ERP components can be reliably measured (Thigpen, Kappenman & Keil, 2017).

5.7.2. Experiment 1: Go/NoGo

With regards to behavioural data, four monolinguals and four bilinguals were found to have d' and RT scores 2 standard deviations +/- the mean. However, when these participants were retained for the behavioural analysis, all behavioural results remained in the same direction, so these participants remain in the analysis from hereon in. The sample remained at 28 monolinguals and 41 bilinguals.

The data collected for several older adult participants were of extremely low quality, containing excessive amounts of slow drift artefacts. It was determined that an equipment issue had been contributing to excessive artefacts, namely a cluster of faulty electrodes. As a result, two monolingual and nine bilingual participants were excluded. To rectify this issue, new electrodes were purchased, and subsequent participants data were recorded using the new electrode set. One older adult bilingual and two older adult monolingual participants data was subject to a technical error.

Participants were required to have at least 30 trials remaining after artefact rejection for each relevant condition to be included in the analysis. This is based on reports that when averages comprise of 30 or more trials, the temporal sequence of ERP components can be reliably measured (Thigpen, Kappenman & Keil, 2017). Five monolinguals and six bilinguals were moved due to excessive artefacts. This created a subsample of 19 monolinguals and 25 bilinguals. Event-related potentials were generated for each participant by averaging across trials for each electrode and condition. Language group grand averages were generated by averaging across the participants within each group.

For the perceptual similarity analysis, the mean number of trials contributing to the ERP was 139.84 (*SD* = 28.10) for Go trials, and 64.29 (*SD* = 17.11) for perceptually similar NoGo, and 62.97 (*SD* = 15.05) for perceptually dissimilar NoGo. These did not significant differ between the two language groups ($p > .50$).

5.7.3. Experiment 2: Visual two-way Simon task

With regards to behavioural data, we wanted to ensure that participants were performing above chance; as a result, participants were required to score over 50% accuracy on all four conditions to be included in the final data set. All younger adults exhibited accuracy over 50%. For older adults, this excluded 2 monolinguals and 5 bilinguals from the sample (all had an accuracy below 50%). Analyses were performed with and without these participants. There were no changes to the pattern of statistical significance. Analysis and graphs reported from hereon in will exclude these participants. This left a sample of 24 younger adults (monolinguals $n = 9$, bilinguals $n = 15$) and 35 older adults (monolinguals $n = 13$, bilinguals $n = 22$).

Previous work with younger adult on the Simon Task has reported a congruency effect size of ~2µV (Kousaie & Phillips, 2012b; 2017). It is reported that for robust effect sizes (>1.5 µV), 20 subjects per group and 30 trials per individual is sufficient to reach 80% power (Gibney et al., 2020). Therefore, a conservative cut-off of 25 trials was chosen to balance minimal participant exclusion alongside maintaining power for between and within subject analysis. This excluded two younger adult and eight older adult participants. Four older adults were also excluded as there was a technical problem during data collection which meant it was not possible to use their data. This left a final sample of 22 younger adults, (monolinguals *n* = 9, bilinguals *n* = 13). and 23 older adults (monolinguals *n* = 9, bilinguals *n* = 14). An independent samples t-test was performed to ensure no differences between the number of retained trials between monolinguals and bilinguals, this indicted no significant difference in the rate of trial rejection (see Appendix G).

5.8. STATISTICAL ANALYSIS PROCEDURES

Statistical analyses were conducted in SPSS Statistics for Windows, version 25 (SPSS Inc., 2017). For all statistical analysis, when the assumption of sphericity is violated, the Greenhouse-Geisser correction is reported (Greenhouse & Geisser, 1959). Separate analyses were conducted for each component of interest (N2 and P3). When $\alpha \leq .05$ the results will be discussed in terms of a significant effect. Behavioural results will be reported first followed by the electrophysiological results.

5.8.1. Experiment 1: Go/NoGo

Independent sample t-tests were used to compare reaction time on Go trials, d' and accuracy on Go, low conflict NoGo and high conflict NoGo between the two language groups.

A 2 x 3 mixed model analysis of variance (ANOVA) was conducted containing the between-subjects factor of language group (monolingual, bilingual) and the within-subjects factor Trial type (Go, low conflict NoGo, high conflict NoGo) on the amplitude and latency of the N2 and P3. Post-hoc tests were conducted to further understand the effects of trial type on the N2 amplitude within each language group.

5.8.2. Experiment 2: Simon

Younger and older adults were analysed separately to establish the presence of Simon-effects, then the size of the Simon-effects was compared using age group and language group as between-subject factors.

A 2 x 2 x 2 mixed model analysis of variance (ANOVA) was conducted containing the between-subjects factor of language group (monolingual, bilingual) and age group (younger adults, older adults) and the within-subjects factor Trial type (congruent, incongruent) on the amplitude and latency of the N2 and P3. Then, a Language Group (monolingual v bilingual) x Age Group (younger vs older) two-way ANOVA was conducted separately on the Simon-effect in RT and accuracy.

5.8.3. Experiment 3: Cross-task convergence

Pearson’s correlations were performed to establish associations with age the behavioural measures in the Go/NoGo and Simon tasks, and the N2 and P3 amplitudes and latencies in both tasks. Partial correlations were then performed accounting for age in instances where age was correlated with the measures to understand whether the behavioural and ERP measures on the two tasks were correlated.

5.9. PARADIGM DESIGN AND PROCEDURES

5.9.1. Experiment 1: Go/NoGo Task sample and task description

Go/NoGo Stimuli

Participants viewed a scene with a green background and cartoon depictions of grass and coloured flowers. At the centre of the scene was a black ‘hole’ which acted as a central fixation point. The target and distractor stimuli would appear from this central hole, to which the participants were instructed to either execute a manual response (Go) or withhold the response (NoGo). The task contained three stimulus types; (1) target stimuli (brown gophers), (2) non-target stimuli which are perceptually similar (red, blue, purple, and green gophers) and (3) non-target which are perceptually dissimilar (different non-gopher cartoon characters) (See Figure 1).

Task difficulty manipulation

Task difficulty was manipulated to understand how task demands, bilingualism and age would influence recruitment of neural resources. In the current Go/NoGo paradigm, perceptually similar trials (B in Figure 1) are expected to recruit more monitoring resources than perceptually dissimilar NoGo trials (C in Figure 1).

In addition to perceptual similarity, task difficulty was manipulated by varying the amount of time stimuli remained on screen. Three stimulus duration trials were utilised; short, medium, and long. Short trials presented the Go/NoGo stimuli for a total of 600-800ms. Medium length trials required the Go/NoGo stimuli to be presented for 800-1000ms. Long trials presented the Go/NoGo trials for 1000-1200ms. However, no significant differences were found in the reaction time (ms) or accuracy (%) of responses between short, medium, and long trials suggesting speed of presentation did not contribute to varying task demands.

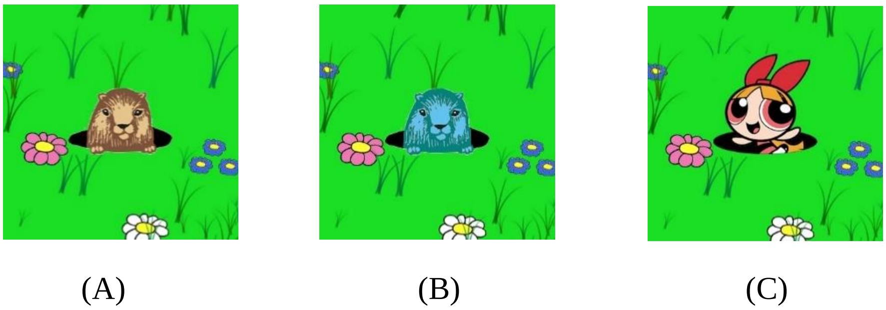


Figure 1. Example Stimuli for the Gopher Paradigm; Go stimuli (A), perceptually similar NoGo (B), perceptually dissimilar (C).

Procedure

The stimuli consisted of a 50/25/25 split between Go, similar NoGo and dissimilar NoGo trials: the experiment consisted of 180 Go trials, 90 perceptually similar NoGo trials and 90 perceptually dissimilar NoGo trials and presentation of stimuli was randomised. These were presented across five blocks, with 72 trials per block (36 Go, 18 similar non-target stimuli (coloured gopher) and 18 perceptually dissimilar non-target stimuli (cartoon characters).

Response Feedback

Participants were instructed to execute a manual button press on a response box for target stimuli (Go trials) and withhold this for non-target stimuli (NoGo trials). Auditory and visual feedback was given in response to correct hits, misses and false alarms.

5.9.2. Experiment 2: Simon Task

Simon task stimuli

Participants were required to respond to one of two task relevant attributes in the Simon task, either shape (circle or triangle) or colour (red or blue). These were manipulated in two separate blocks. In the colour condition blocks, only colour was manipulated, and the shape of the stimuli remained consistent across all stimuli (square). In the shape condition blocks, only shape of the stimuli was manipulated, and the colour of the stimuli remained consistent across all stimuli (purple) (See Figure 2 for example stimuli). These two conditions were presented in two separate blocks, and the order of the blocks and required response button was counterbalanced across participants.

The Simon effect has been reliably established in the visual modality, and the effect has been replicated with several task-relevant attributes including using colour and shape (Kubo-

Kawai & Kawai, 2010; Welch & Seitz, 2013). Within the literature studying the effects of bilingualism on cognition, both colour (Bialystok et al., 2004) and shape (arrows) have been used as task-relevant attributes (De Bruin et al., 2015). Here, we wanted to understand how these two different dimension manipulations (shape/colour) may exhibit differential demands on the attentional or conflict processes required to complete the task.

Colour stimuli consisted of squares (3x3cm) that were either red (*rgb* = 255, 0, 0) or blue (*rgb* = 0, 0, 255). The squares were presented on a light grey background (*rgb* = 128, 128, 128) at either the left (x = -450, y = 0) or right (x = 450, y = 0) of a fixation cross (+) that was constantly displayed in the centre of the screen (x = 0, y = 0). The fixation cross was constantly displayed to reduce eye movements from the participants (See Figure 2). Shape stimuli consisted of either circles (3x3cm) or triangles (3x3cm). The shapes were presented on a light grey background (*rgb* = 128, 128, 128) at either the left (x = -450, y = 0) or right (x = 450, y = 0) of a fixation cross (+) that was constantly displayed in the centre of the screen (x = 0, y =0). The colour of the shapes remained purple (*rgb* = 206, 119, 206).

When the presentation side of the stimuli aligned with the side of the keypad press required (e.g., left and left), this was categorised as a congruent trial. When there was a mismatch between presentation side and keypress side (e.g., left, and right), this was categorised as an incongruent trial. The colour block consisted of four conditions: (1) red square congruent, (2) red square incongruent, (3) blue square congruent and (4) blue square incongruent. The shape block consisted of four conditions: (1) circle congruent, (2) circle incongruent, (3) triangle congruent and (4) triangle incongruent.

Simon task procedure

Participants were presented with written instructions before the start of the task describing the response rules for the task. Participants were instructed to execute a manual response on the keypad using either the left or right button depending on the stimuli on screen.

Each stimulus would remain on screen until the participant executed a manual response and up to a maximum of 1500ms if there was no participant response. This was followed by a 500ms inter-stimulus interval of the central fixation cross. Manual responses were executed on a keypad. Participants received no response feedback. The response-button mapping was counterbalanced across participants for both stimulus types (colour/shape). The task consisted of 400 trials, with 200 trials manipulating colour and 200 manipulating shape. There 4 blocks within each trial type section containing 100 trials, and each of the four stimulus types were presented 25 times; (1) congruent stimuli displayed on the left, (2) congruent stimuli displayed on the right, (3) incongruent stimuli displayed on the left and (4) incongruent stimuli displayed on the right. The order of the stimuli presentation was randomised. The experiment began with a short practice block comprising of 8 trials to ensure that participants were able to utilise the keypad and to become accustomed to the paradigm layout. Reaction times (ms) and accuracy (%) were calculated in Presentation Log Files through stimulus and response triggers registered to the stimulus PC.

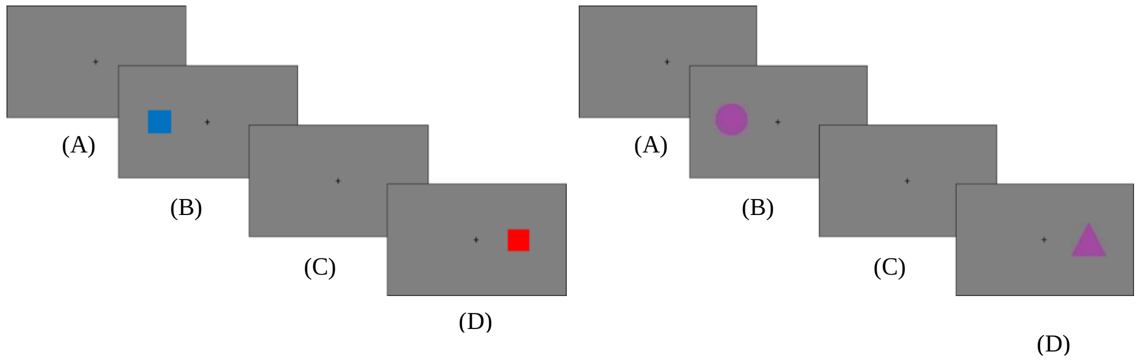


Figure 2. An example of the stimuli progression for the colour block (left) and shape block (right); participants will see a fixation cross for 500ms (A) followed by a target stimulus (B) for 1500ms ($x = -450$, $y = 0$), another fixation cross for 500ms (C) and another trial stimulus (D) for 1500ms ($x = 450$, $y = 0$).

Thirty-seven participants completed an earlier version of the paradigm in which the task consisted of only 200 trials. Within each block, each of the four conditions was presented only 25 times. The remaining 28 participants completed the 400-trial version. Both the 200 trial and 400 trial versions are collapsed in the data here. The second version of task with 400 trials was developed due to data attrition as a result of eye-movements. More trials facilitated an increase in statistical power when computing the EEG analysis. Statistical analysis of the two paradigm lengths was performed which indicated that the pattern of behavioural and ERP results did not differ as a result of paradigm length.

Task attribute manipulation analysis

The paradigm design involved the manipulation of a task-relevant attribute, specifically colour or shape. However, it is noteworthy that the requirement for participants to respond to either colour or shape did not have any significant impact on the magnitude of the Simon Effect, measured in terms of accuracy or reaction time (See Appendix F for in-depth analysis).

Consequently, colour and shape blocks are collapsed for the analysis hereon in, and the Simon effect (incongruent – congruent) was calculated using both conditions (shape and colour).

Chapter 6: Experiment 1- Bilingualism affects the plasticity of cognitive control mechanisms under high task demands in older adults

6.1. BEHAVIOURAL MEASURES

Sample and predictions

Reaction time and accuracy data were measured from an older adult sample comprising of 28 monolinguals and 41 bilinguals. It was predicted that older adult bilinguals would exhibit faster reaction times and better accuracy than older adult monolinguals, and this would be most evident when task demands were harder (i.e., during perceptually similar NoGo trials). Response times (RT) in milliseconds (ms) on Go trials (Go-RT), accuracy (%) on Go and NoGo trials and d prime (d') were calculated from an average of all five blocks.

An independent samples t-test revealed that there were no significant differences between monolinguals (*n* = 28) and bilinguals (*n* = 41) for Go-RT, Go-accuracy, NoGo-accuracy, or d' scores (Table 1). Although the independent t-test is showing a near significance for reaction time comparisons, this is driven by outliers (see Figure 1). When these outliers are removed *p* = .566.

Table 1. Behavioural performance of monolinguals and bilinguals on the visual Go/NoGo task. Means are reported with standard deviations in parenthesis.

	RT (ms)	Accuracy (%)	False alarm hits (%)		Signal detection
	Go	Go	Similar NoGo	Dissimilar NoGo	d'
Monolingual	667.22 (*107.14*)	94.63 (*8.98*)	11.47 (*6.95*)	2.47 (*2.51*)	3.38 (*0.50*)
Bilingual	712.65 (*86.19*)	94.39 (*8.13*)	10.94 (*7.47*)	3.40 (*3.54*)	3.32 (*0.63*)
Sig.	.056*	.912	.768	.231	.679

Note: When outliers are removed *p* = .566.

Perceptual similarity

A paired samples t-test revealed how NoGo stimuli that were perceptually similar to the Go trials elicited a higher percentage of false alarm hits (*M* = 11.15, *SD* = 7.22) relative to NoGo stimuli which was perceptually dissimilar (other Cartoon: *M* = 3.02, *SD* = 3.17), *t*(68) = 10.28, *p* = <.001. The two language groups did not differ in terms of the false alarm rate for either similar NoGo (*p* = .768) or dissimilar NoGo stimuli (*p* = .231) (see Table 1).

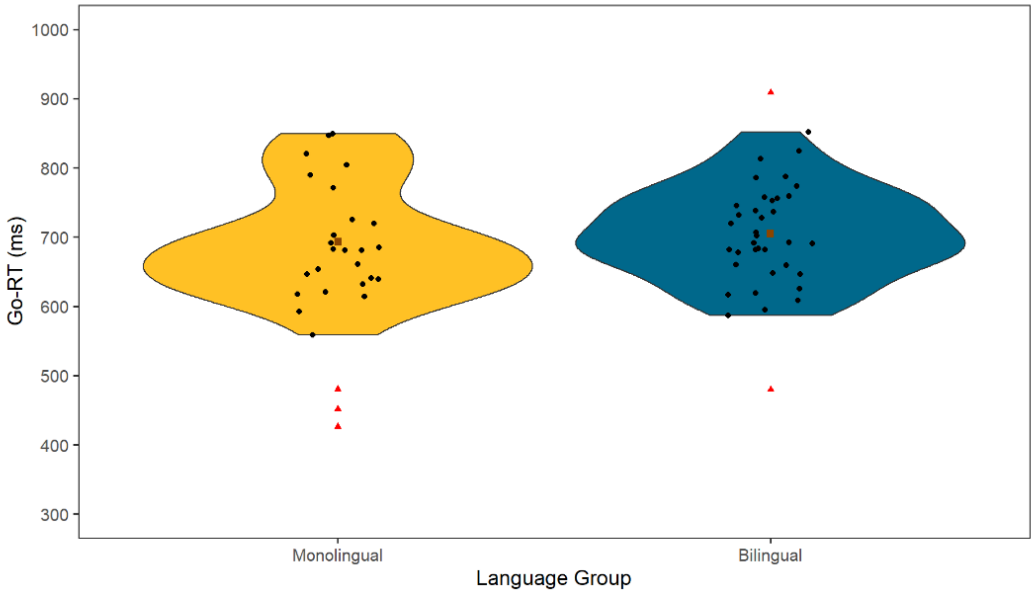


Figure 1. The reaction time scores for both language groups (*ms*). Burgundy boxes indicate the mean RT for each group. Red triangles (*n* = 5) indicate participants with RTs scores 2 standard deviations +/- the mean. Width of the violin plot indicates frequency.

6.2 ELECTROPHYSIOLOGICAL RESULTS

The mean amplitudes and peak latencies of the N2 and P3 was compared between older adult monolinguals (*n* = 19) and older adult bilinguals (*n* =25). The N2 was measured at nine fronto-central electrode sites: FP1, AF3, F1, FPz, FP2, AF4, AFz, Fz, and F2 during a 250-400ms time window. The P3 was measured at electrode sites P1, Pz, P2, PO3, POz, PO4 during a 300-600ms window.

6.2.1. N2

A 2 x 3 ANOVA was conducted with language group (monolingual, bilingual) and trial type (Go, low conflict NoGo, high conflict NoGo), revealed a main effect of condition, *F*(1, 84) = 25.58, *p* < .001, η2 = .350, with larger N2 amplitudes to perceptually dissimilar NoGo (*M* =

3.88, *SE* = 0.72), followed by perceptually similar NoGo (*M* = 5.73, *SE* = 0.79) and the smallest N2 amplitudes were elicited by Go trials (*M* = 6.84, *SE* = 0.88). There was no main effect of language group, *F*(1, 42) = 1.98, *p* =.166, η2 = .045. The predicted interaction between language group and condition was not statistically significant, *F*(1, 42) = 1.69, *p* =.191, η2 = .067.

To test the apriori hypothesis that group differences would be more pronounced with increased task demands, pairwise comparisons were computed. NoGo stimuli that were perceptually similar to Go stimuli had higher task demands that perceptually dissimilar NoGo stimuli, supported by the increase in false alarms for similar stimuli. Thus, pairwise comparisons were conducted separately for the easy (Go vs low conflict NoGo) and difficult (Go vs high conflict NoGo) conditions for each group whilst using Bonferroni to correct for multiple comparisons. As predicted, the bilinguals showed N2 Go-NoGo effects for both the perceptually easy (*Mdiff* = 3.58, *p* < .01) and perceptually difficult conditions (*Mdiff* = 1.87, *p* =.005). In contrast, monolinguals showed an N2 effect for the easy (*Mdiff* = 2.31, *p* = .008) but not the difficult condition (*Mdiff* = 0.34, *p* = 1.00) (see Figure 2 and Figure 3).

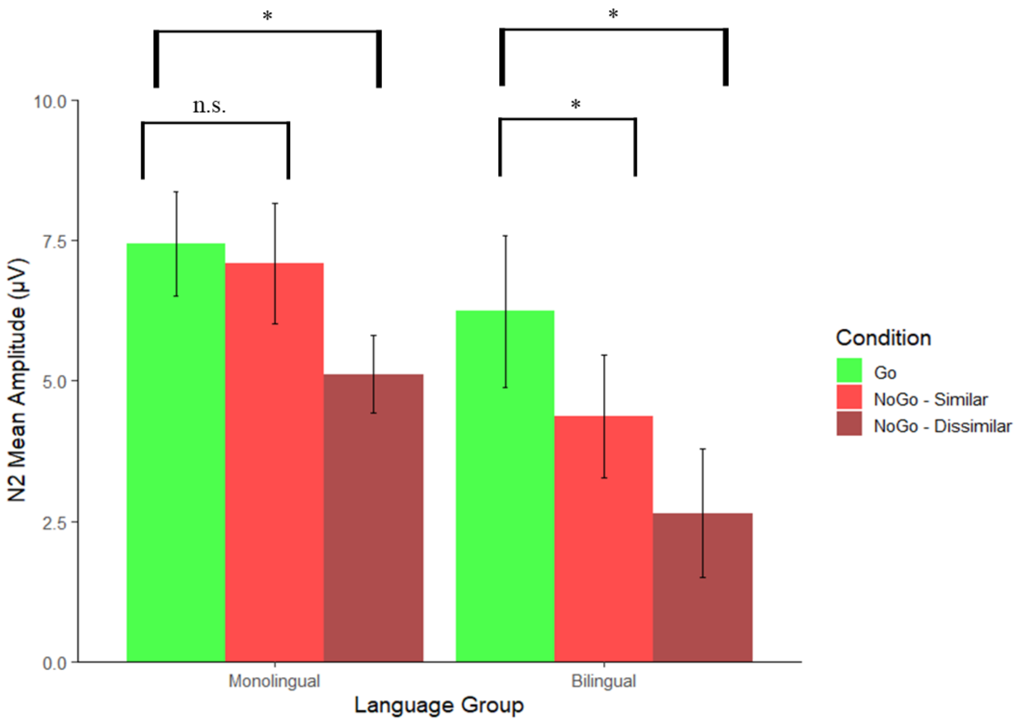
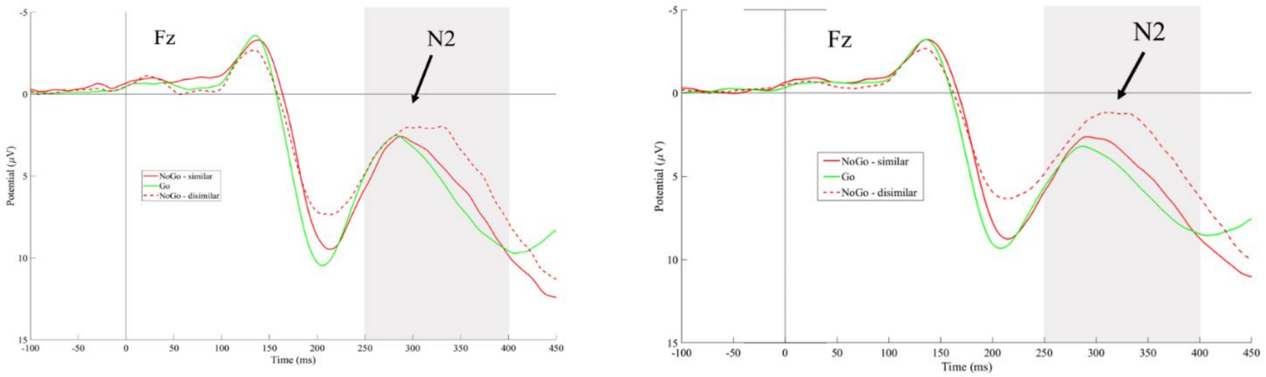


Figure 2. Bilinguals have significantly larger N2 amplitudes for both NoGo types relative to Go. For monolinguals, only perceptually dissimilar trials elicited larger N2 amplitudes relative to Go.

A 2 x 3 ANOVA conducted on N2 peak latency revealed only a main effect of trial type, *F*(2, 84) = 9.25, *p* < .001, η2 = .181. Pairwise comparisons revealed that the longest latencies N2 peak latencies were elicited by perceptually dissimilar/low conflict NoGo trials (*M* = 321.54, *SE* = 4.57), relative to perceptually similar/high conflict NoGo trials (*M* = 306.58, *SE* = 5.11) (*p* = .004) and Go trials (*M* = 303.68, *SE* = 4.00) (*p* = .002), which did not significantly differ from each other (*p* > 1.00). Monolinguals and bilinguals had comparable N2 peak latencies, *F*(1, 42) = 1.43, *p* =.239, η2 = .01. There was no interaction with language group or trial type, *F*(2, 84) = 0.670, *p* = .515, η2 = .016. As there were no apriori hypotheses about peak latency pairwise analyses were not conducted.


(A) Grand average of Monolinguals (*n* =19)

(B) Grand average of Bilinguals (*n* =25)

Figure 3. (A) Grand average ERP for Monolinguals (*n* = 19), (B) Bilinguals (*n* = 25) at electrode Fz. The grey box indicates the time window for analysis for the N2.

6.2.2. P3

There was a main effect of trial type on the P3 amplitude, *F*(2, 42) = 11.64, *p* < .001, η2 = .217. The largest amplitudes were elicited by Go stimuli (*M* = 11.02, *SE* = 0.96), followed by similar NoGo (*M* = 10.27, *SE* = 0.77), and dissimilar NoGo elicited the smallest P3 mean amplitudes, (*M* = 8.29, *SE* = 0.63). Pairwise comparisons revealed that low conflict/dissimilar NoGo trials had significantly smaller P3 amplitudes relative to Go trials, *p* = .001, and high conflict/similar NoGo trials, *p* < .001. However, Go-P3 amplitudes did not differ significantly from similar NoGo trials, *p* = .159. There was no main effect of language group on the P3 amplitude, *F*(1, 42) = 0.45, *p* =.504, η2 = .011. Nor a language group and trial type interaction, *F*(2, 42) = 0.532, *p* = .134, η2 = .053 (see Figure 4 for ERP waveform).

Analysis of P3 latency revealed that there was a main effect of trial type, *F*(2, 42) = 4.79, *p* = .011, η2 = .102, with earliest P3 latencies to Go stimuli (*M* = 469.36, *SE* = 7.55), followed by dissimilar NoGo, (*M* = 495.60, *SE* = 9.04), and similar NoGo eliciting the longest peak latencies, (*M* = 498.77, *SE* = 8.40). Pairwise comparisons revealed that Go stimuli elicited significantly shorter P3 latencies relative to both similar (*p* = .003) and dissimilar NoGo trial types (*p* = .044). The two NoGo trial types did not statistically differ from each other, *p* = .718. There was no main effect of language group on the P3 latency, *F*(1, 42) = 0.001, *p* =.978, η2 = .000. Nor a language group and trial type interaction, *F*(2, 42) = 0.431 *p* = .515, η2 = .010.

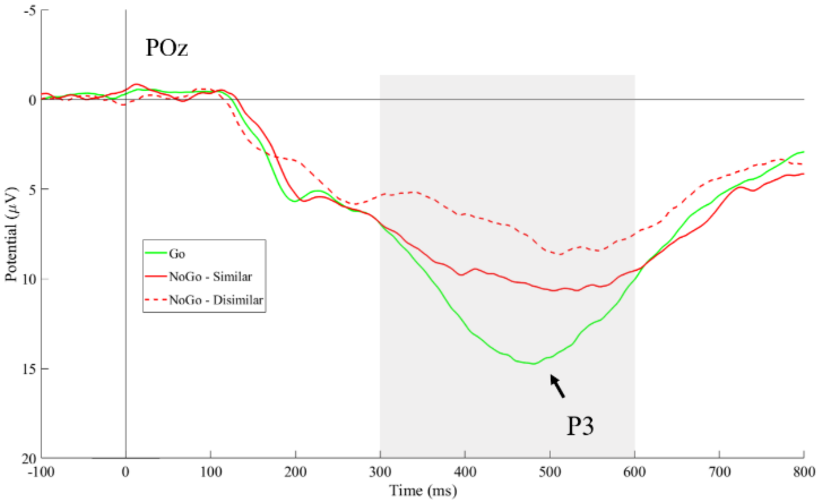


Figure 4. Grand average of Monolinguals (*n* = 19) and Bilinguals (*n* = 25) at electrode POz for Go (green) and perceptually similar NoGo (solid red) trials and perceptually dissimilar NoGo (dotted red). Grey window indicates time window of 300-600ms for analysis.

Consistent with previous literature, Go-P3 latencies were positively correlated with reaction times, *r*(54)= .362, *p* = .006 (Figure 5).

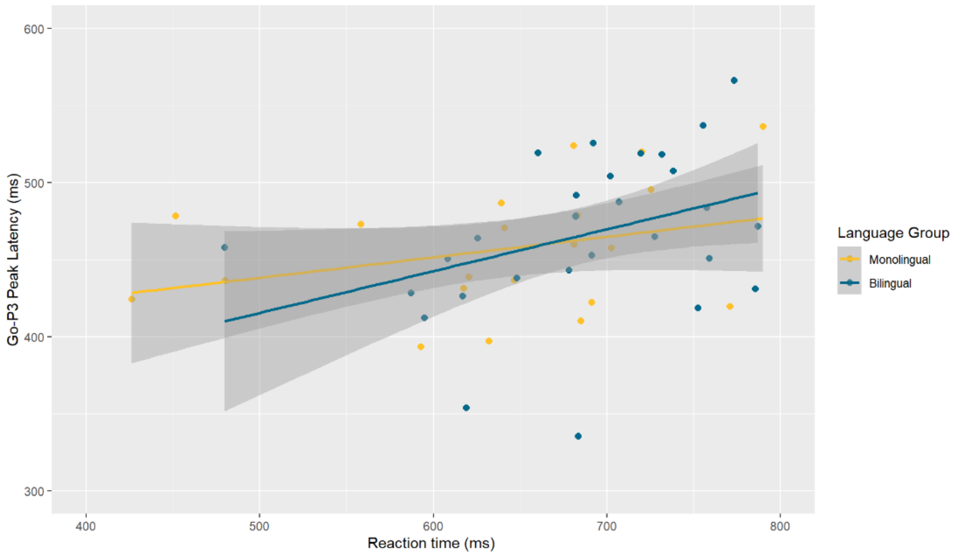
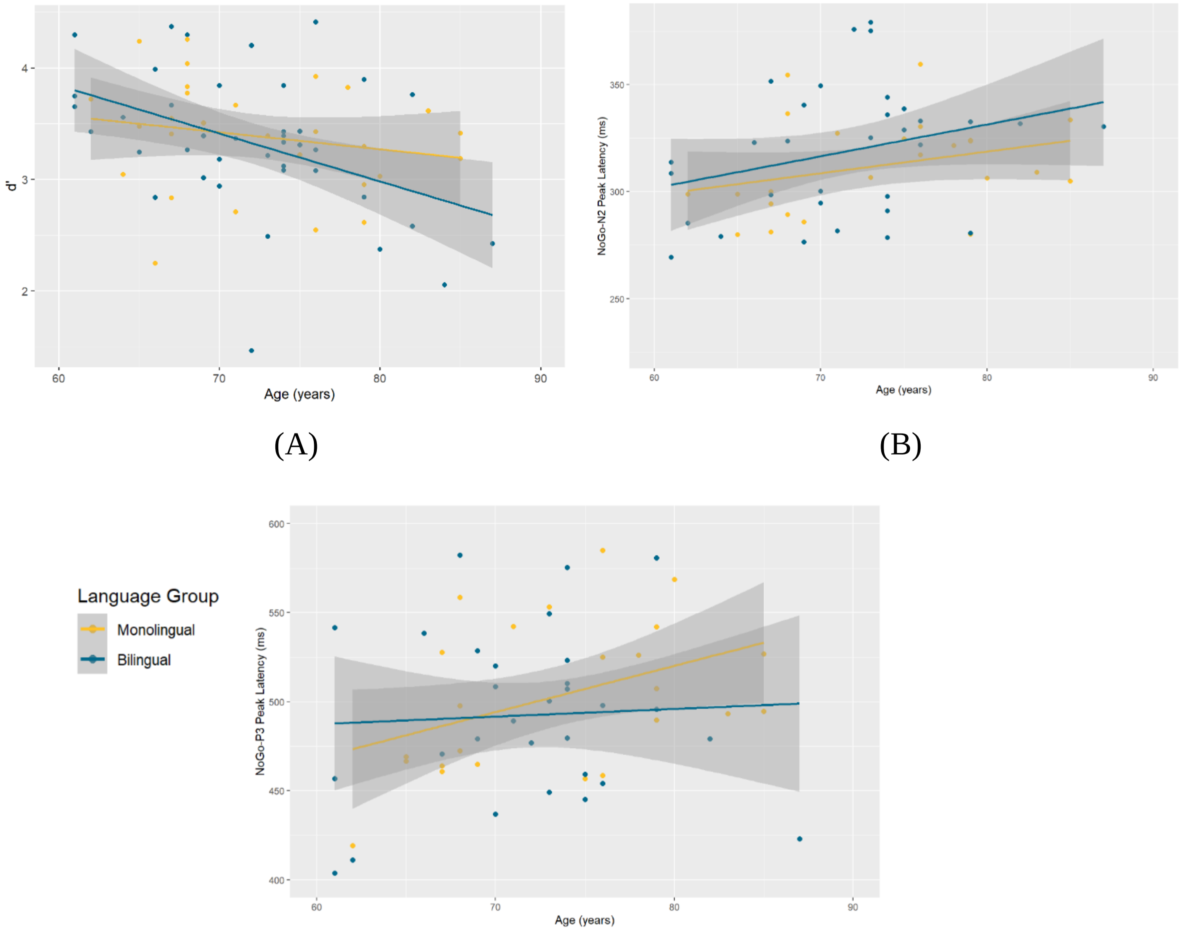


Figure 5. Later reaction time was associated with later Go-P3 peak latencies.

6.2.3. AGE AND SPEED OF INHIBITIORY AND ATTENIONAL PROCESSES

Increasing age was associated with longer reaction times on Go trials, *r*(69) = .261, *p* = .030, lower accuracy, *r*(69) = -.282, *p* = .019 and poorer signal detection as indexed by d', *r*(69) = -.341, *p* = .004 (see Figure 6).

Increasing age was correlated with longer N2 and P3 latencies on NoGo trials (N2, *r*(54) = .227, *p* = .044; P3, *r*(54)= .290, *p* = .030), but not with N2 and P3 amplitudes (all *p* > 150).



(A)

(B)

(C)

Figure 6. Increased age was associated with (A) decreased d’ scores, (B) increased NoGo-N2 latencies and (C) NoGo-P3 latencies. Monolinguals (*n* = 28) in yellow and Bilinguals in blue (*n* =41).

6.2.4. POST-HOC ANALYSIS OF THE P2

There were no apriori hypotheses about the P2, however visual inspection of the grand average ERP waveforms suggested that the amplitude of the P2 differed for the two NoGo trial types. To examine potential language group differences in P2 amplitude, the P2 was measured at nine electrode sites: Fp1, AF3, F1, Fpz, Fp2, AF4, AFz, Fz, and F2, in a 150-250ms post stimulus time window.

Analysis of the P2 amplitude revealed that there was a main effect of trial type, *F*(2, 41) = 13.29 *p* <.000, η2 = .245. The P2 was larger to Go trials (*M* = 5.52, *SE* = 0.76), followed by perceptually similar NoGo trials (*M* = 4.85, *SE* = 0.67), and the smallest P2 was evoked by perceptually similar NoGo trials (*M* = 3.77, *SE* = 0.59). There were no effects of language group on the P2 amplitude, *F*(2, 41) = 2.68, *p* =.109, η2 = .061, nor a language group and trial type interaction, *F*(2, 41) = 0.27, *p* =. 332, η2 = .007 (see Figure 7).

Analysis of the P2 latency revealed that there was no main effect of trial type, *F*(2, 41) = 1.87 *p* =.159, η2 = .043, language group, *F*(2, 41) = 0.96, *p* = .333, η2 = .022, nor interaction between the two, *F*(2, 41) = 1.29 *p* =.261, η2 = .030.

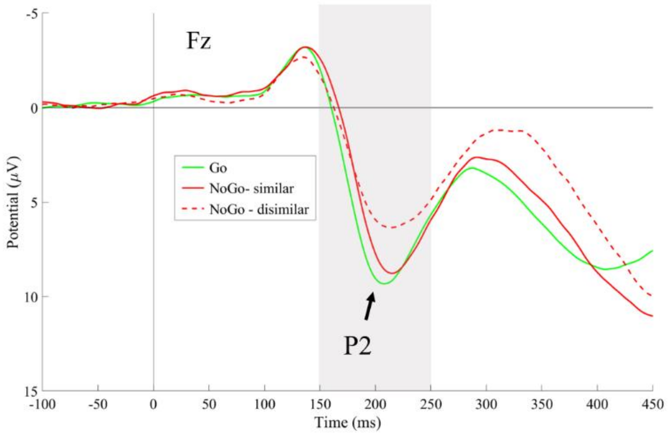


Figure 7. A grand average of participants with 30 trials or above in each perceptual similarity condition (*n* = 44) at electrode Fz for the P2. The grey window indicates the time window for analysis (150-250ms).

6.2.5. YOUNGER ADULT SAMPLE REPLICATION

This Go/NoGo paradigm has been employed with a younger adult sample of monolinguals and bilinguals (Roch, 2015). Roch (2015) found that younger adult bilinguals demonstrated suppression of attention to irrelevant stimuli as indexed by earlier P1 amplitudes, but the results did not show a language group interaction with N2 Go/NoGo differences.

Here, a small sample of younger adults (seven monolingual and eight bilinguals) were collected to replicate these results (see Appendix D). Like with Roch (2015), no language group differences were found in the younger adult sample for the N2 amplitude effect and behavioural measures. Given that the pattern on this paradigm with younger adults is well-established through the results of Roch (2015) and the replication here, the results are not presented for brevity.

Chapter 7: Experiment 2 - Aging, Bilingualism, and the Simon effect: Event-related potentials reveal how bilingualism modulates inhibitory control in the Simon task for older adults

7.1. BEHAVIOURAL DATA

7.1.1. Sample and predictions

Reaction time and accuracy data was measured for a sample of younger adults comprising nine monolinguals and 14 bilinguals, and a sample of older adults comprising 13 monolinguals and 22 bilinguals.

The current study investigated the effects of age and bilingualism on inhibitory control in the Simon task. It was hypothesised that language experience would affect the age-related changes in interference to suppression, as indexed by the Simon effects in RT and accuracy. A typical Simon effect was predicted, with longer reaction times and lower accuracy rates for incongruent relative to congruent trials. It was predicted that older adults would experience a larger interference effect relative to younger adults, resulting in larger Simon effects in RT and accuracy. It was hypothesised that bilingualism would affect the ability to inhibit attention to interference, therefore it was predicted that older adult bilinguals would exhibit smaller Simon effects than older adult monolinguals.

7.1.2. Reaction Time (RT; ms)

A mixed 2 x 2 x 2 ANOVA was conducted on reaction time with congruency, age group and language group as factors. There was a Simon effect in reaction time, *F*(1, 62) = 42.93, *p* < .001, η2 = .409, with significantly faster reaction times for congruent (*M* = 824.97, *SE* = 11.99) than incongruent trials (*M* = 849.11, *SE* = 12.76). Older adults (*M* = 910.11, *SE* = 14.86) were significantly slower than younger adults, (*M* = 763.98, *SE* = 19.46), *F*(1, 62) = 35.59, *p* < .001, η2 = .365, and there was an age group and congruency interaction, *F*(1, 62) = 5.63, *p* =.021, η2 = .083. Pairwise comparisons revealed that both age groups had significant Simon effects, with significantly slower reaction times to incongruent relative to congruent for both younger adults (*Mdiff* = 15.39, *SE* = 5.86, *p* = .011) and older adults (*Mdiff* = 32.88, *SE* = 4.47, *p* < .001). There was no effect of language group on reaction time, *F*(2, 41) = 0.31, *p* =.580, η2 = .005.

To test the apriori hypotheses that older adults would have larger Simon effect that young adults, especially for older adult monolinguals, a two-way ANOVA on the size of the Simon effect revealed that, as predicted, older adults had larger RT-Simon effects than younger adults, *F*(62) = 5.63, *p* = .021, η^2 =.083. However, there were no differences in the magnitude of the Simon effect in reaction time when comparing monolinguals (*M* = 22.32, *SE* = 5.85) and bilinguals (*M* = 25.96, *SE* = 4.47), *F*(62) = 0.24, *p* = .624, η^2 =.004. Age group and language group did not interact, *F*(62) = 0.344, *p* = .560, η^2 =.006 (see Figure 1 for raincloud plots).

7.1.3. Accuracy (%)

A mixed 2 x 2 x 2 ANOVA was conducted with congruency, age group and language group as factors. There was a Simon effect in accuracy, *F*(1, 62) = 30.22, *p* < .001, η2 = .328, with significantly higher accuracy for congruent (*M* = 92.66, *SE* = 0.86) than incongruent trials (*M* = 90.15, *SE* = 0.94). Older adults (*M* = 92.75, *SE* = 1.06) and younger adults (*M* = 90.06, *SE* = 1.38) did not significantly differ in their accuracy scores, *F*(1, 62) = 2.40, *p* =.126, η2 = .037, and there was no age group and congruency interaction, *F*(1, 62) = 0.01, *p* =.921, η2 = .000. There was no effect of language group on accuracy, *F*(2, 41) = 1.74, *p* =.191, η2 = .027.

To test the apriori hypotheses that older adults would have larger Simon effects than younger adults, and older adult bilinguals would have smaller Simon effects relative to older adult monolinguals, a two-way ANOVA with age group and language group as independent factors and Simon effect in accuracy as the dependent variable was computed. The ANOVA revealed that older adults (*M* = -2.55, *SE* = 0.55) *did not* have larger Simon effects in accuracy relative to younger adults (*M* = -2.47, *SE* = 0.73), *F*(62) = 0.10, *p* = .921, η^2 <.001. The magnitude of the Simon effect in accuracy was comparable for both language groups, *F*(62) = 0.14, *p* = .905, η^2 <.001. There was the predicted language group and age group interaction, *F*(62) = 4.59, *p* = .036, η^2 = .069. It was predicted that the Simon effect would be larger in monolinguals relative to bilinguals, especially in the older adult group, thus pairwise comparisons were computed to test this. Pairwise comparisons revealed that the language groups had comparable Simon effects in younger adults (*p* = .160) and older adults (*p* =.101). Looking at Figure 1, as predicted qualitatively monolingual younger adults have a larger Simon effect relative to bilingual younger adults, but contrary to our predictions, the opposite is true for older adults, with bilinguals having larger Simon effects.

However, it is important to note that once outliers were removed from the data (there were two bilinguals with large accuracy effects (> -10%) and one monolingual with an effect in the opposite direction (lower accuracy for congruent ~ 6%), the interaction was no longer significant at *p* =.268. Therefore, given the low sample size in this study, and thus the strong influence of outliers, the interaction should be interpreted with caution.

7.1.4. Behavioural results summary

Older adults showed a larger Simon effect than young adults for reaction time but not accuracy. Contrary to predictions, there were no differences between monolinguals and bilinguals for either age group.

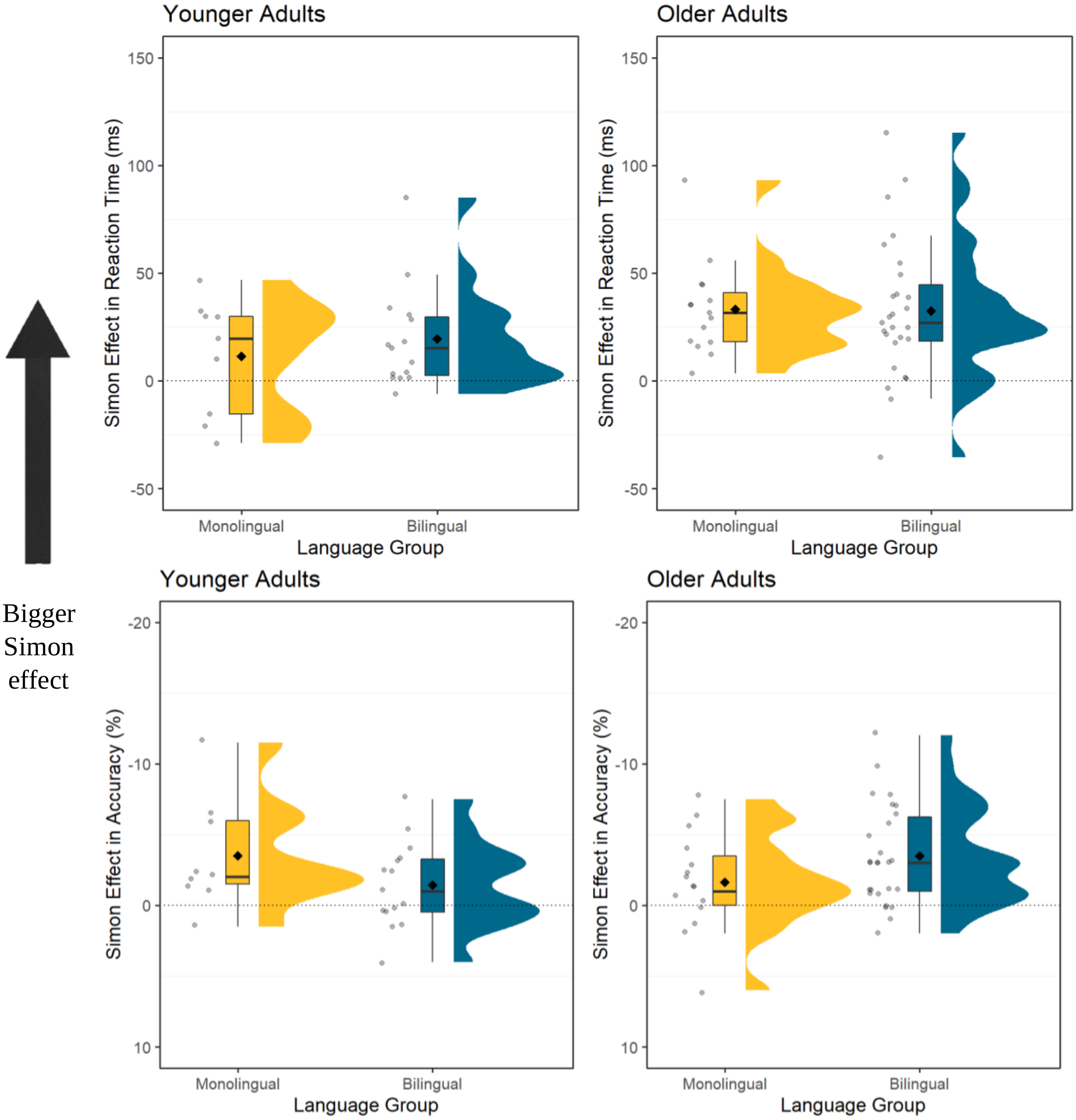


Figure 1. Raincloud plots demonstrating mean Simon Effects. Top row: RT, bottom row: accuracy. Boxplots indicate the interquartile range and lines within the boxplot represent the

median. Boxplot whiskers indicate the minimum and maximum values. Diamond represents the mean. Raincloud plots represent the distribution of the data, with larger areas indicating more participants at this value. All values above the dotted line (at 0ms and 0%) indicates a longer reaction time/lower accuracy to incongruent stimuli.

7.2. ELECTROPHYSIOLOGICAL RESULTS

The amplitude and latency of the N2 and P3 was compared between 22 younger adults (monolinguals: $n = 19$, bilinguals: $n = 13$) and 23 older adults (monolinguals: $n = 9$, bilinguals: $n = 14$). The N2 was measured at nine fronto-central electrode sites: FP1, AF3, F1, FPz, FP2, AF4, AFz, Fz, and F2 during a 250-400ms time window. The P3 was measured at electrode sites P1, Pz, P2, PO3, POz, PO4 during a 300-600ms window.

7.2.1. Inhibition (N2)

Predictions

The current study investigated the effects of age and bilingualism on inhibitory control in the Simon task. It was hypothesised that language experience would affect the age-related changes in interference to suppression, as indexed by the N2. It was predicted that older adults would experience a larger interference effect relative to younger adults, resulting in a larger N2-effect. It was predicted that different patterns of inhibitory control processes would be in observed in older adult bilinguals compared to older adult monolinguals, exhibited by smaller N2-effects relative to older adult monolinguals.

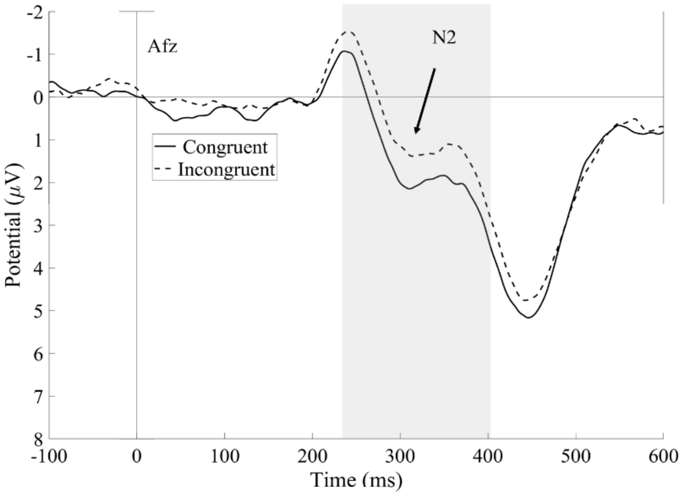
7.2.2. N2 Mean Amplitude (µV)

A mixed 2 x 2 x 2 ANOVA was conducted with congruency, age group and language group as factors. There was a Simon effect in N2 amplitude, $F(1, 41) = 4.74$, $p = .035$, $\eta 2 = .104$, with larger N2 mean amplitudes for incongruent ($M = 3.13$, $SE = 0.53$) relative to congruent trials ($M = 3.75$, $SE = 0.48$). Older adults had significantly smaller N2 mean amplitudes ($M = 4.95$, $SE = 0.66$) compared to younger adults (M = 1.93, SE = 0.71), $F(1, 41) = 9.63$, $p =.003$, $\eta 2 = .190$ (Figure 2). There was no age group by congruency interaction, $F(1, 41) = .007$, $p =.935$, $\eta 2 <.001$. There was no main effect of language group on N2 amplitude, $F(1, 41) = 0.12$, $p =.912$, $\eta 2 < .001$.

There was the predicted three-way interaction between age group, congruency and language, $F(1, 41) = 6.44$, $p =.015$, $\eta 2 = .136$. It was predicted that older adults would exhibit the largest N2-effects, especially the older adult monolinguals. To test this prediction, pairwise comparisons were computed. For younger adults, there was no Simon effect for the N2 amplitude, *F*(1,40) = 1.97, *p* = .215, η2 = 0.76. The N2 was not larger to incongruent (*M* = 1.62, *SE* = 0.95) than congruent stimuli (*M* = 2.24, *SE* = 0.77). There were no effects of language group or interaction, all *p* > .400. For older adults, there was a Simon effect for the N2 amplitude, *F*(1,21) = 4.68, *p* = .042, η2 = .182. The N2 was larger to incongruent (*M* = 4.55, *SE* = 0.48) than congruent stimuli (*M* = 5.28, *SE* = 0.57).

With focus on just the older adult sample, there was a language group and congruency interaction, *F*(1,21) = 7.53, *p* = .012, η2 = 2.64. Pairwise comparisons revealed that older adult monolinguals had significantly larger N2 amplitudes to incongruent trials relative to congruent (presence of Simon effect) (*p* = .005). In contrast, for older adult bilinguals the N2 to congruent and incongruent stimuli did not significantly differ (*p* =.648) (absence of Simon effect) (Figure 3 and 4).

Younger adults (*n* = 22)



Older adults (*n* = 23)

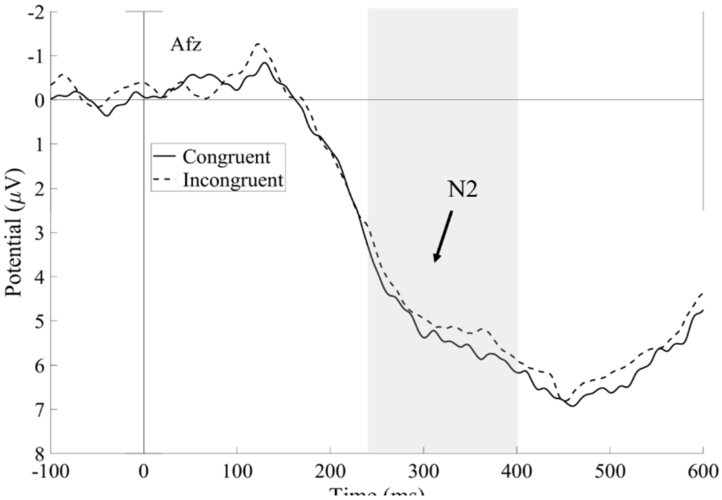
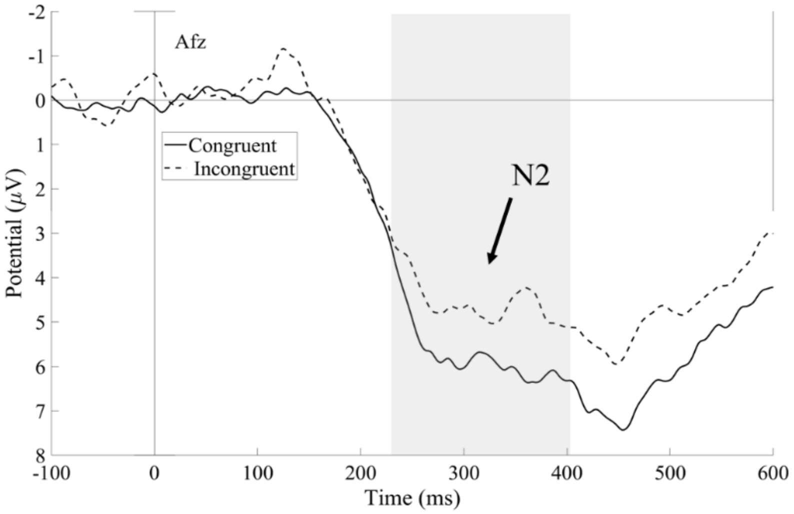


Figure 2. Grand average ERP waveforms at electrode Afz for younger and older adult participants.

Older adult monolinguals (n = 9)



Older adult bilinguals (n = 14)

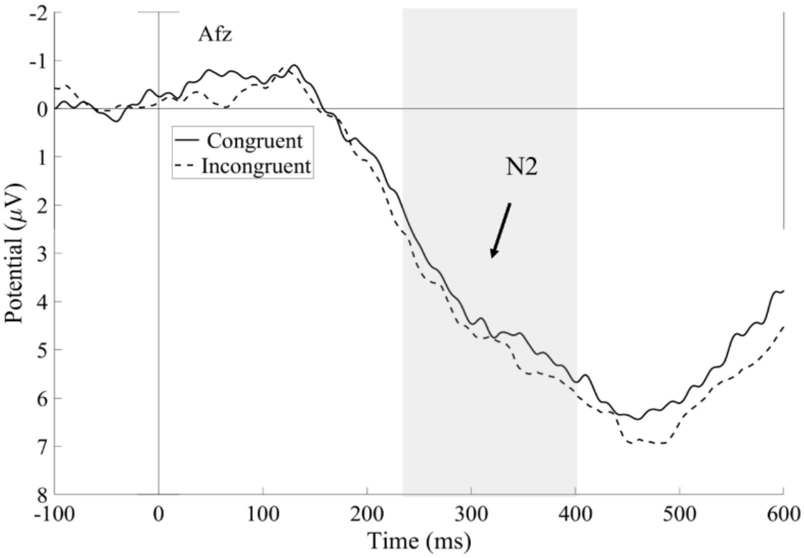


Figure 3. Grand average ERP waveforms at electrode Afz for monolingual and bilingual older adult participants.

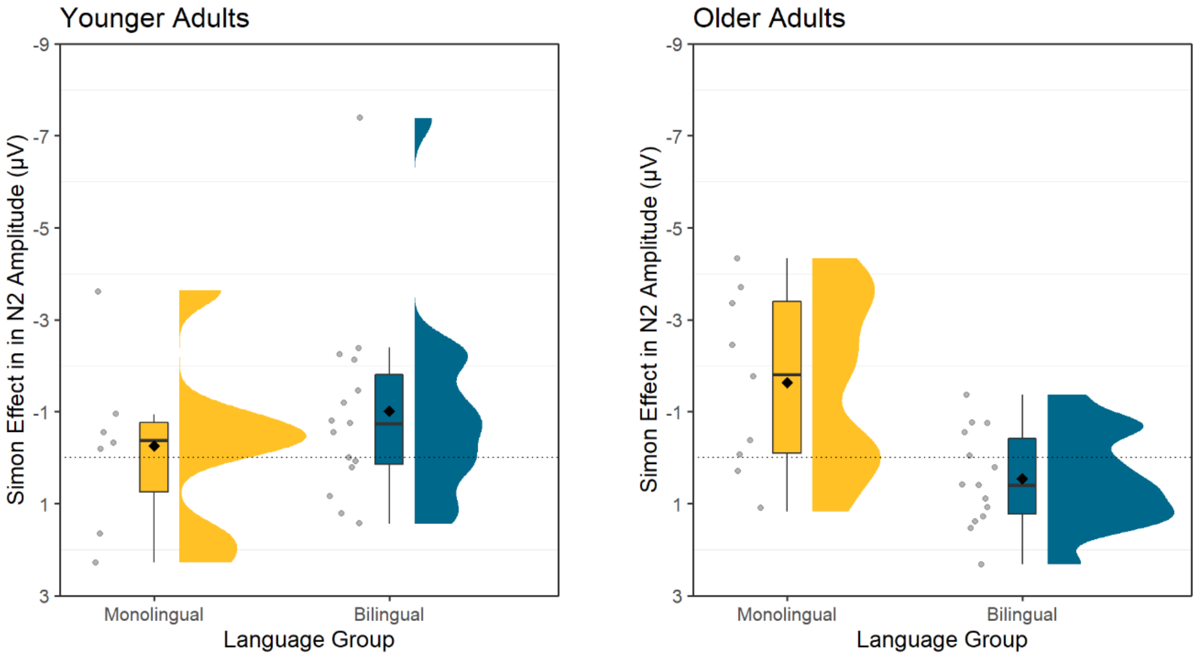


Figure 4. A raincloud plot demonstrating the N2-effect (incongruent – congruent). Values above the 0ms line indicate larger N2 amplitudes to incongruent trials. Younger adult monolinguals and bilinguals had comparable N2-effects. In older adults, older adult monolinguals exhibiting larger N2-effects relative to bilinguals.

7.2.3. N2 Peak Latency (ms)

A mixed 2 x 2 x 2 ANOVA was conducted with congruency, age group and language group as factors. There was no Simon effect in N2 latency, *F*(1, 41) = 2.14, *p* = .151, η2 = .050. There was no effect of age group, *F*(1, 41) = < .001, *p* = .992, η2 <.001, nor a main effect of language group, *F*(1, 41) = 1.25, *p* = .270, η2 = .030. There was a congruency and age group interaction, *F*(1, 54) = 4.49, *p* = .040, η2 = .099.

For younger adults, there was no Simon effect for the N2 latency, *F*(1,40) = 1.38, *p* = .252, η2 = 0.65). The N2 was not later for incongruent (*M* = 309.68, *SE* = 4.35) than congruent stimuli (*M* = 313.68, *SE* = 4.73). There were no effects of language group or interaction, all *p* > .300.

For older adults, there was a Simon effect for the N2 latency, *F*(1,21) = 5.08, *p* = .035, η2 = .195). The N2 was later to incongruent (*M* = 318.74, *SE* = 5.00) than congruent stimuli (*M* = 309.45, *SE* = 5.84). The main effect of language group was trending towards significance, *p* = .097, with later N2 latencies for monolinguals (*M* = 322.83, *SE* =7.85) relative to bilinguals (*M* = 305.36, *SE* = 6.29).

7.2.4. Attention Allocation (P3)

There were no Simon effects for the P3 amplitude (μV) for younger or older adults. There were no differences in the P3 amplitude between either age group or language group. There were no interactions with age group and language group. There were no Simon effects for the P3 latency (*ms*) for younger or older adults. There was an effect of age as older adults had later P3 latencies relative to younger adults, $F(1,41) = 42.95$, $p < .001$, η2 = .512. There were no other main effects or interactions. For more information, please refer to Appendix H.

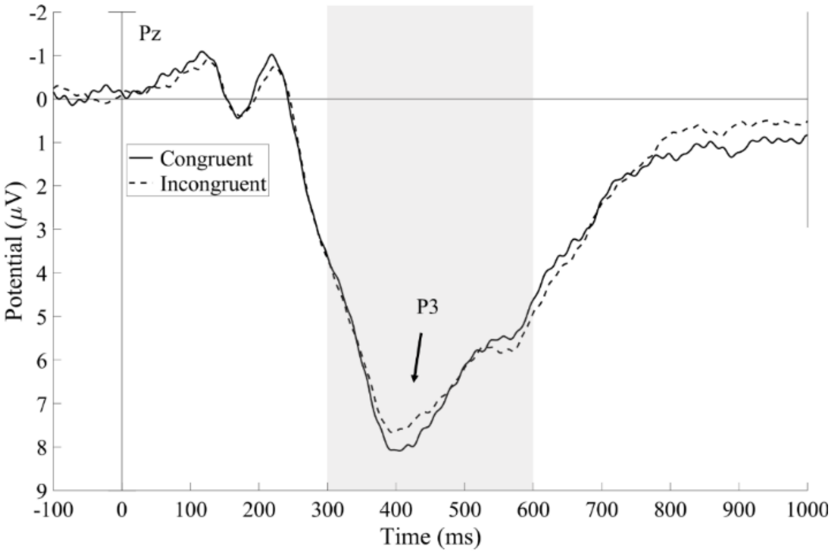


Figure 5. Grand average ERP waveform for all participants ($n = 45$) for congruent and incongruent trials at electrode Pz. There was no significant difference between congruent and incongruent trials for the P3 amplitude.

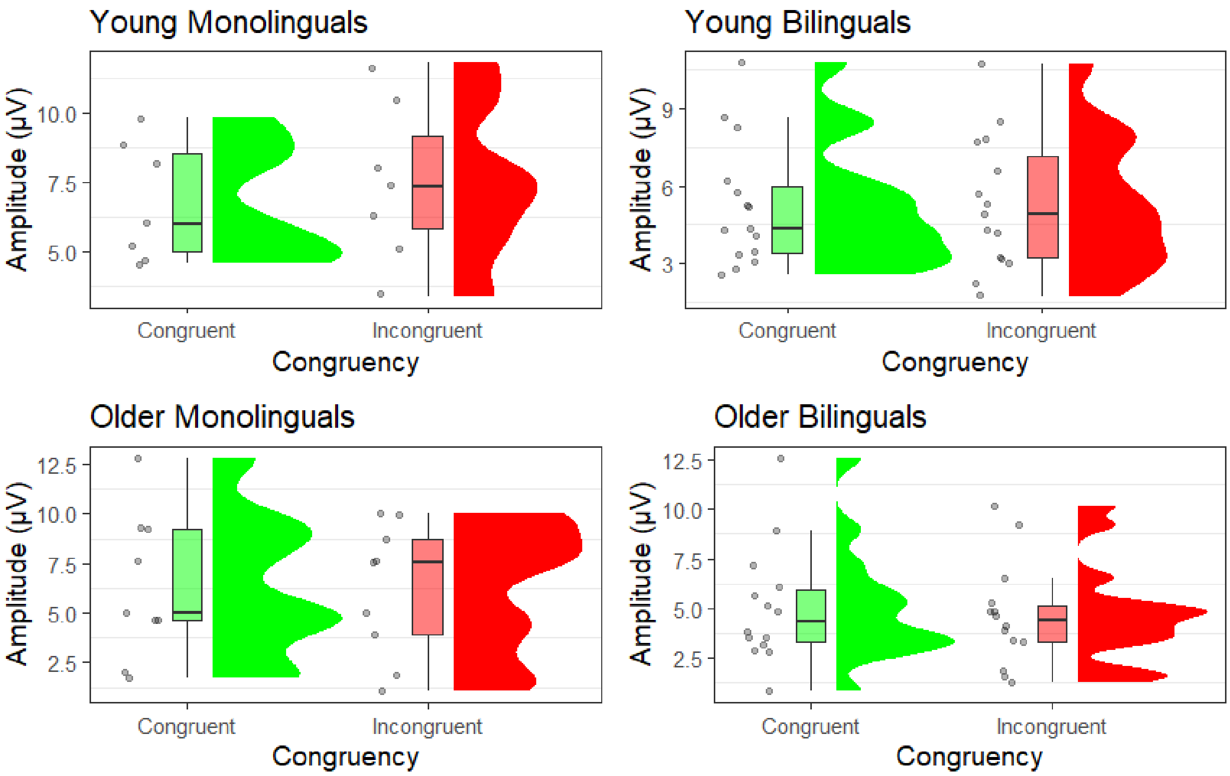


Figure 6. Amplitude of the P3 (µV) for each of the four groups (YAM, YAB, OAM, OAB) for each trial type (congruent, incongruent).

7.3. BEHAVIOURAL AND ELECTROPHYSIOLOGICAL CORRELATIONS

7.3.1. Rationale

Given how the functional significance of the N2 in the Simon task is not clear cut, one goal of the current study was to understand how the size of the N2 effect might be associated with the size of RT effects and accuracy effects, as these measures are all suggested to reflect size of interference. Partial correlations were performed to investigate this, age (in years) was controlled for as reaction time, accuracy and N2 latency effect were highly correlated with age in the data (all p <.02).

7.3.2. Correlations of Simon effects

The behavioural and ERP measures were not correlated in this task (all p > .100) when younger and older adults were grouped together (see Table 1). The correlations remained non-significant when the age groups were divided into younger and older adults, and when the four groups (YAM, YAB, OAM, OAB) were analysed separately.

Table 1. Correlation matrix of N2 amplitude, N2 latency, RT and accuracy effects.

	Accuracy	N2-Amplitude	N2 Latency
RT	-.254	.027	.207
Accuracy	-	-.032	.102
N2-Amplitude	-	-	-.073

Note. Correlation coefficients (*r*) are reported. Values with an * indicates $p < .05$, ** indicates $p < .01$. Age (in years) was controlled for.

7.3.4. Summary of results

Across both age groups, participants were faster and more accurate for congruent than incongruent trials, demonstrating a Simon effect in the behavioural measures on this paradigm. We replicated previous findings with larger Simon effects for older adults compared to younger adult in reaction time. The size of the RT Simon effect was comparable for monolinguals and bilinguals in both age groups.

Analysis of the electrophysiological evidence revealed that older adult monolinguals exhibited the largest Simon effect in N2 amplitude. There was no Simon effect in the N2 amplitude for younger adults, or older adult bilinguals. Older adults had larger N2 effects for latency relative to younger adults, but this did not differ between language groups. There were no Simon effects in the P3 amplitude or latency for any groups.

Chapter 8: Inhibitory control measures on the Simon task and Go/NoGo task lack convergent validity

8.1. BEHAVIOURAL DATA

Data from younger adults (*n* = 18) and older adults (*n* = 42) who had completed both the Simon and Go/NoGo task were analysed. Given that increasing age is associated with a general slowing of reaction times (e.g., Verhaeghen, 2016) and reduced inhibitory control (e.g., Christ et al., 2001; Bialystok, Martin & Viswanathan, 2005), correlational analysis with age and behavioural measures was performed to elucidate whether age was a covariate in the data. Both raw reaction times (RT) and interference scores were recorded. In the Go/NoGo task, no reaction time interference score can be calculated due to the absence of a required behavioural response on NoGo trials.

8.1.1. Inhibition

Previous work has used interference measures (RT-effect, accuracy-effect; Simon task) and NoGo-accuracy (Go/NoGo task) as measures of inhibition (see review by Lehtonen et al., 2018). Here, RT-effect and accuracy-effect from the Simon Task, and d’ and accuracy effect from the Go/NoGo task were used (see Table 1).

For younger adults, Pearson’s correlation demonstrated that age was not correlated with the inhibition measures (see Appendix J), therefore age was not controlled for. There were no significant cross-task correlations in the behavioural measures of inhibition (see Table 2 and Figure 1).

In the older adult sample, Pearson’s correlations illustrated how increasing age was associated with increases in the Simon effect in reaction time, $r(41) = .373$, $p = .015$, and decreases in d’ on the Go/NoGo task, $r(41) = -.317$, $p = .041$. This indicates slower reaction times and poorer signal detection with increasing age. After controlling for age using a partial correlation, there were no cross-task correlations, all $p > .150$ (see Table 2 and Figure 3).

Table 1. Descriptive statistics for measures of inhibition for Go/NoGo and Simon task for both age groups. Larger effects in RT and accuracy reflect larger interference on incongruent trials relative to congruent.

		Simon		**Go/NoGo**	
		RT-effect	accuracy-effect	accuracy-effect	d’
Younger adults	Mean	20.17	2.39	2.84	4.11
(*n* = 19)	(*SD*)	(*24.36*)	(*3.60*)	(*3.09*)	(*0.65*)
Older adults	Mean	33.74	2.75	2.15	3.31
(*n* = 42)	(*SD*)	(*29.50*)	(*3.53*)	(*9.53*)	(*0.61*)

Table 2. Cross-correlations for inhibition measures for the Simon and Go/NoGo task, significant at *p* < .05*, *p* < .01**, *p* <.001***.

				1.	2	3	4
Younger adults (*n* = 19)	1.	Simon-RT	*r*	-	.190	.430	-.396
			sig.		.437	.066	.094
	2.	Simon-Acc	*r*		-	-.044	-.103
			sig.			.859	.675
	3.	Go/NoGo-Acc	*r*			-	
			sig.				
	4.	d’	*r*				-
			sig.				
Older adults (*n* = 42)	1.	Simon-RT	*r*	-	**.412**	.021	-.076
			sig.		**.007****	.897	.635
	2.	Simon-Acc	*r*		-	-.225	-.240
			sig.			.157	.131
	3.	Go-Acc	*r*			-	.214
			sig.				.180
	4.	d’	*r*				**-**
			sig.				

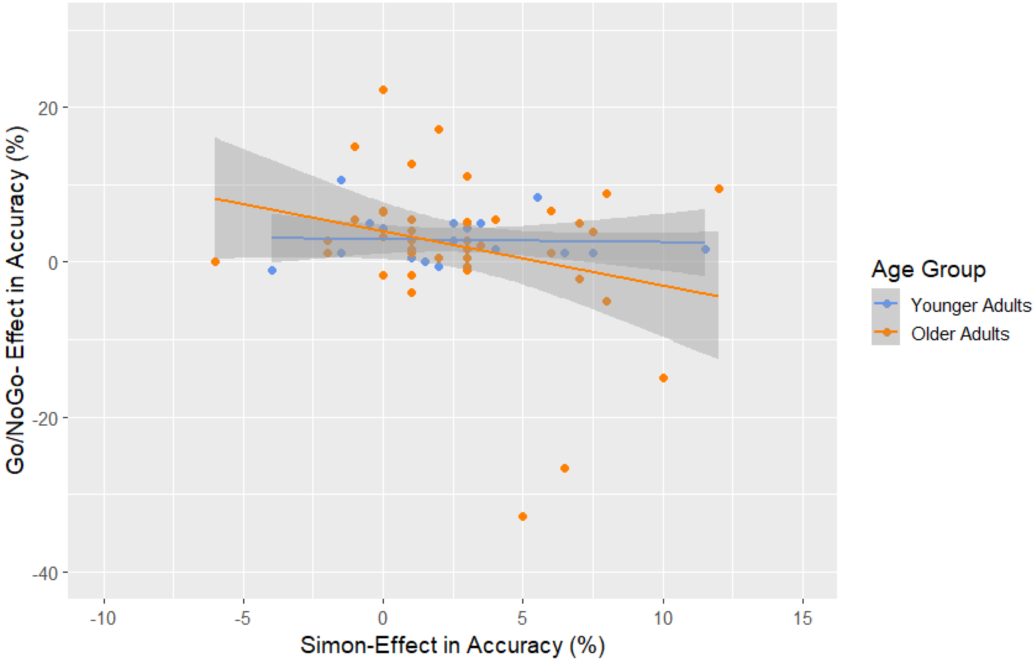


Figure 1. Simon effect in accuracy and Go/NoGo effect in accuracy were not associated in younger or older adults. Positive scores are indicative of better accuracy on congruent/Go relative to incongruent/NoGo trials. Negative scores are indicative of better accuracy in incongruent/NoGo trials relative to congruent/Go.

8.1.2. Monitoring

When cross-task correlations are found it is usually in indices of monitoring (e.g., Keye at al., 2009; Paap & Sawi, 2014; Ross & Merlinger, 2017; Stins et al., 2005). The ability to replicate this finding in the data here was explored. Past work has used RT measures as indices of monitoring (see review by Lehtonen et al., 2018): Go-RT and Congruent-RT were used here (See Table 3).

Table 3. Descriptive statistics for reaction times (RT) posited to reflect the monitoring component of executive function.

		Simon	**Go/NoGo**
		Congruent RT	Go RT
Younger adults	Mean	751.11	587.89
(*n* = 19)	(*SD*)	(*85.15*)	(*61.80*)
Older adults	Mean	901.51	714.42
(*n* = 42)	(*SD*)	(*94.21*)	(*82.93*)

For the younger adults, a Pearson's correlation demonstrated that age was not correlated with reaction time measures in younger adults (See Appendix J), therefore age was not controlled for. Congruent-RT (Simon task) was significantly correlated with Go-RT (Go/NoGo task), $r(17) = .506$, $p = .019$ (Table 4 and Figure 2).

In the older adult sample, Pearson's correlations demonstrated that increasing age was correlated with larger Go-RT, $r(40) = .316$, $p =.041$ (Table 4 and Figure 2), therefore, a partial correlation was performed to see if there was an association between Go-RT (Go/NoGo) and Congruent-RT (Simon) whilst controlling for age (See Appendix J). However, neither before, $r(40)= .253$, $p = .106$, nor after controlling for age , $r(40) = .256$, $p = .106$, were there any cross-task correlations with Go-RT and congruent-RT.

Table 4. Cross-correlations for reaction time (RT) measures for the Simon and Go/NoGo task, significant at $p < .05$*, $p < .01$**, $p <.001$***.

			Go-RT	Age
Younger adults (*n* = 19)				
	1. Congruent-RT	*r*	.531	-.304
		sig.	**.019***	.206
	2. Go-RT	*r*	-	-.198
		sig.		.415
Older adults (*n* = 42)				
	1. Congruent RT	*r*	.252	.032
		sig.	.106	.841
	2. Go-RT	*r*	-	**.326**
		sig.		**.041***
Controlling for age				
	1. Congruent RT	*r*	.256	-
		sig.	.106	
	2. Go-RT	*r*	-	-
		sig.		

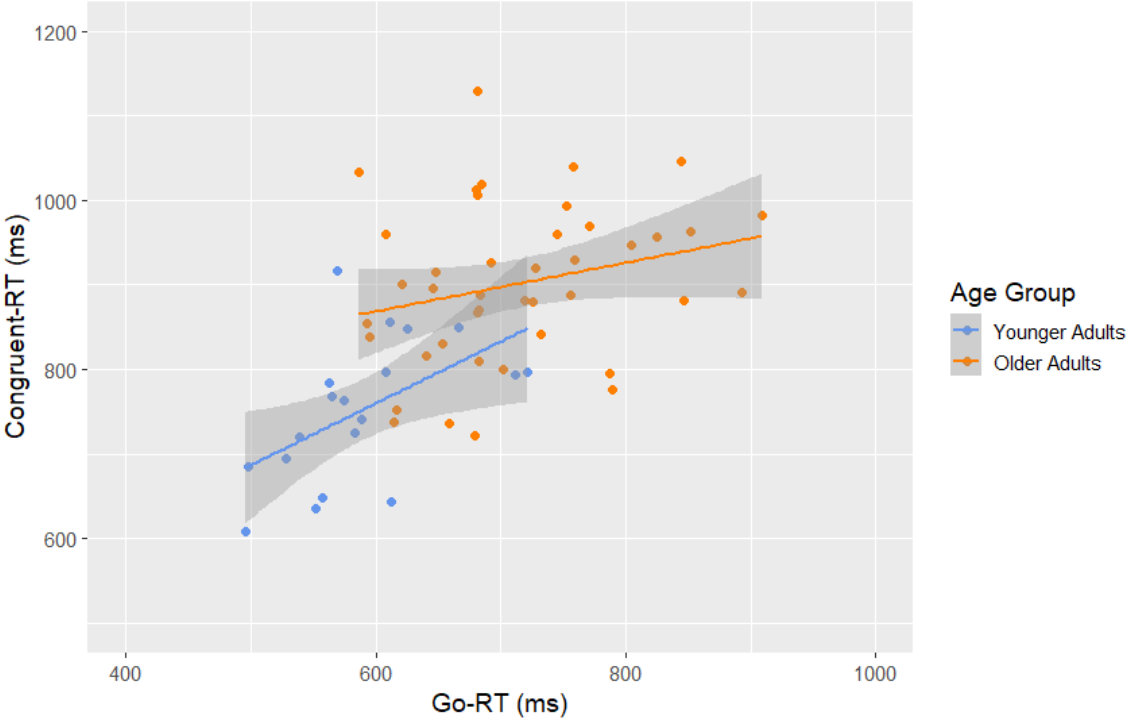


Figure 2. Scatterplot to show how increased reaction times in congruent trials and Go trials are correlated in younger adults (blue) but not older adults (orange).

8.2. ELECTROPHYSIOLOGICAL RESPONSES

8.2.1. N2

The N2 elicited in the Go/NoGo paradigm is posited to be an index of inhibitory control, which is required due to competition between the pre-potent state and the required state (Donkers & Van Boxtel, 2004; Nieuwenhuis et al., 2003). Here, the presence of associations between the N2 in the Go/NoGo and Simon task was tested. Previous work suggests that the two tasks can be dissociated as they require different kinds of inhibition (Friedman & Miyake, 2004). If the amplitude of the N2-effect represents non-identical inhibition-related processes across the two tasks, then the N2-effect may not be correlated. If the amplitude of the N2-effect represents a common inhibition-related processes across the two tasks, then it is predicted that the N2-effects will be negatively correlated.

N2 Mean Amplitude

Firstly, Pearson's correlations were computed on age in years and the six N2 amplitude variables (N2-Go, N2-NoGo, N2-Go/NoGo effect, N2-Congruent, N2-Incongruent, N2-Simon effect) (See Table 5 for descriptive statistics). Neither in younger nor older adults was age correlated with any of the six N2 amplitude measures, therefore, age was not controlled for in the correlations (See Appendix K for correlation matrix).

Table 5. Descriptive statistics for mean amplitude of the N2 for each of the conditions for both paradigms. Mean (SD) are reported.

	Simon Task			**Go/NoGo Task**		
	Congruent	Incongruent	N2-effect	Go	NoGo	N2-effect
Younger adults (*n* = 16)	2.84 (*3.17*)	2.01 (*2.09*)	-.83 (*2.28*)	2.51 (*3.28*)	-1.64 (*3.26*)	-4.15 (*3.05*)
Older adults (*n* = 17)	4.98 (*2.98*)	4.90 (*2.04*)	-.077 (*1.39*)	7.67 (*5.75*)	5.05 (*5.65*)	-2.62 (*2.07*)

In younger adults, there were no cross-task correlations with absolute N2 amplitude on Go trials and congruent trials, *r*(14) = .425, *p* =.101, nor with NoGo trials and incongruent trials, *r*(14)= .176, *p* = .514 (see Appendix K for correlation matrix and Figure 3). The N2-effect in the Simon task was not correlated with the N2-effect in the Go/NoGo task in the data presented here, *r*(14) = -.301, *p* = .257 (Figure 4).

For older adults**, t**he absolute N2-amplitude on congruent trials in the Simon task was correlated with amplitude on Go trials, *r*(15) = .649, *p* = .005 (Figure 3). The N2 amplitude on incongruent trials in the Simon task were correlated with NoGo trials, *r*(15) = .703, *p* =.002. However, the N2-effect in the Simon task was not correlated with the N2-effect in the Go/NoGo task in the data, *r*(15) = .059, *p* = .822 (See Appendix K for correlation matrix and Figure 4 below).

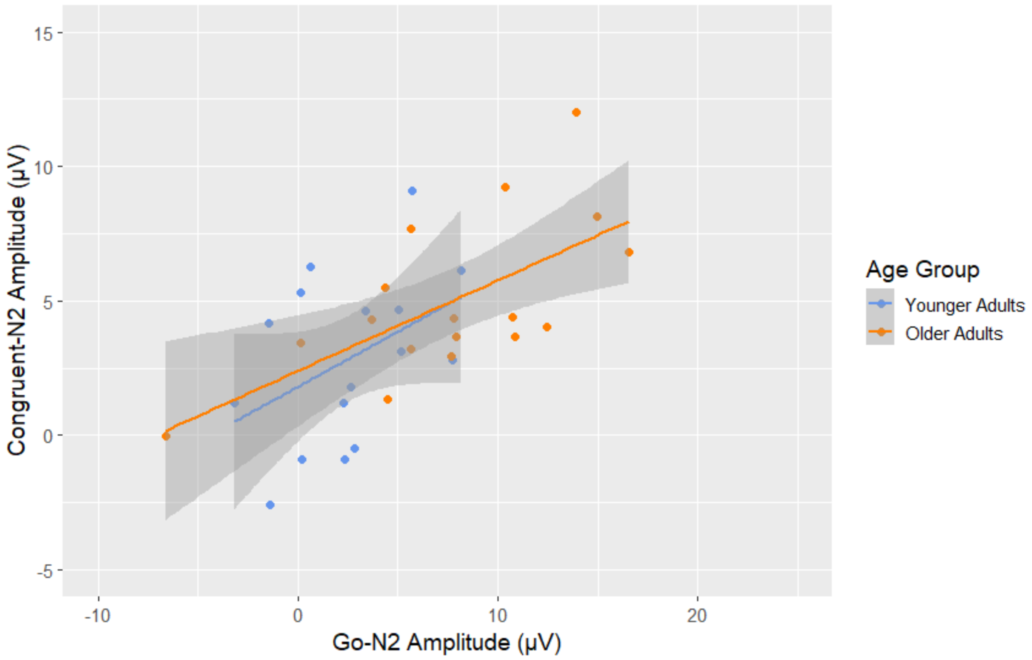


Figure 3. The N2 amplitude on Go trials (Go/NoGo task) was associated with Congruent trials (Simon task) in older adults but not younger adults.

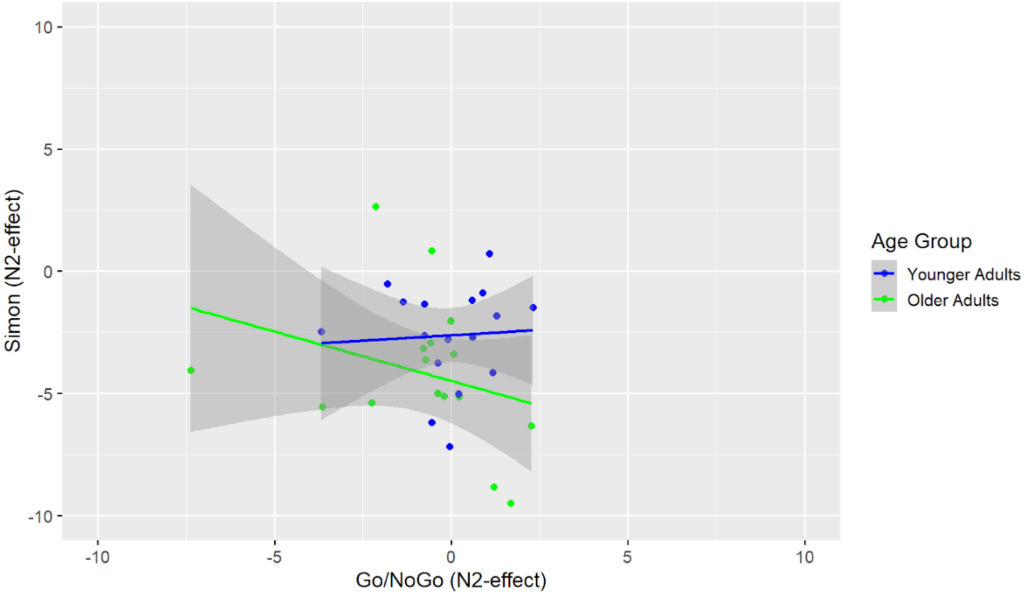


Figure 4. The N2 amplitude effects on the Simon task was not associated with N2-effect in the Go/NoGo task.

N2 latency

Age and N2 latency were not correlated for younger or older adults. There were no cross-task correlations for younger nor older adults. The N2 latency on congruent trials and the N2 latency on Go trials were not correlated in younger nor older adults (See Table 6 below and Table 1 in Appendix L).

Table 6. Descriptive statistics for the peak N2 latency for each of the conditions for both paradigms. Mean (SD) are reported.

	Simon Task			**Go/NoGo Task**		
	Congruent	Incongruent	N2-effect	Go	NoGo	N2-effect
Younger adults (*n* = 16)	314.18 (*23.05*)	312.53 (*19.25*)	-1.65 (*23.28*)	340.97 (*24.00*)	314.74 (*24.09*)	-26.22 (*14.02*)
Older adults (*n* = 17)	302.64 (*41.12*)	311.87 (*28.08*)	9.23 (*28.36*)	311.09 (*23.40*)	312.03 (*22.83*)	0.94 (*28.01*)

8.2.2. P3

The amplitude of the P3 has been associated with intensity of processing (Kok, 2001) and resource allocation (Polich, 1996) and is posited to index updating of working memory (Polich, 2007). On the Go/NoGo task the P3 is reported to be smaller on NoGo trials relative to Go trials (Azizian et al., 2006) and on the Simon task, the P3 is smallest for incongruent trials relative to congruent trials (Galashan et al., 2008; Cespón, Galdo-Álvarez & Díaz, 2013). For both the Go/NoGo and Simon task, the amplitude of the P3 is attenuated in older adults (Cheng, Tsai, and Cheng, 2019; Van der Lubbe & Verleger, 2002). Therefore, it was predicted that the P3 amplitude effect would be correlated in the two tasks given how the P3 has a similar pattern across both paradigms.

P3 Mean Amplitude

Firstly, Pearson's correlations were computed on age in years and the six P3 amplitude variables (P3-Go, P3-NoGo, P3-Go/NoGo effect, P3-Congruent, P3-Incongruent, P3-Simon effect) (See Table 7 for descriptive statistics). Neither in younger nor older adults was age correlated with any of the six P3 amplitude measures, therefore, age was not controlled for in the correlations (See Appendix M for correlation matrix).

Table 7. Descriptive statistics for the mean P3 amplitude for each of the conditions for both paradigms. Mean (SD) are reported.

	Simon Task			**Go/NoGo Task**		
	Congruent	Incongruent	P3-effect	Go	NoGo	P3-effect
Younger adults (*n* = 16)	5.79 (*2.65*)	5.86 (*3.21*)	-0.07 (*1.33*)	13.44 (*5.15*)	6.80 (*1.92*)	5.90 (*3.78*)
Older adults (*n* = 17)	5.82 (*3.55*)	5.37 (*3.04*)	0.44 (*1.19*)	12.33 (*5.86*)	9.12 (*4.73*)	2.36 (*2.41*)

P3 amplitudes were correlated on Go trials and congruent trials, NoGo and incongruent trials, but there were no correlations for the Simon and NoGo effects, for both age groups.

In younger adults, there were correlations with P3 amplitude on Go trials and congruent trials, *r*(14) = .639, *p* =.008, with NoGo trials and incongruent trials, *r*(14) = 6.34 *p* = .008 (see Table 1 in Appendix M for correlation matrix and Figure 5 below). The P3-effect in the Simon task was not correlated with the P3 effect in the Go/NoGo task, *r*(14) = -.223, *p* = .443 (Figure 6). The same pattern was observed in older adults, the P3 amplitude on congruent trials in the Simon task was correlated with amplitude on Go trials, *r*(15) = .784, *p* = .000 (Figure 6). The P3 amplitude on incongruent trials in the Simon task was correlated with NoGo trials, *r*(15) = .703, *p* =.002. The P3 effect in the Simon task was not correlated with the P3-effect in the Go/NoGo task, *r*(15) = .316, *p* = .216 (See Appendix M for correlation matrix and Figure 6 below).

P3 latency

Age and P3 latency were not correlated for younger or older adults. There were no cross-task correlations for younger nor older adults, save for Congruent-P3 and NoGo-P3 latency in younger adults, *r*(15) = .578, *p* =.030. The P3 latency on congruent trials and the P3 latency on Go trials were not correlated in younger nor older adults (See Table 8 below and Table 1 and Appendix N).

Table 8. Descriptive statistics for the peak P3 latency for each of the conditions for both paradigms.

	Simon Task			**Go/NoGo Task**		
	Congruent	Incongruent	P3-effect	Go	NoGo	P3-effect
Younger adults (*n* = 16)	401.37	401.31	0.61	399.92	428.33	6.64
	(*22.16*)	(*25.59*)	(*11.10*)	(*23.72*)	(*49.84*)	(*3.94*)
Older adults (*n* = 17)	488.09	485.52	2.57	473.42	488.58	3.14
	(*67.12*)	(*68.09*)	(*49.81*)	(*42.60*)	(*54.29*)	(*2.95*)

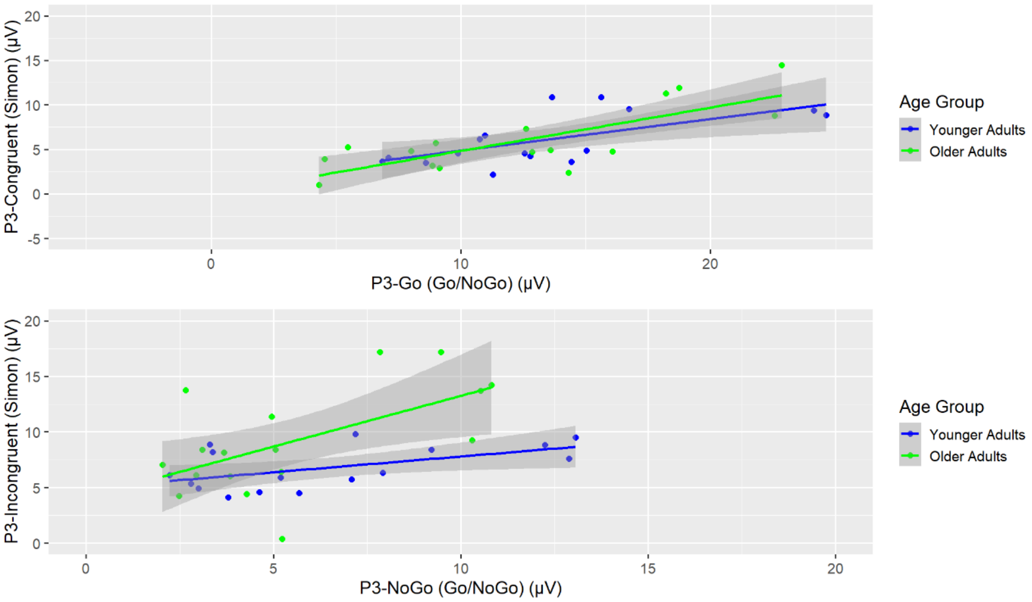


Figure 5. The P3 amplitude on Go trials (Go/NoGo task) was positively associated with Congruent trials (Simon task) in older adults and younger adults. The P3 amplitude on NoGo trials was positively associated with Incongruent trials.

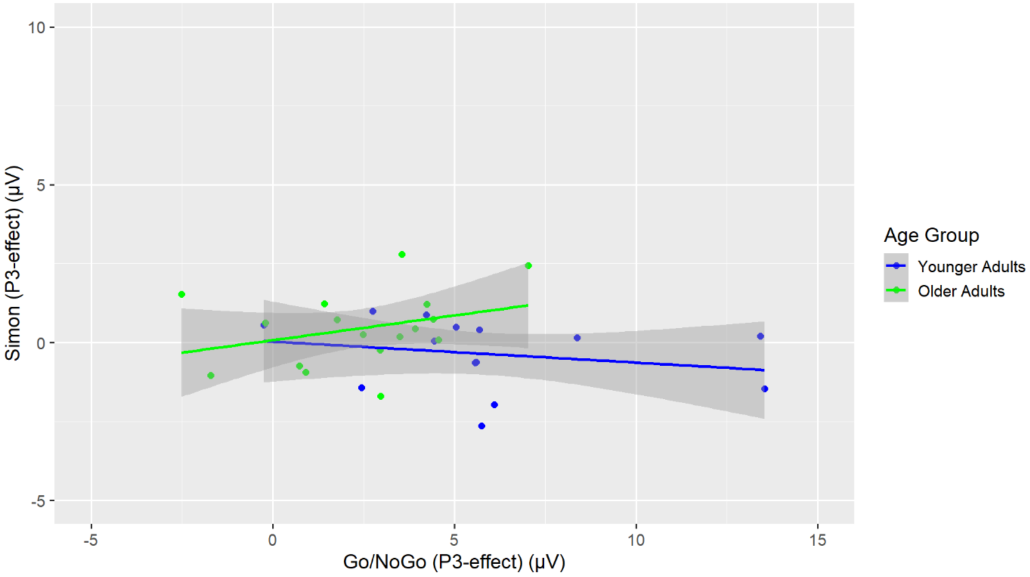


Figure 6. The P3 amplitude effects on the Simon task was not associated with P3-effect in the Go/NoGo task.

8.3. Summary of results

In older adults, there were cross-task correlations with the absolute amplitude of the N2 on Congruent and Go, and Incongruent and NoGo. These associations were not present for younger adults. For both younger and older adults, larger Go-P3 amplitudes were associated with larger Congruent-P3 amplitudes, and larger NoGo-P3 amplitude were associated with larger Incongruent-P3 amplitudes (see Table 9). However, critically, there were no cross-task correlations with the N2-effect or P3-effect in younger or older adults.

Table 9. Summary of results for cross-task correlations.

	Behavioural		**ERP**	
	Inhibition	Monitoring	Inhibition (N2-effect)	Attention (P3-effect)
Younger adults (*n* = 16)	X	✓	X	X
Older adults (*n* = 17)	X	X	X	X

Chapter 9: General Discussion

9.1. THESIS AIMS

Despite the growing body of literature exploring the positive effects of bilingualism on cognitive function, there is no clear consensus on the circumstances under which these cognitive changes occur (Van den Noort et al., 2019). Notably, language group differences in executive function performance are suggested to be more consistently observed in older adulthood, possibly due to increased variability in executive function performance in this age group (Ware, Kirkovski & Lum, 2020). However, the mechanisms underpinning language group differences are argued to be task-dependent, wherein differences in performance between monolinguals and bilinguals are influenced by the paradigm used (Ware, Kirkovski & Lum, 2020). Additionally, it is argued that behavioural measures may lack the sensitivity required to detect subtle differences between language groups, necessitating the use of more sensitive neuroimaging techniques to better understand the specific benefits of bilingualism on distinct aspects of executive functioning (van Heuven & Coderre, 2015). The main objective of this thesis was to explore these three distinct but related arguments by investigating the underlying neurobiological mechanisms of executive function changes in older adult bilinguals on two different non-verbal tasks of executive function. Specifically, four main research questions were addressed across the empirical chapters:

RQ 1: Does bilingualism affect cognitive processing during inhibition of a pre-potent response in older adults?
RQ 2: Does bilingualism influence age-related changes in inhibition to interference?
RQ 3: Are there language group differences in non-inhibition processes such as attention and monitoring?
RQ 4: What is the functional significance of the N2 and P3 in non-verbal executive function tasks?

Firstly, the results of each empirical chapter will be summarised and discussed considering previous work. Following this, the implications of these findings for understanding experience-dependent brain plasticity in older adulthood are discussed.

9.2. SUMMARY OF THE THREE EMPIRICAL CHAPTERS

It is argued that the effects of bilingualism on inhibitory control processes are more easily observed in older adults (e.g., Bialystok, Craik & Luk, 2012; Ware, Kirkovski & Lum, 2020) and under high task demands (Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009). However, the neurobiological underpinnings of the interaction between age, task demands, and bilingualism remains unclear. Using bilingualism as a lens, we aimed to understand how participant age and task difficulty interact to allow us to observe experience-dependent functional plasticity.

In **Chapter 6**: **Experiment 1**, older adult monolinguals and bilinguals performed a visual Go/NoGo paradigm while behavioural and electrophysiological measures of inhibitory control and attention were recorded. The Go/NoGo paradigm included the manipulation of task demands on inhibitory control, wherein NoGo stimuli varied in perceptual similarity to the Go stimuli. Analysis of the behavioural results revealed that the two older adult language groups had comparable reaction times and accuracy rates. In contrast, analysis of the electrophysiological data revealed differences in inhibitory control processes between monolingual and bilingual older adults. Specifically, older adult monolinguals exhibited a typical age-related attenuation of conflict monitoring regulation whilst older adult bilinguals exhibited neural resource allocation akin to younger adults. Moreover, language group differences were most stark on trials placing the largest demands on the inhibitory control system. This chapter highlighted how older adult monolinguals and bilinguals recruit conflict monitoring resources differently during inhibitory control tasks, especially during high task demands.

Chapter 7: Experiment 2 examined the effects of bilingualism and age on ability to inhibit interference from irrelevant stimuli. To do this, younger and older adult monolinguals and bilinguals completed a visual two-way Simon task. On a typical Simon task, participants experience longer reaction times and reduced accuracy to incongruent trials, reflective of increased interference from irrelevant spatial information, known as the Simon effect (for review see Hommel, 2011). Behaviourally, all four groups (younger monolingual, younger bilinguals, older monolinguals, and older bilinguals) exhibited a Simon effect with slower and less accurate responses to incongruent stimuli. This Simon effect was larger for older adult participants, and this age-related increase was comparable across monolingual and bilingual groups. Analysis of the electrophysiological data revealed that for older, but not younger, adults, monolinguals exhibited increased interference from irrelevant stimuli (larger N2-effect) relative to bilinguals. This suggests that older adults experience an age-related change in ability to inhibit interference from irrelevant stimuli, but this age-related change does not extend to older adult bilinguals.

Given both the task-dependant nature of the findings presented above and the argument that tests of executive function using behavioural measures only have little to no convergent validity (Paap & Sawi, 2014, **Chapter 8** aimed to investigate the convergent validity of the electrophysiological measures of inhibition in Simon task and Go/NoGo task. Namely, this chapter aimed to identify whether performance on the Simon and Go/NoGo was underpinned by the same inhibition construct. Correlational analysis revealed that behavioural measures of inhibition were not associated in the two tasks. Similarly, the magnitude of the N2-effect, thought to index inhibition, was not correlated between tasks. The results highlight how performance on these two tasks of inhibition may be underpinned by separable inhibitory control constructs, with the N2-effect in Go/NoGo reflecting magnitude of conflict monitoring and the N2-effect in the Simon reflecting magnitude of interference of irrelevant information.

9.3. EFFECTS OF BILINGUALISM ON INHIBITORY CONTROL

RQ 1: Does bilingualism affect cognitive processing during inhibition of a pre-potent response in older adults?

Research exploring the locus of language group differences in executive function tasks has posited inhibitory control as a potential underpinning mechanism (e.g., Hilchey & Klein, 2011: Bialystok et al., 2004). It is argued that the extensive use of inhibition during language control will confer positive benefits to bilinguals on tasks of inhibition (e.g., Green, 1998). This is supported by research reporting how older adult bilinguals have superior behavioural performance relative to monolinguals on tasks of inhibition (e.g., Bialystok, Craik, Klein & Viswanathan, 2004; Lee Salvatierra & Rosselli, 2011). However, the neurobiological underpinnings of language group differences in older adulthood remain unclear.

In Chapter 6: Experiment 1**,** the aim was to investigate the effect of bilingualism on age-related changes in inhibitory control under different task demands on a non-verbal paradigm requiring inhibitory control and attentional processes. Data from older adult monolinguals and bilinguals were presented with visual Go/NoGo paradigm which manipulated task demands by modulating the perceptual similarity to NoGo stimuli to Go stimuli. Analysis of the behavioural data revealed that the perceptual similarity manipulation did influence the task demands experienced by participants, with more false alarm hits to NoGo stimuli with higher perceptual overlap to the Go stimuli, relative to NoGo stimuli with less perceptual similarity to the Go. However, there were no statistical differences between the rate of these false alarm hits (pressed Go to a NoGo stimuli) between the language groups. This contrasts with evidence from studies employing behavioural measures reporting that bilinguals outperform monolinguals on inhibition tasks, especially when task demands are high (Bialystok et al., 2004; Costa et al., 2009). However, previous work has employed Simon and Flanker tasks, so the contrasting results may be ascribed to the different paradigm choice. This interpretation is supported from the findings of Chapter 8 which demonstrated how different inhibitory control paradigms may not recruit identical inhibitory control processes.

Another notable result from the behavioural analysis is that qualitatively bilinguals appeared to perform overall more slowly than monolinguals. This is not an uncommon finding when comparing monolinguals and bilinguals, with evidence reporting that bilingual children are slower but more accurate during 2-back trials of an n-back task, but comparable on 1-back trials (Janus & Bialystok, 2018). This is also extended to young adults, finding slower but more accurate responses for bilinguals on harder trials of a n-back task (2-back trials), but comparable performance on easier tasks, (2-back trials) (Barker & Bialystok, 2019). One interpretation of this could be that bilinguals are exhibiting slower but more controlled performance. However, bilinguals did not exhibit superior accuracy rates, but this may be linked to high accuracy rates for all participants inducing a ceiling effect. Therefore, it is not possible for us to observe a speed/accuracy trade-off. Moreover, it is important to consider the influence of outliers on the observed trend towards slower reaction times for bilinguals on the Go/NoGo task in Experiment 1. During outlier classification, five datasets were identified with reaction times that deviated by more than two standard deviations from the mean. Following the removal of these outliers, the previously observed trend was no longer present.

Previous research has highlighted how group differences in electrophysiological measures of inhibition can be observed in the absence of behavioural differences (e.g., Moreno et al., 2014). Therefore, electrophysiological measures of inhibition were also taken on the Go/NoGo task in Experiment 1, specifically the amplitude of the N2. The Go/NoGo paradigm elicited typical patterns of N2 amplitude modulations, with larger N2 amplitudes to NoGo stimuli relative to Go stimuli, generating an N2-effect, replicating past work (e.g., Donkers & van Boxtel, 2004; Falkenstein, Hoormann & Hohnsbein, 1999; Gajewski & Falkenstein, 2013; Nieuwenhuis et al., 2003). Larger N2 amplitudes to NoGo stimuli reflects more resources devoted to early conflict processing (Donkers & van Boxtel, 2004).

Similar to behavioural measures of inhibition, evidence suggests that the amplitude of the N2 is also influenced by task demands, specifically perceptual overlap of the NoGo to the Go; a larger N2-effect is elicited when NoGo trials are perceptually similar to the Go compared to instances where the NoGo trials are perceptually dissimilar (Azizian et al., 2006). In contrast to this pattern, analysis of the ERP data in this thesis highlighted how *low conflict* NoGo stimuli (perceptually dissimilar) elicited the *largest* N2 amplitudes, followed by high conflict (perceptually similar) stimuli and then the smallest N2 amplitude was evoked by Go stimuli. While this pattern of results supports the idea that the N2 amplitude is sensitive to task demands, it is contrary to what was predicted.

One interpretation could be that that low conflict NoGo trials are easily distinguished from Go trials allowing for easy conflict monitoring and recognition of the stimuli as conflict. In contrast, high conflict NoGo trials elicit the erroneous activation of the Go response and the bias to respond. In turn, this generates a 'Go-like' N2. This interpretation is supported by the behavioural results which demonstrates higher rates of false alarms on the high conflict NoGo trials, and by research comparing the N2 amplitudes on Go, irrelevant NoGo and conflict NoGo trials. This study found that both younger and older adults exhibited larger N2 amplitudes to the irrelevant NoGo than conflict NoGo (Hsieh, Wu & Tang, 2016). The authors suggest that less control processes were engaged during high conflict NoGo trials due to its similarity to Go and thus producing smaller N2 amplitudes and higher commission errors compared to conflict NoGo.

Latency of the N2 was also found to vary as a result of perceptual overlap; the N2 peaked earlier for high conflict trials relative to low conflict trials. This contrasts with previous work demonstrating that the peak latency of the NoGo-N2 is *elongated* in more complex tasks relative to more simple tasks and this delay is paired with delayed reaction times and decreased accuracy (Gajewski & Falkenstein, 2013). The opposite pattern was observed in the data presented here, with earlier N2 latencies for high conflict trials, which does not seem to align with the interpretation of the NoGo-N2 latency as an index of speed inhibitory control processes overriding a pre-potent response plan (Kopp et al, 1996; Falkenstein et al, 1999). An alternative explanation is that high conflict trials are associated with a faster deployment of inhibition processes, as the conflict is more easily detected.

In Chapter 6: Experiment 1, the hypothesis that language experience affects the neural mechanisms indexing cognitive control was tested. It was predicted that bilinguals would show an N2 Go/NoGo amplitude effect, like younger adults on the same paradigm (Roch, 2015).

Following from previous studies with older adults, it was predicted that monolinguals would not show an N2 Go/NoGo amplitude effect (Cheng, Tsai & Cheng, 2019; Clawson et al., 2017). The absence of the N2-effect in older adults has been linked to reduced sensitivity to conflicting stimuli in older adulthood (Clawson et al., 2017). Previous research utilising reaction time measurements has reported that the effects of bilingualism are only present in high-monitoring conditions (Costa et al., 2009). Analysis of the N2 amplitude revealed that both monolinguals and bilinguals exhibited an N2-effect when comparing low-conflict NoGo trials relative to Go. However, when comparing high-conflict NoGo to Go trials, older adult monolinguals exhibited absence of an N2 amplitude effect, a pattern of typical aging (Cheng, Tsai & Cheng, 2019). In contrast to older adult monolinguals, and similarly to younger adults (Roch, 2015), older adult bilinguals did exhibit an N2 effect on high conflict NoGo trials. This suggests that whilst conflict monitoring processes were modulated by both groups on easily distinguishable, low conflict trials, monolinguals were not able to modulate these processes on harder, high conflict trials. This suggests that bilingualism maintains conflict monitoring regulation efficiency in older adults; that is, bilinguals were able to regulate brain activity as a result of task demands to a greater extent than monolinguals.

The attenuated N2-effect in older adult monolinguals aligns with literature exploring the effects of aging on the amplitude of the N2 suggesting that older adults exhibit an attenuation of the NoGo-N2 amplitude, resulting in a smaller N2-effect (for meta-analysis see Cheng, Tsai & Cheng, 2019). The reduction in the N2-effect is associated with higher false alarm rates (Falkenstein, Hoormann & Hohnsbein, 1999), and the attenuation of the N2-effect may reflect poorer conflict monitoring abilities due to reduced sensitivity to conflicting stimuli in older adulthood and less resources devoted to early conflict monitoring (Clawson et al., 2017; Donkers & van Boxtel, 2004).

Moreover, the attenuation of the N2-effect for monolinguals was constrained to circumstances with higher task demands. This supports findings from behavioural (Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009) and electro-physiological research (Barker & Bialystok, 2019; Comishen & Bialystok, 2021) reporting that the positive effects of bilingualism on cognitive tasks are most evident at higher task demands. A valuable framework for interpreting the data in the context of brain aging can be provided by the Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008). According to the CRUNCH, at higher cognitive loads, older adults over-recruit neural resources to maintain behavioural performance, reflective of a compensatory mechanism to maintain task performance. In the present data, it is possible to interpret the reduced N2-effect in monolinguals during high conflict task demands as a compensatory mechanism given the typical age-related pattern observed. This interpretation is supported by behavioural data as monolinguals exhibited comparable reaction time and accuracies to older adult bilinguals. The notion of the absence of an N2-effect in monolinguals as a compensatory mechanism may also shed light on the inconsistent reports of conflict monitoring advantages in older adult bilinguals (for systematic review see; Van den Noort et al., 2019). Put simply, older adult monolinguals may be over-recruiting neural resources to sustain behavioural performance, leading to null effects in the literature when comparing monolingual and bilingual older adults under low task demands (for systematic review see; Van den Noort et al., 2019).

Work from functional magnetic resonance imaging (fMRI) also supports the interpretation of attenuated N2 amplitudes as a reduction in conflict monitoring processes. Research has implicated the anterior cingulate cortex (ACC) in the generation of the N2 (Van Veen & Carter, 2002). Moreover, the ACC is activated during high conflict task demands (Botvinick et al., 2001). Therefore, attenuation of the N2-effect as a result in reduction of the NoGo-N2 indicates that conflict is not being detected as efficiently in older adult monolinguals, but that bilingualism may impact these age-related changes. This is in line with a review of fMRI studies concluding that bilingualism is associated with a model of efficient brain recruitment (Grundy, Anderson & Bialystok, 2017).

However, this interpretation can be disputed by the lack of behavioural differences between the language groups. With accuracy rates of over 95% for both monolingual and bilinguals on all trial types, an observable reduction was not present in behavioural performance as low demands did not outstrip resources. Future work should endeavour to increase task demands even further to evidence how monolingual behavioural performance will reduce relative to bilinguals as a consequence of over-recruiting resources at lower task demands.

RQ 2: ***Does bilingualism influence age-related changes in inhibition to interference?***

Current research suggests that language group differences are observable on *interference suppression* tasks but not *response inhibition* tasks (e.g., Luk et al., 2010). However, it is important to note that work focusing on the functional significance of the N2 in the Go/NoGo task has highlighted how the N2 does **not** reflect suppression of a motor response (Donkers & van Boxtel, 2004). Here, it is important to distinguish between *inhibition of a motor response* and *inhibition of a prepotent response*. Inhibition of a motor response requires the process of a physical motor response to be withheld (e.g., NoGo trials). Whereas inhibition of a prepotent response refers to the requirement to overcome a bias to a pre-potent response irrespective of whether this response is associated with the withholding or execution of a response. For example, inhibition of a prepotent response would be required on Go trials, when the Go is the most frequent stimuli presented. Participants are biased towards Go response and must overcome this on NoGo trials. However, when NoGo stimuli is frequent, the NoGo response is the pre-potent response to be suppressed. This process has also been called conflict monitoring (Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003). Based on this distinction and building upon the findings presented in the first empirical chapter, the second experimental chapter aimed to explore the impact of bilingualism on age-related changes in both behavioural and electrophysiological measures of inhibition to interference. A sample comprised of younger and older adult participants categorised as monolingual or bilingual completed a visual Simon task, with behavioural and electrophysiological measures of task performance.

Typically, in a Simon task, longer reaction times and decreased accuracy are observed for incongruent trials relative to congruent trials, known as the Simon effect (Simon & Rudell, 1967). It is argued that the Simon effect is driven by the lack of stimulus-response (S-R) compatibility between the spatial location of the stimuli and the spatial locations of the required response (e.g., Craft and Simon, 1970; Simon & Rudell, 1967). To effectively resolve the conflict participants must inhibit interference from the irrelevant spatial location and selectively attend to the task -relevant attribute of the stimuli. Larger Simon effects are associated with increased interference from the irrelevant stimuli-attribute (Hommel, 2011).

In the data presented in this thesis, all groups experienced a Simon effect in reaction time and accuracy. The presence of this effect is indicative that the paradigm did in fact induce interference as a result of conflict spatial-response mapping on the incongruent trials. Moreover, older adults had larger Simon effects in reaction time relative to younger adults. This aligns with past work reporting that older adults typically show larger interference effects relative to younger adults, evidenced by larger reaction time differences (Kubo-Kawai & Kawai, 2010; Proctor, Vu & Pick, 2005; Van der Lubbe & Verleger, 2002) and larger N2 effects (Millner et al., 2012). This age-related increase is thought to be reflective of decreased ability to resist interference to distractor information (Proctor, Vu & Pick, 2005) and increased variability in inhibition task performance in older adulthood (McAuley et al., 2006). Increased difficulty to ignore irrelevant information is thought to be related to reduced efficiency in attentional control (Jennings & Jacoby, 1993) and a reduced ability to inhibit unwanted responses and inputs, suggesting a decline in resistance to interference (Hasher, et al., 1999).

It is suggested that as a consequence of employing domain-general inhibition during language control, bilinguals will exhibit smaller interference effects on the Simon task, and this has been reported in younger adults, manifesting as smaller interference effects in reaction time (Bialystok et al., 2004). Moreover, the positive consequences of bilingualism are suggested to be age-dependant, with smaller observable effects in younger adults and larger effects of bilingualism in older adults.

In the younger adult sample presented here, no language group differences were observed in reaction time or accuracy. This mirrors past work finding no differences between the interference effects of young adult monolinguals and bilinguals on a Simon task (e.g., Bialystok, Martin & Viswanathan, 2005; Paap & Greenberg, 2013). The absence of observable language group differences in younger adults on this paradigm can be attributed to the phenomenon known as the ceiling effect. Younger adults typically operate at peak cognitive performance, and as a result, this population may not receive a cognitive benefit from bilingualism (for review see - Ware, Kirkovski & Lum, 2020; Paap & Greenberg, 2013). Additionally, the ease of the task can contribute to the ceiling effect. When participants do not need to exert inhibition processes to a great extent, it will be difficult to detect any group differences in this measure due to consistently high performance across all individuals resulting in limited variability. This interpretation is supported by the high accuracy rates in the present study (exceeding 90%) as well as in other work where similar null effects of bilingualism were reported in younger adults (98% in Paap & Greenberg, 2013, 99% in Bialystok, Craik & Luk, 2008).

In the older adult sample in the current study, the magnitude of the Simon effect in reaction time did not differ between monolingual and bilingual older adults. This is contrary to previous work reporting smaller Simon effects for bilinguals in younger adult (Bialystok et al., 2004; Bialystok, 2006;) and older adult populations (Bialystok, Craik & Luk, 2008; Bialystok et al., 2004). One factor driving these conflicting results could be task design. Bialystok and colleagues (2004) reported how bigger Simon effects were observed for older adults and for monolinguals, but that this effect was smaller when task demands were lower. This suggests that the task demands in the Simon task employed here did not reach a threshold high enough to distinguish the two language groups behaviourally. Here, we aimed to increase task demands by manipulated stimulus type (colour or shape), but this was an unsuccessful manipulation as there were no differences in reaction time or accuracy between the two stimulus types. There are several other approaches to increasing task demands in the Simon task. Bialystok and colleagues (2004) successfully employed a 4-way Simon task to increase task demands. Other manipulations could include varying the inter-stimulus interval to reduce temporal expectation effects. Moreover, manipulation of the frequency of congruent trials in a task has been shown to affect the magnitude of the Simon effect (Stürmer et al., 2002), therefore decreasing the proportion of congruent trials relative to incongruent trials could increase task demands allowing group differences to be observed more reliably.

Whilst the behavioural data did not distinguish the two older adult language groups, electrophysiological data did. As with the Go/NoGo paradigm presented in Chapter 6: Experiment 1, the amplitude of the N2 was measured. In the Simon task, the amplitude of the N2 is considered to be a measure of magnitude of interference (e.g., Melara et al., 2008; Millner et al., 2012). In line with our predictions, when looking at the electrophysiological data, older adult bilinguals exhibited smaller Simon effects in the N2 amplitude (N2-effect) when compared to older adult monolinguals. Put simply, the increase of the N2 amplitude on incongruent trials relative to congruent trials was larger for older adult monolinguals. Importantly, the two older adult language groups displayed equivalent behavioural performance meaning that interpretation of these differences is not confounded by behavioural performance differences.

It is important to note that the functional significance of N2 amplitude modulations in the Simon task remain unclear as most reviews have focused on other components such as the P3 (e.g., Van der Lubbe & Verleger, 2002) or on Go/NoGo tasks (Cheng, Tsai & Cheng, 2019). Interpretation can be guided by a study which trained younger adults on the Simon task - relative to pre-training, participants showed reductions in reaction time effects and N2-effects in amplitude (Millner et al., 2012). The reductions in Simon effects were driven by a reduction in RT and N2 amplitude on *incongruent* trials (Millner et al., 2012). This suggests that, like RT-effects, the magnitude of the N2-effect in the Simon task indexes magnitude of interference experienced by participants. As a result, the data from the Simon task employed here reflects decreased interference from irrelevant stimuli by older adult bilingual participants, relative to monolingual older adults, at the neural level. Following this interpretation, the smaller N2-effects exhibited by bilinguals suggests that this group experienced similar demands on congruent and incongruent trials, mirroring the pattern observed in the younger adults. In contrast, older adult monolinguals experienced larger interference effects on incongruent relative to congruent trials. Interestingly, the two younger adult language groups were not distinguished by their electrophysiological responses. It is possible that both language groups in this age group were performing at ceiling, therefore the lack of variability in the data will not allow a language group difference to be observed.

The interpretation of the N2 amplitude as an index of the magnitude of cognitive control resources devoted to processing stimuli is supported by work employing functional magnetic resonance imaging (fMRI). Such work proposes that the N2 may be produced by the anterior cingulate cortex (ACC) (Van Veen & Carter, 2002), an area typically activated when control is engaged as a result of high conflict task demands (Botvinick et al., 2001). This is supported by work finding that for the Simon task, incongruent trials are associated with activity in the ACC (Liu et al., 2004), an activation which is thought to reflect the need for behavioural adjustments to improve performance (Kerns, 2006). Consequently, the increased N2 amplitude effect for monolingual older adults may reflect an increased need for control as a result of increased interference. In turn, this suggests that older adult bilinguals experienced less interference as a result of incompatible spatial-response mapping requiring less activation from the ACC to complete the incongruent trials successfully, in turn eliciting smaller N2 amplitude effects.

The interpretation of N2 amplitude changes is made difficult by the lack of a clear understanding of the functional significance of the N2 in the Simon task. Whilst age-related changes have been well documented for behavioural data, reported as increases in reaction time and decreases in accuracy (Van der Lubbe & Verleger, 2002), age-related changes on inhibitory control as indexed by the N2 in the Simon task are not well understood. A meta-analysis (Cespón & Carreiras, 2020) has highlighted how only two empirical papers focusing on the effects of bilingualism on the inhibitory control processes employed during the Simon task utilise both behavioural and electrophysiological measures (Kousaie and Phillips, 2012b; 2017). The current results replicated the findings from Kousaie and Phillips (2012b) with younger adults, finding how language group did not modulate the magnitude of the N2-effect in the younger adult sample in the present study.

However, the findings from the older adult sample presented here conflict with those of Kousaie & Phillips (2017). In their paper, the effects of bilingualism on age-related changes in inhibitory control processes on the Simon task using behavioural measures and event-related potentials were investigated. It was reported that monolingual older adults exhibited larger N2 mean amplitudes overall relative to bilingual older adults, and this was interpreted as the need for monolinguals to monitor to a greater extent than bilinguals. Secondly, in contrast to our finding that *monolinguals* exhibited larger N2 **mean** amplitude effects, this study reported larger N2 **peak** amplitude effects for *bilinguals*. There are theoretical frameworks explaining why a larger Simon effect indexes increased interference (Hommel, Proctor & Vu, 2004) and there is no work explaining why a *larger* Simon effect would be reflective of more efficient processing. Despite this, the authors interpretated this larger Simon effect in N2 amplitude for bilinguals as superior processing, suggesting that monolinguals exhibit interference to an equal extent from both congruent and incongruent stimuli. However, given past work exploring the functional significance of the N2 on the Simon task, the larger Simon effect in N2 peak amplitude reported by Kousaie and Phillips (2017) for bilinguals would reflect increased interference.

The conflicting findings can be explained by differences in methodological choices. Firstly, Kousaie and Phillips (2017) reported comparable N2-effects for the two language groups for *mean* amplitude, but larger N2-effect for bilinguals in the *peak* amplitude measure. The use of peak amplitude measures has been shown to be more susceptible to noise relative to mean amplitude measures (Luck & Gaspelin, 2017), and may consistently overestimate the true measuring of the ERP waveform (Clayson, Baldwin & Larson, 2013). Therefore, the contrasting language group differences observed in the N2-effect in their study between peak amplitude and mean amplitude measures could potentially be attributed to noise artefact. Consequently, results presented here and the findings of Kousaie and Phillips (2017) may differ due to the presence of noise in their study, and the utilisation of different measurement approaches, a factor shown to yield different results (Clayson, Baldwin & Larson, 2013). Secondly, the authors determined the time window for analysis based on visual inspection of the grand average waveform, a procedure known to increase the rate of false positives (Luck, 2014). Further to this, EEG was only recorded at two frontal electrodes (Fz and FCz) despite data being collected with a 64-cap electrode. Although there is debate surrounding how many electrode sites are optimal, averaging across a cluster of sites in your region of interest is best practise to avoid biasing the selection of specific electrodes (Kappenman & Luck, 2016) and in order to improve signal-to-noise ratio (Zeman et al., 2007). Given these methodological caveats, the findings of this paper should be interpreted with caution. Differences in methodological choices between this thesis and the paper presented by (Kousaie & Phillips, 2017) can explain differences in the data outcomes. It is clear that the interpretation of the effects of bilingualism on age-related changes in interference control on the Simon task could be supported by a meta-analysis of event-related potential studies employing the Simon task.

One such meta-analysis has been conducted for Go/NoGo studies, allowing age-related changes to be documented and for mediating factors such as task difficulty to be explored (for meta-analysis see Cheng, Tsai & Cheng, 2019).

The observed larger N2 amplitude effects of older adult monolinguals in the Simon task appears to be primarily driven by changes in the N2 on congruent trials. This finding aligns with the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008) which posits that even for low task demands older adults employ compensatory mechanisms to achieve equivalent behavioural performance to younger adults. With this in mind, in the present study, it is possible that the older adult monolingual group experienced heightened demands on the cognitive process indexed by the N2, even on congruent trials. As a result, this group employed compensatory mechanisms to maintain task performance. In contrast, the older adult bilingual group may not have required such compensatory mechanisms due to accruing superior cognitive performance as a consequence of bilingualism.

Evidence suggests that language group differences are more consistently observed under high task demands (e.g., Barker & Bialystok, 2019; Bialystok et al., 2004; Comishen & Bialystok, 2021; Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009). Moreover, task demands are also shown to modulate the inhibitory control processes on other tasks such as the Go/NoGo task, wherein with increasing task difficulty the NoGo-P3 decreases (Gajewski & Falkenstein, 2012) and the NoGo-N2 is increases (e.g., Donkers & van Boxtel, 2004). This is supported by evidence from Chapter 6: Experiment 1 of this thesis which suggests that the effects of bilingualism on age-related changes in inhibitory control are most apparent under high task demand conditions. Future work should aim to modulate task demands on the Simon task and document the effects of this manipulation on the effects of bilingualism on age-related changes in inhibitory control processes. Modulating task demands to a greater extent than in the present study could also offer evidence to support the CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008). Specifically, if task demands can increase so that a reduction in behavioural performance in older adult monolinguals is observed, paired with a language group difference in inhibitory control measures (N2), it can be assumed that monolinguals are over-recruiting at lower task demands. Elucidating the mechanism underpinning language group differences in older adult populations would provide insight into how experiential factors may modify the trajectory of age-related changes.

9.4. EFFECTS OF BILINGUALISM ON NON-INHIBITION SPECIFIC DOMAINS

RQ 3: ***Are there language group differences in non-inhibition processes such as attention and monitoring?***

Discussion above has focused on inhibition, but now researchers are moving more towards a non-inhibition specific focus, specifically the role of attentional control in language group differences (e.g., Bialystok, 2015; Bialystok, 2017; Bialystok & Craik, 2022). There is work to support this, with evidence finding that bilinguals outperform monolinguals on tasks that do not involve conflict in samples of children (Martin-Rhee & Bialystok, 2008), adolescents (Chung-Fat-Yim et al., 2018), young adults (Costa et al., 2009; Hilchey & Klein, 2011) and older adults (Bialystok et al., 2004).

The presence of language group differences beyond pure inhibition can be tested behaviourally by comparing the reaction time and accuracy of monolinguals and bilinguals on trials which do not contain conflict, and reaction times globally. In this thesis, such analysis did not reveal any observable language group differences. A global RT advantage was not experienced by bilinguals on the Go/NoGo or Simon task, nor were there any differences between language groups in either younger or older adults on any RT or accuracy measures. However, the presence of language group differences on non-inhibition specific processing can also be assessed using electrophysiological data, specifically through measuring the P3, and the amplitude and latency of the P3 was compared between language groups in both Chapter 6: Experiment 1 (Go/NoGo) and Chapter 7: Experiment 2 (Simon).

Firstly, in Chapter 6: Experiment 1 during the Go/NoGo task, the trial type differences reported in the P3 amplitude and latency provide insight into the processes that the P3 may reflect. The results of the current thesis found that in the Go/NoGo task, the P3 amplitude differed as a result of task demands, larger P3 amplitudes were observed for Go trials, followed by high-conflict NoGo trials and finally the smallest amplitude was elicited by low-conflict NoGo trials. In Go/NoGo paradigms, the amplitude of the P3 is proposed to reflect the magnitude of attentional processing devoted to a stimulus (Azizian et al., 2006). Following this interpretation, the results suggest that as Go trials were relevant to responding, participants allocated the most attention to these trials, followed by 'Go-like' perceptually similar NoGo trials and finally low conflict/perceptual dissimilar NoGo trials. This is in line with past work reporting how the P3 is modulated by perceptual similarity – target trials elicit the largest P3 amplitudes, followed by similar nontargets and then finally dissimilar (Azizian et al., 2006). However, the findings here contrast with work demonstrating that the amplitude of the P3 is also sensitive to local probability. Research has reported how the P3 decreases in amplitude as target stimulus probability increases (Polich & Margala, 1997; Squires et al., 1976). However, in this thesis Go trials were the most probable stimuli (50%) yet elicited the largest amplitudes. This supports the interpretation of the P3 amplitude as an index of attentional resource allocation rather than as an index of novel stimulus evaluation.

The latency of the P3 was also influenced by task demands; the latest P3 was elicited by the trials with the least perceptual overlap, replicating past research (Azizian et al., 2006). The latency of the P3 is suggested to be a measure of processing speed (Kok, 2001), and delayed P3 latencies are suggested to reflect slower stimulus categorisation times (Polich & Donchin, 1988). As the perceptually dissimilar NoGo took the longest to categorise, this delayed may be associated with the increased complexity of dissimilar NoGo stimuli – similar NoGo stimuli were simply different coloured version of the Go stimuli, whereas dissimilar NoGo were different cartoon characters altogether. Moreover, increased age was associated with later NoGo-P3 latencies replicating past research (Freidman, 2012; Polich, Ellerson & Cohen, 1996). Given the interpretation of latency as speed of categorisation, the results suggest that older adults took longer to categorise stimuli which aligns with reported delays in processing speed in older adulthood (e.g., Salthouse, 2000).

With focus on language group comparisons, the P3 amplitude and latency (along with P3-effects) were comparable between monolinguals and bilingual participants. This suggests that attentional resource allocation and stimulus categorisation speed was comparable between groups. The lack of language group differences replicates research with younger adults reporting comparable the P3 amplitude between language groups on Go/NoGo paradigms (Roch, 2015; Fernandez et al., 2013). This suggests that the attentional resource allocation processes indexed by the P3 are influenced by the effects of age, but bilingualism is not an experiential factor than can influence these age-related changes.

In Chapter 6: Experiment 2, during the Simon task, the P3 was comparable across all trial types, age groups and language groups. The amplitude and latency of the P3 did not differ between trial types: congruent and incongruent trial elicited comparable P3 amplitudes and latencies. This is contrary to previous work reporting larger P3 amplitudes to congruent relative to incongruent stimuli on the Simon task (Galashan et al., 2008; Cespón, Galdo-Álvarez & Díaz, 2013), and larger P3 amplitudes to easier trials (Gajewski & Falkenstein, 2013) and delayed latencies for more difficult trials (Ragot & Renault, 1981; Melara, et al., 2008) on different EF tasks. However, the results do align with previous work by Kousiae and Phillips

(2012; 2017) who also reported comparable P3 amplitudes for congruent and incongruent trials, in both younger and older adult samples. This absence of a P3 amplitude effect is in contrast with the N2 amplitude results, wherein larger N2-effects for older adults were observed, especially in the monolingual group. These findings allow us to draw two conclusions, firstly, that the locus of the Simon effect is not at the stimulus evaluation stage (as measured by the P3) and occurs at the response selection stage and a result of response competition (as measured by the N2) as suggested by Hommel (1995). Secondly, that on this Simon task, the attentional mechanisms engaged may not be sensitive to language group differences.

The absence of language group differences in the P3 amplitude is difficult to interpret given the lack of research investigating the functional significance of the P3 in the Simon task. Therefore, it is difficult to postulate why the attentional mechanisms indexed by the P3 amplitude might be comparable across language groups. Some researchers suggest that the amplitude of the P3 reflects magnitude of attentional resource allocation, given this interpretation it is tempting to conclude that language groups do not differ in their attentional processing. However, it should be noted that the P3 has been implicated in many cognitive processes including attentional processes, memory encoding and context updating (Luck, 2014). As a result, the functional significance of the P3 in the Go/NoGo task and the Simon task is yet to be definitively established. In reality, the underlying processes indexed by the P3 are likely task-dependent and reflects different processes in different paradigms. Thus, given how the functional significance of the P3 is unclear, it is not possible to simply conclude that attentional processing differences between monolinguals and bilinguals are not observable. Moreover, the Simon and Go/NoGo tasks are not commonly used as measures of attention, paradigms such as the Attentional Network Task and Test of Everyday Attention are more commonly employed (Privitera & Weekes, 2022).

It is possible that attentional processing differences do occur between monolinguals and bilinguals, but that this is indexed on the Go/NoGo task through language group differences in the N2. This interpretation is based on the framework proposed by Bialystok and Craik (2022) which posits that attentional mechanisms underpin other cognitive processes, including inhibitory control. Task demands in Chapter 6: Experiment 1 were manipulated through differing perceptual overlap of the target to the non-target, wherein higher perceptual overlap resulted in higher task demands, and it was assumed that the differential task demands would exert differing demands on the inhibitory control system. This was supported by differences in N2 amplitude, a component thought to index inhibitory control. However, as inhibition is posited to be underpinning by a general attentional process, these task demands may also be exerting differing demands on the attentional control system. This would also explain the lack of P3 amplitude differences on the Simon task between language groups – the attentional demands simply did not exceed the attentional resources of monolinguals as a result, no language group differences were observed. This is supported by the absence of age-related differences in accuracy rates. While the behavioural data suggest that the task difficulty manipulation through S-R congruency was successful as lower accuracy rates were observed for incongruent trials. Age group comparisons demonstrated that older adults did not exhibit an increase in accuracy Simon-effects relative to younger adults, a pattern typically observed (Kubo-Kawai & Kawai, 2010; Proctor, Vu & Pick, 2005). This lack of age group difference in our accuracy data suggests that perhaps the increase in task demands for the incongruent trials was not extensive, and as a result no age group effect in accuracy or a trial type effect in the P3 amplitude was observed.

The role of attention in explaining language group differences is supported by resting-state functional connectivity (rsFC) evidence, which reports how better performance of bilinguals on an attentional network task was correlated with rsFC for seeds in altering and orienting network and that rsFC varied with different levels of bilingualism (Dash, Joanette, Ansaldo, 2022). However, the omission of an inhibitory control task in this investigation means that it is not possible to conclude that these regions are also involved in inhibitory control tasks. It would have been informative to the current investigation if this research had outlined how performance on inhibition tasks was also underpinned by attentional network regions which varied as a function of bilingualism.

It is important to note that the role of attention in explaining language group differences is not concrete. Meta-analysis synthesising evidence evaluating the performance of children and adults with ADHD has reporting that language group differences were not observed (Köder et al., 2022). However, attention is not monolithic; attention is multifaceted including sustained, selective, divided, and alerting attention. Evidence exploring the effects of bilingualism on sustained attention and divided is scarce, and extant literature is affected by methodological issues (for review see Chung-Fat-Yim, Calvo, & Grundy, 2022). However, selective attention is thought to be enhanced in bilinguals on visual paradigms, and this is supported by work with younger adults in the Go/NoGo paradigm used here (Roch, 2015) who reported how younger adult bilinguals were able to suppress irrelevant visual information (as indexed by smaller P1 amplitudes) to a greater extent that monolinguals. The role of attention in language group differences on non-verbal cognitive tasks is not clear, and whether all age groups experience attention benefits from bilingualism in the same way remains to be elucidated. Further to this, research utilising electrophysiological measures with well-established paradigms are lacking.

Moreover, central to the argument posed by Bialystok and Craik (2022) is the role of task demands in modifying observable language group differences in attention, a facet which has not been explored through electrophysiological techniques in older adults. Future work should attempt to parse the effects of task demands on attentional control and inhibitory control systems by comparing trials which both do and do not contain inhibition whilst including different levels of task demands, creating a factorial design whereby process (inhibition/attention) and task demands (low/medium/high) are both manipulated. Performance of monolinguals and bilinguals should be compared to help elucidate the locus of benefits experienced by bilinguals and to understand whether magnitude of task demands modifies the observable presence of language group effects in both processes or whether these processes receive distinct modification as a result of bilingualism.

9.5. BILINGUALISM AND AGE-RELATED SLOWING

At the group level, aging is associated with general slowing of motor responses suggested to reflect slowing the speed of processing (e.g., Salthouse, 1991; Verhaeghen & Cerella, 2002). Behaviourally, this manifests as slowed reaction times and reduced accuracy (Salthouse, 1991). Moreover, at the electrophysiological level, increasing age is associated with smaller N2 amplitudes and later N2 peak latencies relative to younger adults on Go/NoGo tasks (Falkenstein, Hoormann & Hohnsbein, 2002; Hämmerer, Li, Müller & Lindenberger, 2010). Increasing age is also associated with less efficient stimulus categorisation and age-related slowing of stimulus categorisation, this is manifested as later P3 peak latencies relative to younger adults (Friedman et al. 2007; Polich, 1996; Polich & Donchin, 1988; van Dinteren, Arns, Jongsma & Kessels, 2014; for meta-analysis see Cheng, Tsai & Cheng, 2019). However, past work suggests that bilingualism may be able to attenuate age-related changes in cognitive processes (e.g., Bialystok et al., 2004).

In this thesis, electrophysiological measures were used alongside behavioural measures to index speed of processing. To investigate the impact of bilingualism on age-related slowing on inhibition and attentional processes, comparisons of N2 and P3 latencies between older adult monolinguals and bilinguals were made. In the Chapter 6: Experiment 1, a Go/NoGo paradigm was completed by monolingual and bilingual older adults. Analysis of the reaction time, accuracy, and latency of the N2 and P3 revealed that that bilingual language experience does not impact on the timing of cognitive control processes, but age did. Increasing age was associated with longer reaction times on Go trials, lower accuracy, and poorer signal detection. Increasing age was also associated with later NoGo-N2 and NoGo-P3 latencies. The elongation of reaction times as a result of age is consistent and well replicated finding in aging research (e.g., Salthouse, 1991; Verhaeghen & Cerella, 2002).

Moreover, the presence of delayed N2 latencies with increasing age also replicated past research (Falkenstein, Hoormann & Hohnsbein, 2002; Hämmerer, Li, Müller & Lindenberger, 2010). In Go/NoGo tasks, the latency of the N2 is suggested to reflect speed of conflict detection processes (Falkenstein, Hoormann & Hohnsbein, 2002; Hämmerer, Li, Müller & Lindenberger, 2010). Typically, older adults exhibit longer N2 latencies (Falkenstein, Hoormann & Hohnsbein, 2002), and this has been interpreted as a reflection of the general age-related slowing reported in behavioural literature (e.g., Salthouse, 1991,2000; Verhaeghen & Cerella, 2002). However, this age-related slowing was experienced to a comparable extent by monolinguals and bilinguals, suggesting that while aging is consistently associated with slowing in the speed of conflict detection processes, language experience does not impact on this. This is in contrast to conclusions of previous work with behavioural measures, reporting that older adult bilinguals may not experience age-related slowing to the same extent as monolinguals (e.g., Bialystok et al., 2004).

The findings of Chapter 7: Experiment 2, employing the Simon task with younger and older monolinguals and bilinguals, revealed that older adults experienced larger Simon effects in reaction time and in N2-latency relative to younger adults. For the Simon task, N2 latencies are suggested to reflect time taken to overcome interference to distracting information (Gajewski, Stoerig & Falkenstein, 2008), but little work has been done to investigate the effects of age on the latency of the N2 in the Simon task. It is possible to posit that if aging induces a general slowing, then both the Go-N2 latency and NoGo-N2 latency will be delayed relative to younger adults, in turn the N2-effect in latency will not differ between the age groups as the magnitude of the timing interference is not constrained to one trial type. In contrast, if aging only influences the time taken to overcome interference to distracting information, older adults will experience a later NoGo-N2 relative to Go trials generating a larger N2 latency effect, relative to younger adults. In the data presented here, older adults experienced a larger N2 latency effect relative to younger adults, suggesting that older adults took longer to overcome the interference from incongruent trials. The increase of N2 latency confined to NoGo trials refutes the idea that age-related increases reflect general slowing. In fact, these findings suggest that on the Simon task, aging is associated with increases in the time taken to process irrelevant stimuli relative to relevant stimuli. The notion that N2 latency is sensitive to changes in processing efficiency is supported by past work which has reported later N2 latencies for older adults with MCI relative to controls (e.g., Bennys et al, 2007; Missonnier et al., 2007).

In a similar fashion to Chapter 6: Experiment 1, the latency of the N2 did not differ between monolingual and bilingual older adults, in contrast to past work with the Simon task (Kousaie & Phillips, 2017). This suggests that while language group can distinguish between the neural recruitment of inhibition to interference from irrelevant stimuli processes between monolingual and bilingual older adults (N2 amplitude effect), it may not impact on age-related slowing of inhibition processes (N2 latency).

The latency of the second component measured in this thesis, the P3, is suggested to index speed of stimulus categorisation, as shorter latencies are elicited by less demanding tasks (Polich & Donchin, 1988). Shorter P3 latencies are argued to represent faster stimulus classification and thus superior cognitive performance (Magliero et al., 1984). Past research has reported how the P3 peaks later in older adults relative to younger adults in both Go/NoGo tasks and the Simon task (Friedman, 2012; Polich, 1996; for meta-analysis see: Cheng, Tsai & Cheng, 2019; Van der Lubbe & Verleger, 2002). In both the Chapter 5: Experiment 1 (Go/NoGo) task and Chapter 6: Experiment 2 (Simon task), it was found that increasing age was associated with later NoGo-P3 latencies and like the NoGo-N2 this was not influenced by language group in either paradigm. Taken together, these results suggest that aging impacts on the speed of processing (as indexed by latency) on trials which require inhibition, but this age-related slowing is not influenced by language experience. Support for this interpretation comes from the behavioural data in our studies demonstrating how older adults experience slower reaction times, but that this is comparable across language groups.

What does the absence of language group differences on the speed of processing tell us about how bilingualism impacts brain plasticity? With aging comes slowing, and this slowing account for the majority of age-related variance on many executive function tasks (Salthouse, 1996). The absence of a language group effect may be due to the processes behind age-related slowing. Age-related slowing is a robust finding that is replicated across studies in the aging literature (for review see Salthouse, 2000). Slowing is associated with physical brain changes, specifically, reduced integrity in the axon myelination. Axon myelination results in the conduction of action potentials which increases signal transmission speed (Waxman, 1977) and enhances the integration of information across spatially distributed neural networks (Bartzokis et al., 2010). Breakdown of myelin content and integrity is associated with healthy aging (Bartzokis et al., 2010) and as a result cognitive processing speed is reduced (Lu et al., 2013). Aging is also associated with changes in the efficiency of neural resource allocation. The Compensation Related Utilisation Hypothesis (CRUNCH: Reuter-Lorenz & Cappell, 2008) proposes that older adults over-recruit pre-frontal brain regions on easy tasks to allow them to maintain behavioural performance. This compensatory mechanism means that as the task gets harder available neural resources are outstripped by task demands. Brain imaging studies have demonstrated how bilingualism alter the pattern of these recruitment processes. For example, in a cognitive control task, older adults displayed behavioural reductions whilst also over activating pre-frontal regions, but overactivation was only present in older adult monolinguals (Gold et al., 2013). Older adult bilinguals outperformed monolingual peers while displaying decreased activation in the lateral frontal cortex and cingulate cortex. The attenuation of age-related over-recruitment by older adult bilinguals was directly correlated with better performance on the task. Given the distinction between age -related slowing and age-related over-recruitment, it is possible that bilingualism is an experiential factor that can modulate efficiency of neural resource allocation but not age-related slowing.

Taken together, these experimental chapters demonstrated that age and task demands have the potential to influence the observable presence of language group differences on inhibitory control processes. In this thesis, the recruitment of inhibitory control processes in older adults differed between monolinguals and bilinguals. This difference was observable at the neural level yet both older adult language groups performed comparably. Moreover, these language group differences were task-specific; in the Go/NoGo task, a larger N2-effect was observed for older adult bilinguals, suggestive of more effective conflict monitoring processes, in contrast in the Simon task, a smaller N2-effect was observed for older adult bilinguals, possibly reflecting a reduction of interference from irrelevant stimuli. This leads us to our third research question and final empirical chapter, Chapter 8.

RQ 4: What is the functional significance of the N2 and P3 in non-verbal executive function tasks?

Chapter 8 investigated the cross-task convergence of the Go/NoGo and Simon task in a group of younger and older adults using both behavioural and electrophysiological measures.

Correlational analysis of the behavioural and electrophysiological measures across both tasks revealed that there were no cross-task correlations in the behavioural measures of inhibition (interference effects) nor electrophysiological measures of inhibition (N2-effect). These findings are in line with past work which have found no significant correlations between the inhibitory control measures on two tasks (e.g., Kousaie & Phillips, 2012b; 2017; Paap & Greenberg, 2013; Paap & Sawi, 2014). This suggests that although inhibitory control tasks are commonly grouped together and assumed to tap into the same EF construct, performance on these tasks may not be underpinned by the same domain-general mechanism. One factor driving the lack of correlations in behavioural data may be task impurity, the idea that executive function tasks such as Go/NoGo and Simon task do not yield process-pure measures of inhibition (Friedman, 2016). Other extraneous variables such as learning, episodic memory and response selection processes contribute to the performance on these tasks (e.g., Miyake et al., 2000; Valian, 2015). Therefore, a lack of correlations between Go/NoGo and Simon task could also be indicative of how different task-relevant processes are engaged during the performance of these tasks.

Moreover, it is argued that a behavioural ceiling effect in easy executive function tasks may mask any correlations (Poarch & van Hell, 2019). In the current study, the accuracy rates across both tasks were high (> 80%), supporting the idea that the behavioural paradigms had low task difficulty. In order to circumvent limitations with behavioural data, the amplitude of the N2 was also included as a measure of inhibition, and there were no cross-task correlations in the N2-effect on these tasks. Moreover, whilst there is a wealth of research investigating the functional significance of N2 amplitude modulations on the Go/NoGo task (e.g., Nieuwenhuis, Yeung & Cohen, 2004; Folstein & Van Petten, 2008), little work has been done to highlight the significance of the N2 on the Simon task. The work presented here contributes to the understanding of the functional significance of the N2, suggesting that there may be differences in the inhibitory control processes that the N2 indexes on these tasks.

Another interpretation of the absence of correlations is that the tasks are underpinned by separable inhibitory control related constructs. This conclusion has implications which are two-fold. Firstly, it challenges the methodological procedure commonly employed in meta-analyses of executive function tasks and bilingualism which groups these two paradigms under the same umbrella term of 'inhibition' (e.g., Lehtonen et al., 2018). This grouping may yield null results if bilinguals experience an advantage in one type of inhibition but not another. Secondly, it calls into question Miyake's (2000) early tripartite model of executive function which argued that there are 3 separable but related constructs that comprise executive function: inhibition, updating and switching. In 2004, another framework was developed which created a distinction between three types of inhibition (Friedman & Miyake, 2004). Through the use of latent variable analysis, inhibition was separated into three distinct processes: Prepotent Response Inhibition, Resistance to Distractor Interference and Interference Resistance to Proactive Interference. Following this taxonomy, the data presented in this thesis supports the notion that bilinguals may experience an attenuated in age-related decline in prepotent response inhibition and resistance to distractor interference. So, why might bilinguals exhibit differences in inhibition-related processes relative to monolinguals? A bilingual speaker must establish and maintain a goal, such as speaking in one language rather than another. Given that bilinguals experience cross-language activation of their L1 and L2 (e.g., Kroll, Gullifer & Rossi, 2013; Marian & Spivey, 2003; Thierry & Wu, 2004; Wu & Thierry, 2010), and both languages are competing for representation, this goal maintenance requires processes that control interference. Two control processes have been identified that are suggested to contribute to the maintenance of the current language goal: a control processes that monitors for conflict (conflict monitoring) and a process that suppresses interference (interference suppression) (Kerns et al., 2004). Therefore, it is possible that this language experience allows bilinguals to develop a more efficient system for both conflict monitoring and resolution of interference. As a result, older adults bilinguals exhibit N2 amplitude effects akin to younger adults in tasks that require conflict monitoring (Go/NoGo) and interference suppression (Simon).

However, it is evident that more work is required in order to highlight which types of inhibition are recruited on a Go/NoGo task and which inhibition-related functions experience an advantage as a result of bilingualism. Moreover, the conclusion that the N2 in the Simon and Go/NoGo tasks represent separable inhibition control processes could be bolstered by future working employing functional magnetic resonance imaging (fMRI). Past work employing fMRI has highlighted how response inhibition and interference suppression is underpinned by distinct neural networks, and that these networks are employed differentially by monolinguals and bilinguals (Luk et al., 2010). This distinction elucidates a factor which may be driving inconsistent findings in research comparing monolinguals and bilinguals when focusing on inhibition: not all inhibitory control tasks employ the same inhibitory control construct, and as a result, differential effects of bilingualism are observed.

9.6. THE BILINGUAL EXPERIENCE AND OTHER LIFESTYLE FACTORS

Understanding how bilingualism may impact age-related changes in executive function processes was the main goal of the work presented in this thesis. However, other factors outside of language experience can contribute to experience-dependant plasticity. In the aging literature, the Scaffolding Theory and Aging and Cognition (STAC; Park & Reuter-Lorenz, 2008) proposes that there are factors which can have either a positive or negative influence on the trajectory of age-related changes. For example, increased exercise and higher level of education are protective factors against cognitive decline, which result in the need for less compensatory scaffolding through mechanisms such as over-recruitment. In contrast, life course factors such as stress and toxin exposure can contribute to neural resource deletion (negative influences on brain structure, neural function, and cognition). The notion that other lifestyle factors beyond bilingualism can contribute to changes in processing is supported by research utilising event-related potentials. Younger individuals who consume a higher quantity of cigarettes and alcohol have reduced NoGo-N2 amplitudes in Go/NoGo tasks (e.g., Luijten, Littel & Franken, 2011; Oddy & Barry, 2009), a pattern associated with poor conflict detection (Falkenstein, Hoormann & Hohnsbein, 1999). Moreover, increased physical fitness is associated with a decrease of amplitudes in N2 on the Flanker task, indexing more efficient executive control processes (e.g., Stroth et al., 2009).

In the current thesis, the influence of lifestyle factors such as smoking, drinking and exercise was investigated alongside bilingualism. Older monolingual and bilingual adults had comparable self-reported measures on factors such a frequency of cigarette and alcohol intake, frequency of strength and aerobic exercise and sleep duration and quality. However, these factors were not found be associated with any measures of inhibition or attention in our study. One reason for this may be the lack of variability in our data. For example, only 1 younger adult and 2 older adults reported smoking, and 53% of younger adults and 31% of older adult participants reported participating in vigorous exercise once or twice a week. The lack of variability in our sample could be reflective of the questionnaire design. Participants were asked to report these factors on a 5-point Likert Scale. Potentially using a different approach, such as asking participants to record exercise/smoking/alcohol intake frequency over a week would provide a more accurate representation and a more variable measure. The lack of variability in our data meant that null effects are more likely to be observed. Investigating how other factors may mediate the presence of language group differences would provide an important contribution to understand experience-induced plasticity in older adults.

9.7. LIMITATIONS AND FUTURE RESEARCH

One main limitation of the research presented here is low statistical power as a result of small sample sizes, specifically in the Simon task. It is not uncommon in ERP studies investigating the impact of language experience on cognition to have sample sizes under 20 per group (e.g., Fernandez et al., 2013; Fernandez et al., 2014; Moreno et al., 2014). Yet, it has been argued that such studies are underpowered as a consequence of "risky small numbers" of participants (Paap, Johnson & Sawi, 2014), and that studies with small numbers of participants are more likely to report superior performance from bilinguals (Paap et al., 2014). To tackle the issue of power in this thesis, an a priori power analysis was conducted using reported effects sizes from published studies (from Moreno et al., 2014; Kousaie and Phillips, 2017). For the Go/NoGo task, sample size estimates calculated using G*Power (Faul, Erdfelder, Lang & Buchner, 2007) recommend a sample size of at least 52 participants to reach 80% power. This study met these requirements and recruited sixty-nine participants. More participants were collected for three reasons, (1) to increase power, (2) in the event participants data could not be used we could still meet power requirements and (3) a larger sample would allow us to have power for correlations with age and bilingual factors such as age of acquisition and proficiency. The current thesis investigated associations of the N2-effect with bilingualism measures such as proficiency and AoA but no measures were correlated. For brevity, that analysis was not included in the thesis.

The limited number of participations in the younger adult and older adult groups was reduced further for analysis of the ERP data. A post-hoc power analysis using G*Power indicated that low power was present for the third empirical study focussing on cross-task correlations between the N2-effects (0.23 power, indicating that there is only a 23% probability that an effect would be observed if a true effect was present). Therefore, future work should endeavour to replicate these findings with a larger sample size. Whilst we did observe significant correlations with the Go-N2 and Congruent-N2, and NoGo-N2 and Incongruent-N2, these associations should be interpreted carefully. Although it may seem that this is evidence that these tasks employ the same underlying inhibitory control construct, significant correlations in raw amplitude measures that do not include subtractive logic simply tell us that an individual with large ERPs in one task, have large ERPs in another. These correlations are evidence for systematic individual differences across these tasks.

For the Simon task, a power analysis was conducted based on data from a comparison of N2 in older adults on a Simon task (Kousaie & Phillips, 2017). G*Power calculated that the recommended sample size was 51 for the simplest between group comparison. Sixty-six participants were recruited for this study (24 younger and 42 older adults). The power requirements were met for between group comparisons of age as 66 participants were recruited, however within each age group the power requirements were not met to compare language groups. This was a result of the COVID-19 pandemic during which complete cessation of data collection occurred.

Another factor related to the issue statistical power is the high rate of trial rejection resulting from artefact rejection in the older adult population reported, especially in the Simon task. Artefacts are signal from non-neural sources such as electrical signals from the recording environment or biological signals such as blinks, eye movements and muscle activity (Luck, 2004). Artefacts decrease the signal-to-noise ration of the averaged ERP waveform, therefore minimising the effect of artefacts through data processing procedures is required. The inherent design of visuo-spatial properties of the Simon task may have induced a higher rate of ocular artefacts. The Simon task presented stimuli at either side of a fixation point and despite instructing participants to maintain their fixation on a central cross, many participants did execute eye movements and, anecdotally, older adults reported that it was often difficult to avoid moving their eyes to view the stimuli in the centre of their vision. As a consequence, many trials contained eye movement artefacts and in some participants these eye movement artefacts were present on nearly all trials meaning that their data could not be used. There are two possible ways to circumvent this problem, (1) use a paradigm in which stimuli are presented centrally avoiding possible automatic eye movements to focus on stimuli, (2) using artefact correction techniques to remove eye artefacts from the data. The issue with solution one is that the spatial-response incompatibility of the Simon task is suggested to be the driving force behind the interference effect (Hommel, 2011), therefore presenting information centrally may not induce an interference effect that we can compare between groups.

Solution two (using artefact correction) would be beneficial to cleaning the data. Research has shown that independent component analysis (ICA) is an effective method of artefact correction (Jung et al., 2000). However, ICA subtracts an estimated value from the data, therefore it might distort the ERP waveforms and there is no way to measure the extent of this distortion on the true data (Luck, 2014). Further to this, ICA requires a lot of computing power, a practical issue which we encountered during this process. However, it should be noted that a comparison of artefact rejection and artefact correction on a sample was computed and there were no differences in the pattern of statistical significance of the data when comparing these two artefact handling techniques. A potential way to circumvent these systematic eye-movements would be to increase the inter-stimulus jitter during the Simon paradigm so that visual stimuli is presented at a more varied rate.

While the event-related potential technique offers myriad benefits due to its high temporal sensitivity, one drawback of the ERP technique is that the interpretation of later event-related potentials (ERPs) such as the N2 and the P3 can be limited when there are differences in the earlier components such as the P2. With focus on Chapter 6: Experiment 1, the Go/NoGo data presented in this thesis, an early exogenous component was present before the components of interest, specifically the P2. The P2 was larger and earlier in amplitude to Go trials, followed by similar Go and finally dissimilar NoGo, and there were no differences in this pattern between language groups. There is limited understanding of the functional significance of the P2 in the visual Go/NoGo paradigm (see Benikos, Johnstone & Roodenrys, 2013 for a discussion of this). A recent meta-analysis looking at bilingualism and age on ERP components highlighted how only one paper reported on the P2 (meta-analysis by Cespón & Carreiras, 2020). This paper found no amplitude differences between Go and NoGo trials (Moreno et al., 2014). Given this, the effects of age and bilingualism on this component were not explored as any interpretation would difficult. Future work should endeavour to build a clear understanding of the functional significance of the P2 on a Go/NoGo paradigm before exploring how age and bilingualism may impact its amplitude and latency.

A further limitation of the research presented here is the inclusion of only two measures of executive function. It is argued that researchers focusing on the impact of bilingualism on cognition should include multiple tasks that target the same underlying executive function construct (e.g., Paap & Greenberg, 2013). However, as highlighted in Chapter 1: General Introduction, Chapter 8: Simon task and Go/NoGo task lack convergent validity, and in past work, executive function tasks have little to no convergent validity (Paap & Sawi, 2014). Future work should endeavour to tackle the limitations of small sample size and the use of only two executive function measures through using a large-scale battery of tests (including Simon, Go/NoGo and other executive function tests such as Flanker, Stroop) administered on a larger sample of individuals. This large-scale investigation would allow researchers to perform a confirmatory factor analysis (CFA) to understand whether tasks used ubiquitously to study inhibitory control advantage in bilinguals (such as Go/NoGo and Simon task) are underpinned by a common latent variable. This CFA approach requires participants to complete several executive function (EF) tasks thought to target the same underlying EF constructs. A set of manifest (or observed) variables are combined into latent variables. The latent variables are variables that are measured indirectly using the manifest variables. Multiple tasks measuring behavioural and ERP measures of inhibition and non-inhibition related EF constructs would provide support to the conclusion drawn in this thesis.

It was not possible to perform a factor analysis in the current study for two reasons (a) sample size and (b) low number of paradigms *(k* = 2). Confirmatory factor analyses require sufficient power which is derived from sample size and paradigm count in order to identify latent variables (Kyriazos, 2018), and the sample size and paradigm count were not sufficient in this current study to do so. Past work that has employed CFA to understand more about the construct of executive function (Miyake et al., 2000), however, this study only recruited university age students and only employed the Stroop, Simon, and Flanker paradigms. Through recruiting a sample with a range of ages (younger to older adults), it is also possible to investigate whether the construct of executive function remains stable across development or changes with age.

Understanding cross-task convergence and age-related changes in the construct of executive function and has implications for research investigating the presence of language group differences. Previous work has suggested that the presence of language group differences is task specific (Ware, Kirkovski & Lum, 2020). If tasks do not correlate, then this suggests that differences between language groups is focussed on one specific executive function domain. However, without the use of large-scale CFA it is difficult to specify which inhibitory or executive function domain these differences stem from.

Moreover, the impact of immigration was not considered in this thesis. Participants reporting a range of birth countries. For example, in younger adults included in the analysis in Chapter 7: Experiment 2 (Simon), 12 of the 19 participants reported Wales or England as their place of birth, the remaining seven participants reported Afghanistan, Bulgaria, Burma/Myanmar, China, Cyprus, Hungary or Romania as their place of birth. In the older sample, all participants reported England, Wales or Ireland as their place of birth. Despite these differences between the age groups, the impact of immigration was not considered. Previous research has argued that the effects of socio-economic status and bilingualism are independent (Calvo & Bialystok, 2014), but this may be dependent on context. For example, in Canada bilingual children often come from immigrant Canadian families whose educational level is on average higher than that of monolingual Canadian families (PCEIP; Statistics Canada, 2003 as reported in Ladas, Carroll & Vivas, 2015). In British studies, low SES bilingual samples can be composed of first-generation immigrants, some of whom are refugee and/or asylum seekers (e.g., Naeem et al., 2018). It is well-established that SES influences executive function performance (Hackman, Gallop, Evans & Farah, 2015; Lawson, Hook & Farah, 2018), therefore exploring how immigration may impact EF in the context of SES is important to understand. It is important to note that the monolingual and bilingual groups in the research presented here had comparable SES scores as measured by the Barratt Simplified Measure of Social Status (Barratt, 2006).

Finally, researchers have advocated for the use of bilingualism as a continuous variable rather than a dichotomous variable (Incera & McLennan, 2018), especially in the aging population (Dash, Joanette & Ansaldo, 2022). However, conflicting findings have been reported, with some researchers reporting that higher levels of bilingualism (as defined by percentage of time exposed to their L2) are correlated with better task performance, and other studies reporting no associations with bilingual factors and task performance (Paap et al., 2018). The current experiments did not find associations between bilingualism factors such as L2 age of acquisition (AoA), proficiency or daily use, and neurophysiological or behavioural measures (these correlations were not reported here for brevity). This contrasts with previous research which has demonstrated functional brain organisation differences in early and late bilinguals (Hull & Vaid, 2007). Also, past work has shown that the N2 is modulated by proficiency (Fernandez, Tartar, Padron & Acosta, 2013). Therefore, the evidence presented here does not contribute to a clear consensus on the circumstances under which bilingualism variables are correlated with behavioural or electrophysiological outcomes on executive function tasks.

Moreover, the reliability of self-reported categorisation as monolingual or bilingual has been called into question when compared to objective measures of language experience (Wagner, Bialystok & Grundy, 2022). Future work should endeavour to using objective measures to quantify proficiency and use this information to further understand the relationship between L2 proficiency, L2 usage and behavioural and electrophysiological measures of inhibition and attention. Understanding the circumstances under which bilingualism confers the most benefit to cognition can provide key insight into the mechanisms underpinning experience-induced plasticity.

9.9. SUMMARY AND CONCLUSIONS

This is the first set of studies to compare the behavioural and electrophysiological measures of younger and older adult monolinguals and bilinguals in two tasks argued to engage inhibitory control processes, and to then compare these measures across the two tasks. In younger adults, language group difference did not differentiate behavioural performance, inhibitory control (as measured by the N2) or attentional processes (as indexed by the P3) on Go/NoGo or visual Simon task. In the Simon task, older adults experienced longer reaction times and lower accuracies relative to younger adults, but this did not differ between language groups. Bilingualism did attenuate age-related changes in conflict monitoring (Go/NoGo task) and inhibition (Simon task) processes. Aging was associated with a slowing of inhibition and attention processes, but there were no differences in this slowing between language groups. Moreover, the attentional processes indexed by the P3 amplitude are influenced by aging, but not bilingualism. However, it should be noted that the functional significance of the P3 in the Go/NoGo and Simon task is still unclear, and the role of attention in the performance of these tasks and in turn the language group differences on attentional processes remains unclear.

The third empirical chapter highlighted how the indices of inhibition between the Go/NoGo task and Simon task were not correlated, suggesting that performance on these tasks may be underpinned by two separable processes. More work is required to understand more about the distinct inhibitory control processes required on these paradigms, and to understand the functional significance of the N2 and P3 on the Simon and Go/NoGo task. The findings elucidate how researchers should be cautious when drawing comparisons between studies that employ different paradigms.

This thesis provides evidence that bilingualism may impact age-related reductions in the efficiency of neural resource allocation, but age-related slowing may not be influenced by bilingualism. Moreover, not all tasks reported to employ inhibitory control processes are alike and different tasks may recruit different inhibitory-related processes, but more research is required in order to clearly identify these processes.

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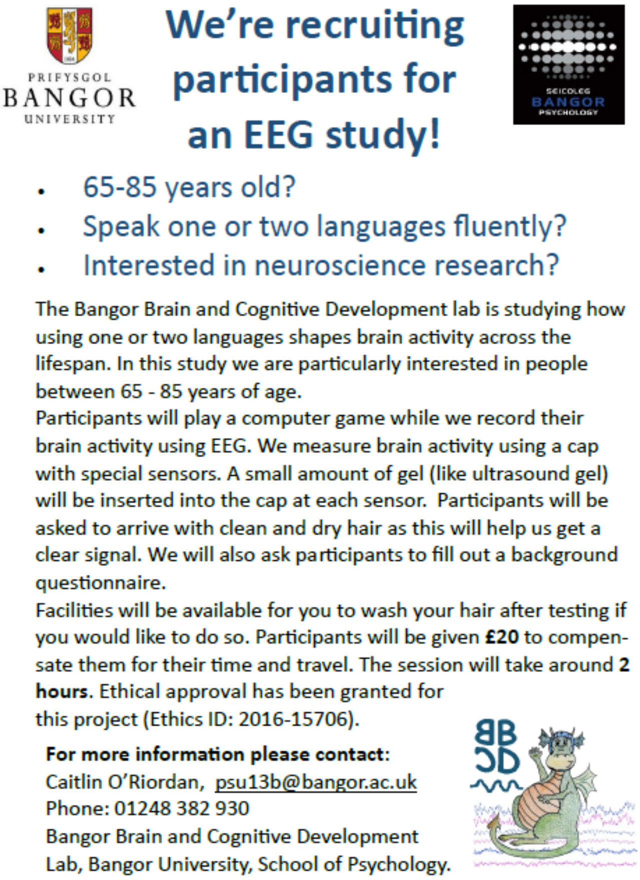
Appendices

Appendix A. Recruitment Flyers



We're recruiting participants for an EEG study!

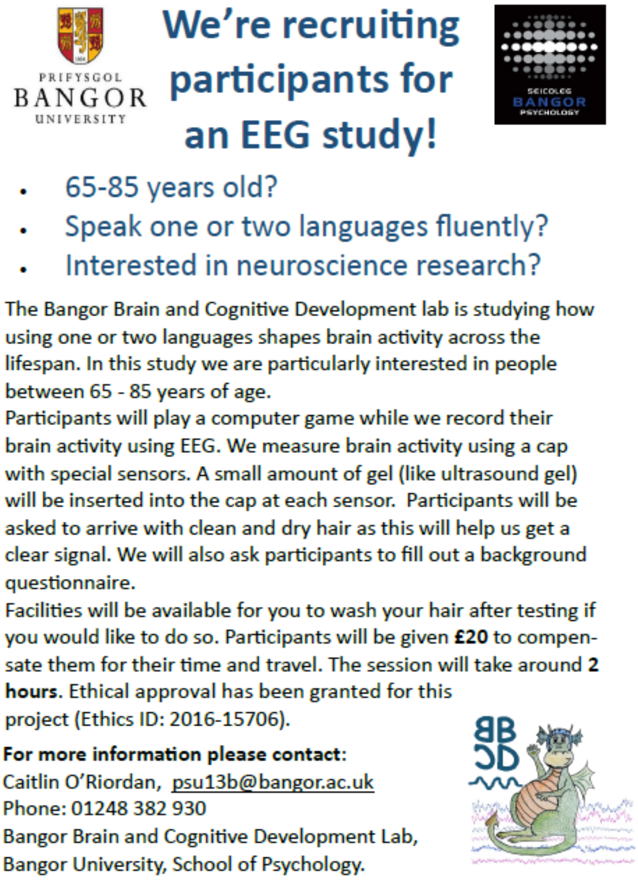
- 65-85 years old?
- Speak one or two languages fluently?
- Interested in neuroscience research?

The Bangor Brain and Cognitive Development lab is studying how using one or two languages shapes brain activity across the lifespan. In this study we are particularly interested in people between 65 - 85 years of age.

Participants will play a computer game while we record their brain activity using EEG. We measure brain activity using a cap with special sensors. A small amount of gel (like ultrasound gel) will be inserted into the cap at each sensor. Participants will be asked to arrive with clean and dry hair as this will help us get a clear signal. We will also ask participants to fill out a background questionnaire.

Facilities will be available for you to wash your hair after testing if you would like to do so. Participants will be given **£20** to compensate them for their time and travel. The session will take around **2 hours**. Ethical approval has been granted for this project (Ethics ID: 2016-15706).

For more information please contact:
Caitlin O'Riordan, psu13b@bangor.ac.uk
Phone: 01248 382 930
Bangor Brain and Cognitive Development
Lab, Bangor University, School of Psychology.


PRIFYSGOL BANGOR UNIVERSITY
SEICOLEG BANGOR PSYCHOLOGY
BBCD

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Appendix B. Demographic Questionnaires

The Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005) was administered by the experimenter to assess the presence of mild cognitive decline in participants. The highest possible score on the MOCA is 30 points.

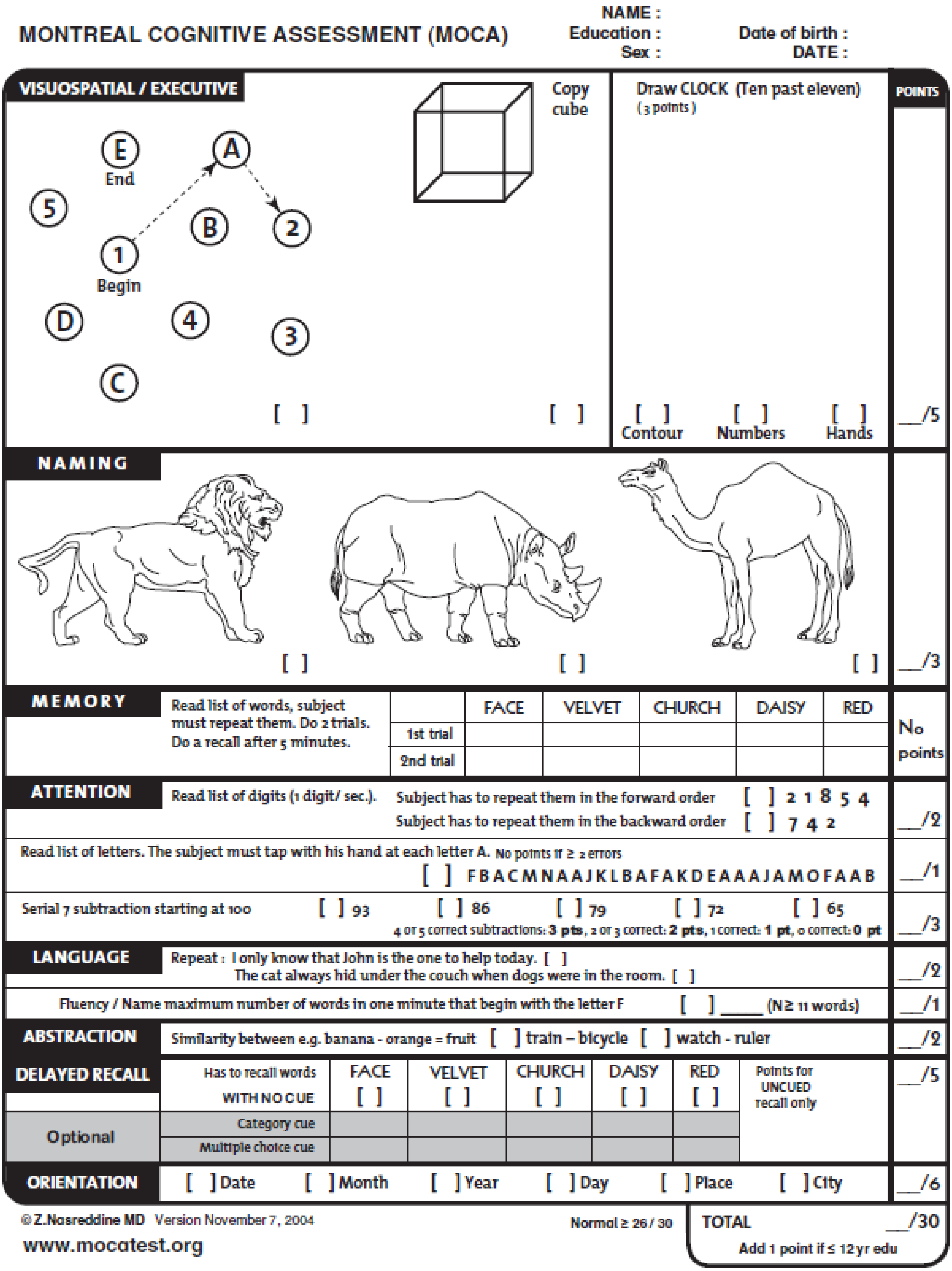
The Edinburgh Handedness Inventory (Oldfield, 1971) was utilised to assess whether participants were left dominant, right dominant, or mixed. A laterality quotient is produced for each individual based on their self-reported hand, eye and food preference on 12 tasks. The laterality quotient is along a continuum of -100 (fully left dominant) to +100 (fully right dominant). Individuals scoring -100 to -71 are classed as left dominant, -70 to +70 as mixed and +71 to +100 as right dominant, as defined by previous research (Dragovic, 2004).

In order to measure socio-economic status (SES), participants were also asked to complete the Barratt Simplified Measure of Social Status (BSMSS; Barratt, 2006), a measure based on the Hollingshead Index (Hollingshead, 1975). The BSMSS considers education and occupation of the participant, their parents and their spouse. The scores from this measure are ordinal only and are not used to classify individuals into a particular social-economic status. The BSMSS generates a score between 8 and 66, and a higher score indicates higher socio-economic status.

Edinburgh Handedness Inventory (Oldfield, 1971)

Please mark the box that best describes which hand you use for the activity in question.

	Always Left	Usually Left	No preference	Usually Right	Always Right
Writing					
Drawing					
Throwing					
Scissors					
Toothbrush					
Knife (without a fork)					
Spoon					
Broom (upper hand)					
Match (when striking)					
Opening box (lid)					
Which foot do you prefer to kick with?					
Which eye do you use when using only one?					



MONTREAL COGNITIVE ASSESSMENT (MOCA)

NAME :
Education :
Sex :
Date of birth :
DATE :

			POINTS
VISUOSPATIAL / EXECUTIVE [ ]	Copy cube [ ]	Draw CLOCK (Ten past eleven) (3 points) [ ] Contour [ ] Numbers [ ] Hands	___/5

NAMING

[ ] [ ] [ ] ___/3

MEMORY Read list of words, subject must repeat them. Do 2 trials. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED	
1st trial						No points
2nd trial						

ATTENTION Read list of digits (1 digit/ sec.).
Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2 ___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B ___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt** ___/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ] ___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] ____ (N≥ 11 words) ___/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler ___/2

DELAYED RECALL	Has to recall words	FACE	VELVET	CHURCH	DAISY	RED	Points for UNCUED recall only	___/5
	WITH NO CUE	[ ]	[ ]	[ ]	[ ]	[ ]		
Optional	Category cue							
	Multiple choice cue							

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City ___/6

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www.mocatest.org

Normal ≥ 26 / 30

TOTAL ___/30
Add 1 point if ≤ 12 yr edu

The Barratt Simplified Measure of Social Status (BSMSS)

Measuring SES

Will Barratt, Ph.D.

Mark the appropriate box for your Mother's, your Father's, your Spouse / Partner's, and your level of school completed and occupation. If you grew up in a single parent home, mark only the box from your one parent. If you are neither married nor partnered, only mark the box relevant to you. If you are a full time student mark only the boxes for your parents.

Level of School Completed	Mother	Father	Spouse	You
Primary School (Age 11)				
Partial Comprehensive				
Comprehensive School (GCSE)				
6th Form College (AS/A Levels)				
Partial University (at least one year)				
Undergraduate Degree				
Postgraduate Degree				

Mark the appropriate box for your Mother's, your Father's, your Spouse / Partner's, and your occupation. If you grew up in a single parent home, mark only the box for your parent. If you are not married or partnered mark only the box relevant to you. If you are still a full-time student only mark the boxes for your parents. If you are retired use your most recent occupation.

Occupation	Mother	Father	Spouse	You
Day laborer, janitor, house cleaner, farm worker, fast food sales, food preparation worker, or waiter/waitress.				
Refuse collector, fast food cook, taxi driver, shoe sales, assembly line worker, masons, or baggage porter.				
Painter, skilled construction trade, sales assistant, truck driver, cook, sales counter or general office clerk.				
Car mechanic, typist, locksmith, farmer, carpenter, receptionist, construction laborer, or hairdresser.				
Machinist, musician, bookkeeper, secretary, insurance sales, cabinetmaker, personnel specialist, or welder.				
Supervisor, librarian, aircraft mechanic, artist and artisan, electrician, administrator, military enlisted personnel, or buyer.				
Nurse, skilled technician, medical technician, counselor, manager, police and fire personnel, financial manager, physical, occupational, or speech therapist.				
Mechanical, nuclear, and electrical engineer, educational administrator, veterinarian, military officer, elementary, high school and special education teacher.				
Physician, attorney, professor, chemical and aerospace engineer, judge, company director, senior manager, public official, psychologist, pharmacist, or accountant.				

Language and background questionnaire for adults

Thank you for agreeing to participate in this study. We would like to get some background information on your language. Please feel free to answer these questions in any way you feel is appropriate, and if there is any question you would rather not answer, that is fine too. Just leave it blank and pass on to the next question.

1 (a) Which languages do you speak? When did you begin speaking these?
Please tick all that apply.

☐ English:

☐ This is a native language **or** ☐ I began speaking this language at age ……….

☐ Welsh:

☐ This is a native language **or** ☐ I began speaking this language at age ……….

☐ Other (please specify): ……………

☐ This is a native language **or** ☐ I began speaking this language at age ……….

(b) Approximately what percentage of the time do you speak these languages?
Please put a cross on the scale in the position that best applies.

Overall:

English English/Welsh Welsh*

100% 50%/50% 100%

In the home:

English English/Welsh Welsh*

100% 50%/50% 100%

Outside the home:

English English/Welsh Welsh*

100% 50%/50% 100%

*if you speak another language alongside English besides Welsh please specify here

Optional: If you have stated that you speak a low percentage of one your languages, approximately how many hours a week do you speak this language? And in what context (i.e. in a formal class, at work, with a friend)

Hours: ……………………………..
Context:……………………………………………………………

2. Which languages were spoken **<u>in your home</u>** when you were the following ages? (Including the language used by grandparents and siblings in speaking to you). Please place an 'x' on the line to indicate the percentage of language use.

Birth – 2 years

English English/Welsh Welsh*

100% 50%/50% 100%

3 – 4 years

English English/Welsh Welsh*

100% 50%/50% 100%

5-6 years

English English/Welsh Welsh*

100% 50%/50% 100%

Primary School age

English English/Welsh Welsh*

100% 50%/50% 100%

Secondary School age

English English/Welsh Welsh*

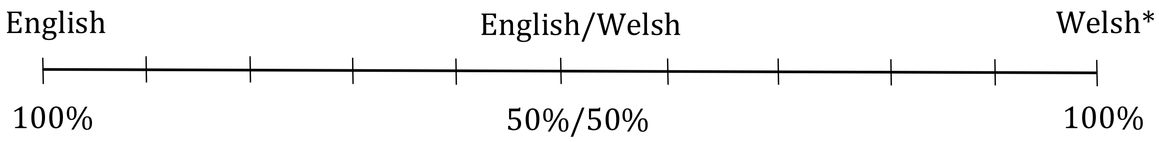
100% 50%/50% 100%

Younger adult (20 -59 years)

English English/Welsh Welsh*

100% 50%/50% 100%

Older adulthood
(60+years)



3(a) On a scale of 0 to 6 (6 highest), how well do you feel you **speak** Welsh*?

0	1	2	3	4	5	6
I have no proficiency in this language	Only know some words and expressions		Can carry out basic conversations		Can carry out extended conversations	I have native like proficiency

(Optional) Comments: ____

(b) On a scale of 1 to 6 (6 highest), how well do you feel you **speak** English?

0	1	2	3	4	5	6
I have no proficiency in this language	Only know some words and expressions		Can carry out basic conversations		Can carry out extended conversations	I have native like proficiency

(Optional) Comments: ____

4 (a) On a scale of 1 to 6 (6 highest), how well do you feel you **understand** Welsh*?

0	1	2	3	4	5	6
I have no proficiency in this language	Only know some words and expressions		Can understand basic conversations		Can understand almost all conversations	I have native like proficiency

(Optional) Comments: ____

(b) On a scale of 1 to 6 (6 highest), how well do you feel you **understand** English?

0	1	2	3	4	5	6
I have no proficiency in this language	Only know some words and expressions		Can understand basic conversations		Can understand almost all conversations	I have native like proficiency

(Optional) Comments: ____
____

5 (a) On a scale of 1 to 6 (6 highest), how well do you feel you **read** Welsh*?

0	1	2	3	4	5	6
I have no proficiency in this language	I can only read a little		I can read most things reasonably well		I can read almost anything very well	I have native like proficiency

(Optional) Comments: ____

(b) On a scale of 1 to 6 (6 highest), how well do you feel you **read** English?

0	1	2	3	4	5	6
I have no proficiency in this language	I can only read a little		I can read most things reasonably well		I can read almost anything very well	I have native like proficiency

(Optional) Comments: ____

6 (a) On a scale of 1 to 6 (6 highest), how well do you feel you **write** in Welsh*?

0	1	2	3	4	5	6
I have no proficiency in this language	I only know how to write a few words and expressions		I can only write simple things		I can write practically anything I want	I have native like proficiency

(Optional) Comments: ____

(b) On a scale of 1 to 6 (6 highest), how well do you feel you **write** in English?

0	1	2	3	4	5	6
I have no proficiency in this language	I only know how to write a few words and expressions		I can only write simple things		I can write practically anything I want	I have native like proficiency

(Optional) Comments: ____

7. When individuals can speak more than one language, they often switch between languages within a single conversation. This can be using words or whole sentences from another language. This is known as “language switching”.
Please indicate how often you engage in language switching in the following contexts.

☐ **OR** does not apply as I only speak one language

(a) With parents and family

|—|—|—|—|—|—|—|—|—|—|

Almost Never

Roughly half the time

Almost Always

(b) With friends

Almost Never | Roughly half the time | Almost Always

(c) At work

Almost Never | Roughly half the time | Almost Always

(d) In the community

Almost Never | Roughly half the time | Almost Always

(Optional) (e) **Other (please specify)…………..**

Almost Never | Roughly half the time | Almost Always

Please continue onto the next page to continue the

8. On a scale from zero to ten, please select how much the following factors contributed to you learning your second language (English or Welsh or Other).

☐ **OR** does not apply as I only speak one language

Interacting with family and/or friends	/10
Formal instruction (school or evening classes)	/10
If formal instruction, when did you receive this, how many years did you receive instruction, and how often? (i.e. in 2015 when I was 50 years old, for 2 years, 2 hours a week)	In the year(s) ________________ When I was age _______________ For _____________years For _____________ hours per week
Self-instruction	/10
Watching TV/listening to the radio/reading	/10

9. If you know more than one language, what was your main motivation for learning this language?

☐ To speak with family/friends

☐ My spouse speaks this language

☐ To communicate at work

☐ I moved to the area and wanted to learn the language

☐ Other (please specify) ……………………………….

☐ **OR** does not apply as I only speak one language

Background Questionnaire

1. Have you ever been treated for a hearing problem? Yes ☐ No ☐
   If **yes**, do you wear a hearing aid? Yes ☐ No ☐
2. Are you colour blind? Yes ☐ No ☐
   If **yes**, what type? ____
3. Have you ever been diagnosed with dyslexia or language delay? Yes ☐ No ☐
   If **yes**, where and when was this diagnosis received?
   ____
   If **yes**, have you received treatment for dyslexia or language impairment? If so, please explain.
   ____
4. Have you ever been diagnosed with a neurological disorder (e.g. epilepsy, Parkinsons, Stroke, Alzheimer's Disease) Yes ☐ No ☐

If **yes**, please indicate the neurological disorder ___________________________________

If **yes**, when was this diagnosis received? ____

Thank you for completing this questionnaire!

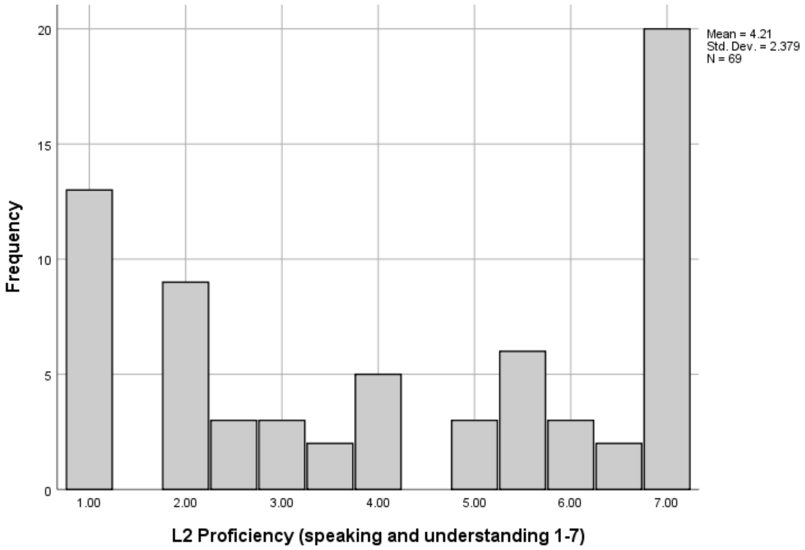
LIFESTYLE QUESTIONNAIRE FOR ADULT PARTICIPANTS

Thank you for agreeing to participate in this study. Research suggests lifestyle choices could be important factors to consider when interpreting our findings. Your answers will be kept confidential and only linked to your participant code. Please feel free to answer these questions in any way you feel is appropriate. If there is any question you would rather not answer, that is fine too. Just leave it blank and pass on to the next question. Please circle the box indicating the most appropriate answer.

Questions	**0**	**1**	**2**	**3**	**4**
How often do you have a drink containing alcohol?	Never	Monthly, or less	2-4 times a month	2-4 times a week	5 or more times a week
How many drinks contain alcohol do you have on a typical day when you are drinking?	1 or 2	3 or 4	5 or 6	7 or 9	10 or more
How often do you smoke cigarettes?	Never	Monthly, or less	2-4 times a week	5-6 times a week	Everyday
In the past 6-months have you used prohibited drugs, so called legal highs, or misused prescription drugs? If so, how often do you use them?	Never	Once or twice – not regularly	2 – 4 times a week	5 -6 times a week	Everyday
How many days a week do you engage in vigorous physical activity for 30 minutes or more? (e.g. running, singles tennis)	Never	Once or twice – not regularly	2 – 4 times a week	5 -6 times a week	Everyday
How many days a week do you engage in moderate physical activity? (e.g. walking fast, pushing a lawn mower, doubles tennis, riding a bike on level ground)	Never	Once or twice – not regularly	2 – 4 times a week	5 -6 times a week	Everyday
How many days a week do you engage in activities that strengthen your muscles? (e.g. weight lifting, yoga, exercises such as sit-ups & push-ups)	Never	Once or twice – not regularly	2 – 4 times a week	5 -6 times a week	Everyday
Thinking of the last month, how many nights a week do you have trouble sleeping?	0-1	2	3	4	5-7
On a typical night, how would you describe your sleep quality?	Very Poor	Poor	Average	Good	Very Good

Appendix C. Further information about bilingualism categorisation (Go/NoGo)

Self-reported L2 proficiency is an accurate predictor of second-language performance and are strongly correlated with behavioural proficiency measures (Marian, Blumfield & Kaushanskaya, 2007). Moreover, proficiency in second language speaking and comprehension have been identified as important factors for describing degree of bilingualism (Anderson, Mak, Chahi, & Bialystok, 2018). Average scores of understanding and speaking proficiency have previously been used to categorise individuals into language groups (e.g., Paap & Greenberg, 2013; Pelham & Abrams, 2014). Pelham and Abrams (2014) required monolinguals to score 3 or below (out of 10), indicating "fair" proficiency. Paap and Greenberg (2013) classified participants as monolinguals if they scored a 3 out of 7 or below, referring to "intermediate" proficiency. However, given that research has identified that how second language proficiency modulates executive control in bilinguals (e.g., Singh & Mishra, 2013), we wanted to include low proficient individuals in our sample. An average score was calculated from self-reported L2 speaking and comprehension proficiency. Individuals who scored above 3/7 (at least basic knowledge of a second language) were categorised as bilingual. Individuals who scored 3/7 or below were categorised as monolingual. Participants also reported the percentage of L2 exposure in the home, all monolinguals reported speaking 0% L2 in the home.



Above (Fig 1.) you can see the distribution for self-reported L2 proficiency.

Changes to language group classification

Classification of participants into monolingual or bilingual categories varies from study to study and this categorisation is shown to influence language group difference seen in results (Champoux-Larsson & Dylman, 2021). Therefore, I investigated whether decreasing or increasing the cut-off of 3 out of 7 would alter the pattern of statistical significance within the results of interest.

1 out of 7

When decreasing the cut off to 1 out of 7, so that monolinguals report they "I have no proficiency in this language".

2 out of 7

When decreasing the cut off to 2 out of 7, so that monolinguals report they "Only know some words and expressions" or below.

3 out of 7

The current cut-off for the reported data, monolinguals report proficiency between 2 and 3 (unlabelled in the Likert).

4 out of 7

When increasing the cut off to 4 out of 7, so that monolinguals report they "Can understand basic conversation" or below.

A group 1-2 and a group 5-7

Here, I wanted to know whether creating two groups – one of no or low L2 proficiency, which would be my monolingual group report either "I have no proficiency in this language" or "Only know some words and expressions". For the bilingual group, they report either "Can understand most conversations" or "native like proficiency".

Table 1 demonstrates that the statistical pattern of results (with bilinguals having an N2-effect for both NoGos, and absence of an N2-effect for monolinguals on high conflict NoGo) remains irrelevant of language group split. However, when only extreme groupings are used (last row), individuals who have middle-range proficiency do not exhibit an N2, like typical older adults, however this could be driven by low sample size. No conclusions can be drawn without further research with a larger sample.

Table 1. Analysis performed to understand whether changing the cut-off for language groups would alter the pattern of significance. P values are reported.

Monolingual classification (out of 7)		N	N2-effect Go Vs LC	N2-effect Go vs HC
1	Mono	9	.020	.658
	Bi	35	.000	.001
2 or below	Mono	16	.002	.542
	Bi	28	.000	.004
3 or below	Mono	19	.003	.592
	Bi	25	.000	.002
4 or below	Mono	22	.002	.327
	Bi	22	.000	.004
1-2	Mono	16	.002	.543
5-7	Bi	20	.000	.003
3,4,5	Ungrouped	8	.169	.408

Appendix D. Younger adult replication information

In order to examine the replicability of the findings reported by Roch (2015) on the Go/NoGo paradigm employed here, a small replication study was conducted. Seven monolingual and 8 bilingual younger adults were recruited. We replicated the findings of Roch (2015), in that bilingualism did not modulate the N2 or P3 components in terms of amplitude or latency.

For the N2 amplitude, there was a main effect of trial type, *p* = .001, with larger N2 amplitudes to NoGo (*M* = -1.61 , *SD* = .81) relative to Go (*M* = 2.19, *SD* =.941). There was no interaction with language group and trial type (*p* = .801) demonstrating that both language groups experience this N2-Effect to the same magnitude.

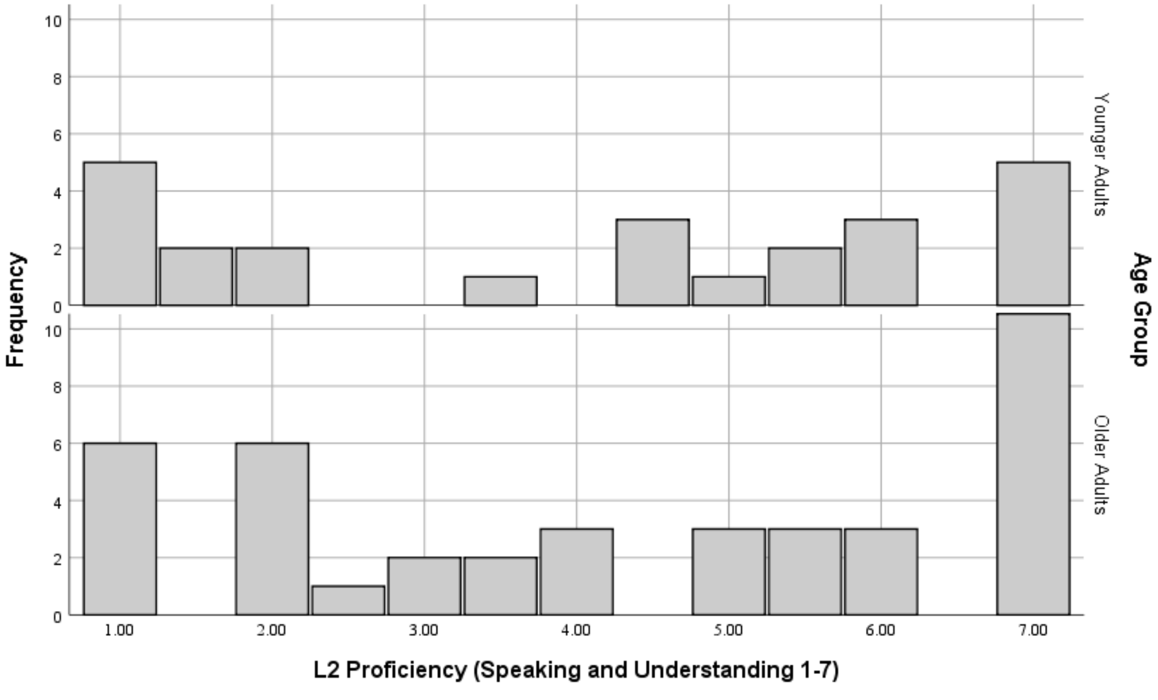
For the N2 latency, there was a main effect of trial type, *p* = .003, with earlier N2 latencies to NoGo (*M* = 338.13 , *SD* = 7.13) relative to Go (*M* = 316.62, *SD* =.58). There was no interaction with language group and trial type (*p* = .264) demonstrating that both language groups experience this N2-Effect to the same magnitude.

For the P3 amplitude, there was a main effect of trial type, *p* = .001, with smaller P3 amplitudes to NoGo (*M* = 7.52 , *SD* = .622) relative to Go (*M* = 14.47, *SD* =1.19). There was no interaction with language group and trial type (*p* = .187) demonstrating that both language groups experience this N2-Effect to the same magnitude.

For the P3 latency, there was a main effect of trial type, *p* = .009, with later P3 latencies to NoGo (*M* = 414.89 , *SD* = 7.08) relative to Go (*M* = 405.60, *SD* =6.59). There was no interaction with language group and trial type (*p* = .889) demonstrating that both language groups experience this N2-effect to the same magnitude.

Appendix E. Language group categorisation and the Simon task

Self-reported L2 proficiency is an accurate predictor of second-language performance and are strongly correlated with behavioural proficiency measures (Marian, Blumfield & Kaushanskaya, 2007). Moreover, proficiency in second language speaking and comprehension have been identified as important factors for describing degree of bilingualism (Anderson, Mak, Chahi, & Bialystok, 2018). Average scores of understanding and speaking proficiency have previously been used to categorise individuals into language groups (e.g., Paap & Greenberg, 2013; Pelham & Abrams, 2014). Pelham and Abrams (2014) required monolinguals to score 3 or below (out of 10), indicating "fair" proficiency. Paap and Greenberg (2013) classified participants as monolinguals if they scored a 3 out of 7 or below, referring to "intermediate" proficiency. However, given that research has identified that how second language proficiency modulates executive control in bilinguals (e.g., Singh & Mishra, 2013), we wanted to include low proficient individuals in our sample. An average score was calculated from self-reported L2 speaking and comprehension proficiency. Individuals who scored above 3/7 (at least basic knowledge of a second language) were categorised as bilingual. Individuals who scored 3/7 or below were categorised as monolingual. Participants also reported the percentage of L2 exposure in the home, all monolinguals reported speaking 0% L2 in the home.



Above (Fig 1.) you can see the distribution for self-reported L2 proficiency.

Changes to language group classification

Classification of participants into monolingual or bilingual categories varies from study to study and this categorisation is shown to influence language group difference seen in results (Champoux-Larsson & Dylman, 2021). Therefore, I investigated whether decreasing or increasing the cut-off of 3 out of 7 would alter the pattern of statistical significance within the results of interest.

1 out of 7

When decreasing the cut off to 1 out of 7, so that monolinguals report they "I have no proficiency in this language".

2 out of 7

When decreasing the cut off to 2 out of 7, so that monolinguals report they "Only know some words and expressions" or below.

3 out of 7

The current cut-off for the reported data, monolinguals report proficiency between 2 and 3 (unlabelled in the Likert).

4 out of 7

When increasing the cut off to 4 out of 7, so that monolinguals report they "Can understand basic conversation" or below.

A group 1-2 and a group 5-7

Here, I wanted to know whether creating two groups – one of no or low L2 proficiency, which would be my monolingual group report either "I have no proficiency in this language" or "Only know some words and expressions". For the bilingual group, they report either "Can understand most conversations" or "native like proficiency".

***Table** 1.* Analysis performed to understand whether changing the cut-off for language groups would alter the pattern of significance.

Monolingual classification (out of 7)	Monolinguals (younger, older)	Bilinguals (younger, older)	RT-effect *Sig.*	N2-effect *Sig.*
1	5, 6	19, 36	Age – .038 Lang - .679 Inter - .558	Age – .930 Lang - **.446** Inter **-.310**
2 or below	9, 12	15, 30	Age – .020 Lang - .747 Inter - .466	Age – .828 Lang - .275 Inter - .021 (Mono bigger)
3 or below	9, 15	15, 27	Age – .021 Lang - .624 Inter - .560	Age – .935 Lang - .241 Inter - .015
4 or below	10,17	14,25	Age – .026 Lang - .567 Inter - .940	Age – .675 Lang - .545 Inter - .019
1-2 5-7	9,11	11,19	Age – **.063** Lang - .920 Inter - .643	Age- .741 Lang – **.036** Inter- .041

Note: Analysis performed on the magnitude of the Simon effect in RT and N2 amplitude, and to understand whether monolinguals had larger N2 amplitudes to congruent stimuli (independent t-test). P values reported here. Age= - main effect of age, Lang = main effect of language group, Inter = interaction between age group and language group. Bold numbers indicate changes in significance (from sig to n.s., or visa versa).

This table demonstrates that a language group difference in behavioural data is not found even when moving the cut-off point. The larger N2-effects for monolinguals are found when bilinguals are defined as individuals who know more than some words and expressions (> 2/7) up to highly proficient bilinguals.

Appendix F. Further information about task attribute manipulation

We attempted to manipulate task difficulty by having both shape and colour stimuli. These were presented in separate blocks. In summary, it is possible that the participants found the colour trials easiest as they elicited the shortest reaction times and the earliest and smallest P3 amplitudes. The effect of age was only observable on these easier colour stimuli, with larger RT-effects and longer N2 latencies for older adults on colour but not shape trials. However, it would be expected that age group differences would be observed on harder trials – this indicates that these task difficulty effects may be spurious due to a low sample size.

Accuracy was not modulated by trial type, suggesting that the difficulty was not increased enough to cause participants to have a reduction in accuracy rates (only an increased reaction time).

We did not see an interaction with trial type age and language group. This could be due to an exposure effect wherein monolinguals may have gained enough practice with the paradigm to overcome any initial disadvantage relative to bilinguals.

Reaction times

There was a main effect of trial type (Shape/Colour), $F(1,62) = 40.24$, $p < .001$, $\eta^2 = .394$. Trials in which participants were required to respond to the colour of the stimuli were significantly quicker ($M = 812.68$, $SE = 12.12$) compared to trials in which participants were required to respond to the shape of the stimuli ($M = 862.69$, $SE = 13.64$). However, there was no significant interaction between trial type and congruency ($p = .341$) indicating that both trial types elicited larger reaction times to incongruent trials. A paired t-test confirmed this, with both trial types (shape and colour) having significantly longer reaction times in incongruent trials.

A multivariate ANOVA was performed, with the fixed factors of Language Group and Age, and the Simon Effects in the reaction time for colour and shape stimuli as the dependent variables.

There was a main effect of age group when comparing the Simon Effect for the Colour stimuli, $F(1, 62) = 6.21$, $p = .015$, $\eta^2 = .091$, with larger Simon effects for older adults ($M = 38.45$, $SE = 5.58$) compared to younger adults ($M = 15.56$, $SE = 7.30$).

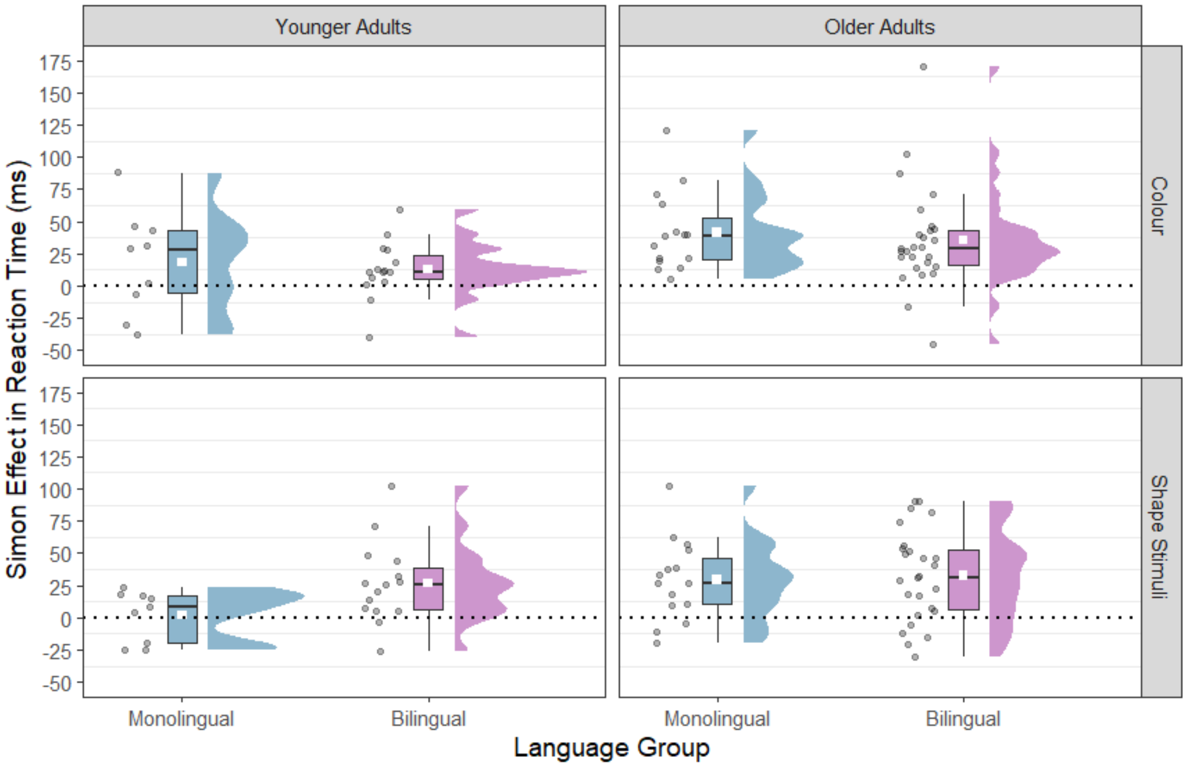
There was no age effect for the Simon Effect elicited by the shape stimuli, *F*(1, 62) = 2.99, *p* = .089, η^2 = .046. Simon Effects for older adults (*M* = 29.48, *SE* = 5.35) and younger adults (*M* = 14.23, *SE* = 7.00) were comparable.

There was no main effect of language group on the Simon Effect in reaction times for either colour (*F*(1,62) = 0.395, *p* =.532, η2 = .006.) nor shape stimuli (*F*(1,62) = 1.986, *p* = .164, η^2 = .031.). Despite qualitatively different Simon effect sizes, pairwise comparisons revealed that both language groups had comparable reaction times across all trial types (*p* > .05).

Table 1. Descriptive statistics of the reaction time Simon effect for each task attribute type.

		Simon Effect (Shape)	Simon Effect (Colour)
Younger			
	Monolingual	1.83 (11.07)	18.36 (11.54)
	Bilingual	26.63 (8.57)	12.76 (8.94)
Older			
	Monolingual	29.46 (8.57)	41.42 (8.94)
	Bilingual	29.49 (6.39)	35.47 (6.66)

Figure 1. Raincloud plots of the reaction time Simon effect for each task attribute type.



Accuracy

There was a no main effect of trial type (Shape/Colour), *F*(1,62) = 0.44, *p* =. 506, η^2 = .007.

N2 Amplitude

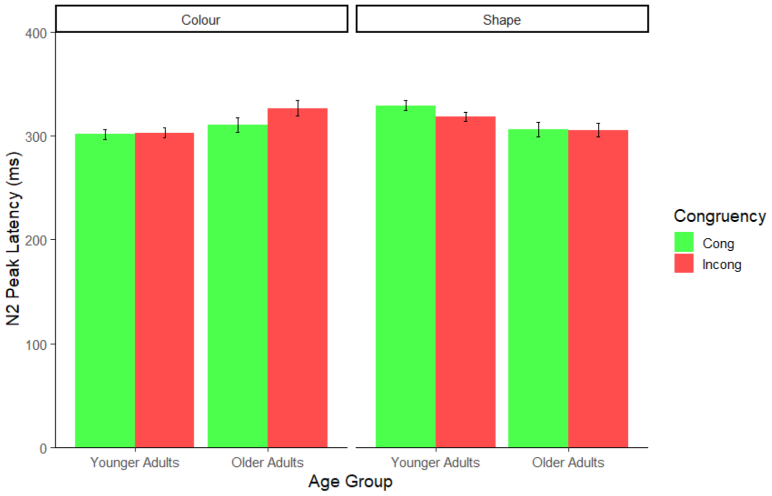
There was no significant main effect of trial type (Shape v Colour), *F*(1, 41) = 0.80, , *p* = .376, η^2 = .019 indicating that both stimulus types elicited similar N2 amplitudes.

N2 Latency

There was no main effect of trial type, *F*(1,41) = 0.79, *p* = .377 η^2 = .019

There was a trial type and age group interaction, *F*(1,41) = 15.59, *p* < .001, η^2 = .276. On colour stimuli, older adults had significantly later N2 latencies relative to younger adults (M*diff* = 19.98, SE = 7.91, *p* =.016). On shape stimuli, the N2 latencies were comparable for both age groups (M*diff* = 15.11, SE = 8.06, *p* =.068).

Figure 2. Bar chart demonstrating peak latency (in ms) of the N2 for both age and language groups. The bar chart divides colour and shape stimuli.



P3 Amplitude

There was a main effect of trial type, *F*(1,41) = 5.47, *p* = .024, η^2 = .118. Shape trials elicited larger P3 amplitudes (*M* = 6.24, *SE* = .47) compared to colour trials (*M* = 5.47, *SE* = 0.44) (see Table 2).

Table 2. Estimated means and standard errors (in parenthesis) of the amplitude of the P3 component.

		Congruent Shape	Incongruent Shape	Congruent Colour	Incongruent Colour
Younger					
	Monolingual	7.10 (1.23)	8.03(1.17)	6.44 (1.15)	6.71 (1.08)
	Bilingual	5.40 (0.84)	5.71 (0.80)	4.97 (0.79)	4.82 (0.74)
Older					
	Monolingual	6.45 (1.09)	6.70 (1.04)	6.28 (1.02)	5.69 (0.95)
	Bilingual	5.83 (0.87)	4.67 (0.83)	4.38 (0.82)	4.49 (0.76)

P3 Latency

There was a main effect of trial type, $F(1,41) = 18.74$, $p < .001$, $\eta^2 = .314$. Shape trials elicited later P3 latencies ($M = 454.62$, $SE = 6.55$) compared to colour trials ($M = 433.91$, $SE = 6.89$).

Appendix G. Further information about trial rejection rate

Table 1. The mean number of trials rejected and retained for each language group. Minimum and maximum in parenthesis.

	Colour		**Shape**	
	Congruent	Incongruent	Congruent	Incongruent
Younger Adults				
Monolinguals	79.00 (65-95)	78.66 (48-92)	76.55 (54-95)	72.44 (34-93)
Bilinguals	70.07 (53-97)	67.53 (40-97)	67.00 (44-95)	67.31 (45-96)
Sig.	.099	.134	.163	.509
Older Adults				
Monolinguals	51.66 (28-82)	51.55 (26-86)	45.55 (27-66)	47.44 (29-74)
Bilinguals	39.33 (27-50)	38.13 (29-48)	39.20 (29-48)	39.06 (26-46)
Sig.	.110	.127	.235	.133

Appendix H. P3 Component Analysis in the Simon Task

P3 Amplitude

The amplitude of the P3 is suggested to be indicative of intensity of processing (Kok, 2001) and resource allocation (Polich, 1996), with decreased amplitudes on more difficult tasks (Gajewski & Falkenstein, 2013). Therefore, it was predicted that congruent trials would elicit larger P3 amplitudes than congruent trials. Due to age-related reductions in the P3 amplitude (Freidman, 2012; Polich, 1996) and P3 amplitude effect (Scrivano & Kieffaber, 2022), it was expected that older adults would have smaller P3 amplitudes and amplitude effects compared to younger adults. Specifically, it was expected that the reduction in the P3 amplitude effect for older adult monolinguals would be driven by a decreased P3 amplitude to congruent trials relative to bilinguals, reflective of deploying increased attentional resources. Younger adult monolinguals and bilinguals are not expected to be distinguished with the P3 amplitude and latency, as observed in previous work (Kousaie & Phillips, 2012).

However, with all participants together, there was no Simon effect on the amplitude of the P3, the mean amplitude of the P3 did not differ between congruent (*M* = 5.86, *SE* = 4.47) and incongruent trials (*M* = 5.85, *SE* = 0.44). Age did not modulate the P3 amplitude, the mean amplitude of the P3 did not differ between younger adults (*M* = 6.15, *SE* = 0.63) and older adults (*M* = 5.56, *SE* = 0.59). Language group did not modulate the P3 amplitude, The mean amplitude of the P3 did not differ between monolinguals (*M* = 6.68, *SE* = 0.69) and bilinguals (*M* = 5.04, *SE* = 0.51). There were no interactions with age group and language group (See Table 1for ANOVA summary).

Table 1. ANOVA summary table for the P3 amplitude. * *p* <.05, ** *p* <.01, *** *p* <.001.

Predictor	*Df*	*Mean Square*	*F*	Sig.	η2
Congruency	1	.008	0.01	.979	<.001
Age Group	1	84.27	0.46	.499	.011
Language Group	1	659.13	3.63	.064	.081
Age*Language	1	10.17	.056	.814	.001
Error	41	181.26			

P3 Peak Latency

Previous research has highlighted how, in the Simon task, the latency of the P3 is delayed for incongruent trials (Ragot & Renault, 1981; Melara, Wang, Vu & Proctor, 2008), and peaks later in older adults (Van der Lubbe & Verleger, 2002). In line with the hypothesis that bilingualism modulates age-related changes in attentional processes, previous research reports delayed P3 latencies in older adult monolinguals relative to older adult bilinguals (Kousaie & Phillips, 2017). It is predicted that this will also be observed in our older adult sample, and we will extend these findings by reporting no language group differences in our younger adult sample as a result of ceiling effect.

There was no Simon effect observed for the P3 latency. Language group did not modulate the latency of the P3. As predicted, age related slowing of the P3 was observed, with later P3 latencies for older (M = 485.44, SE = 8.57) compared to younger adults (M = 403.09, SE = 9.18) (See Table 2 for ANOVA summary). However, this did not differ for monolinguals and bilinguals. There was no age group and language group interaction.

Past research suggests that the latency of the P3 is reflective of the timing of the attentional, stimulus classification process as it is strongly associated with reaction times

(Melara, Wang, Vu & Proctor, 2008). We explored this in our data. Pearsons correlations revealed that reaction time (*ms*) on congruent trials and latency of the P3 on congruent trials was correlated, *r*(45) = 313, *p* =.037. Similarly, reaction time (*ms*) on incongruent trials and latency of the P3 on incongruent trials was not correlated, *r*(45) = .251, *p* = .156.

Table 2. ANOVA summary table for the P3 latency. * *p* <.05, ** *p* <.01. *** *p* <.001.

Predictor	*Df*	*Mean Square*	*F*	Sig.	η2
Congruency	1	2521.98	.315	.578	.008
Age Group	1	1660614.62	42.95	**<.001*** **	.512
Language Group	1	2200.53	0.06	.81	.001
Age*Language	1	4072.84	0.10	.747	.003
Error	41				

Appendix I. Studies included for Figure 1. Chapter 3

	N	Age (years)	Language breakdown	Paradigm(s)	Language group effects	Inhibitory Control correlations (effects)	Monitoring (Raw-RTs)
Shilling, Chetwynd, & Rabbitt, 2002	49	70.9 (7.54)	NR	Figure-ground task Numbers task Arrows task Colour-word task	NR	Uncorrelated	NR
Fan, Flombaum, McCandliss, Thomas and Posner (2003) – Experiment 1	12	24.7 (4.6)	NR	Flanker, Spatial-conflict task (Simon like), Stroop	NR	Interference scores uncorrelated	NR
Fan, Flombaum, McCandliss, Thomas and Posner (2003) – Experiment 2	40	Mean age 30 (20-44)	NR	Flanker, Spatial-conflict task (Simon like), Stroop		No correlations for conflict measures (I -C or I -N)	Mean RT for all 3 tasks were positively correlated.
Fan, Flombaum, McCandliss, Thomas and Posner (2003) – Experiment 3	24	NA	NR	Flanker Hybrid Stroop-Flanker	NR	Effects correlated	NR
Stins, Polderman, Boomsma, & de Geus, 2005	164	12 year old twins	NR	Simon (RT, accuracy, effect) Flanker (RT, accuracy, effect) Stroop (RT, RT-effect)	NR	Effects not correlated	All general RTs correlated Simon and Flanker acc correlated
Keye at al (2009)	150	18-36	NR	Simon Flanker	NR	No RT-conflict/effect correlations Acc effect correlated	General RT correlated General acc correlated
Unsworth and Spillers (2010)	181	18.74 years (1.06)	NR	Anti-saccade (accuracy) Arrow Flankers (RT - Flanker effect) Stroop (RT-effect) Psychomotor vigilance task (PVT) (RT for slowest 20% of trials)	NR	All DV’s were correlated significantly with each other. Strongest for Flanker and Anti-saccade) r= -.35)	AC accuracy and PVT RT positively correlated r = .16.

Humphrey and Valian (2012)	208	Young adults	NR	Simon Flanker		No	
Kousaie and Phillips (2012)	51	Young Adults 18-35	25 Monolinguals 26 Bilinguals	Simon, Flanker, Stroop	No language group effects in any tasks	Effects did not correlate	NR
Paap and Greenberg (2013)	82-109	University age	Not divided for the correlations section	Simon Flanker (Anti-saccade and colour switching also administered but data not presented)	No RT differences Smaller Simon effect for monos (*p* = .050)	Effects did not correlate (p > .900)	Simon global RT and Flanker Global RT positively correlated (n 107, r = 0.73, p <.001)
Paap and Sawi (2014)	120	Bilinguals = 24.4 (0.78) Monolinguals = 24.8 (1.1)	58 Bilinguals 62 Monolinguals	Anti-saccade ANT/Flanker Simon Colour-shape switching	Faster RT for monolinguals in Simon and Anti-saccade Smaller Simon effect for Monolinguals	Simon effects and Flanker effect not correlated Anti-saccade RT costs and switching costs correlated	Flanker and ANT/Simon RTs positively correlated
Ross and Merlinger (2017)	147	6 - 9 years	54 Bilinguals 48 Bidialectal 48 Monolinguals	Simon and Flanker	No differences between groups in error rates or reaction times.	NR	Congruent errors (.042) Incongruent errors (p <.001) Congruent RT (p >.001) Inconguent RT (p < .001)
Kousaie and Phillips (2017)	43	60-83	21 Monolinguals 22 Bilinguals	Stroop Simon Flanker	Stroop ; B more acc and faster on incong only Simon; No lang effect Flanker; B more acc, no RT.	Interference effects did not correlate for monos, bi or groups as a whole.	NR
Poarch, van Hove and Berthele (2019)	34	22.6 (4.1)	Bidialecticals	Flanker Simon		These flanker and Simon effects were correlated at *r* = 0.46	NR
Poarch and van Hell (2019)	55	5-8 years	L2 learners (19) Bilinguals (18) Trilingual (18)	Simon ANT	Larger Simon effects for monolinguals Bilinguals and Trilinguals	RT - effects did not correlate Accuracy effects not reported.	Raw-RTs did not correlate Raw accuracy not reported.

	outperformed L2 learners in ANT.

Appendix J. Age and behavioural measures correlations

Table 1. Younger adults, RT accuracy and age zero-order correlations

Conditions and congruency effects				Age
Simon Task	3.	Congruent-RT	*r* *sig.*	-.304 .206
	4.	Incongruent-RT	*r* *sig.*	-.313 .192
	5.	Simon effect-RT	*r* *sig.*	-.103 .675
Go/NoGo	6.	Go-RT	*r* *sig.*	-.198 .415
Simon Task	7.	Congruent-Accuracy	*r* *sig.*	.103 .676
	8.	Incongruent-Accuracy	*r* *sig.*	.149 .542
	9.	Simon effect-Accuracy	*r* *sig.*	.079 .747
Go/NoGo	10.	Go-Accuracy	*r* *sig.*	.162 .507
	11.	NoGo-Accuracy	*r* *sig*	-.068 .783
	12.	d'	*r* *sig*	.052 .833

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Table 2. Older adults, RT, accuracy and age zero-order correlations.

Conditions and congruency effects			Age
Simon Task	1. Congruent-RT	*r* *sig.*	.032 .841
	2. Incongruent-RT	*r* *sig.*	.138 .383
	3. Simon effect-RT	*r* *sig.*	.373 **.015****
Go/NoGo	4. Go-RT	*r* *sig.*	.326 **.041***
Simon Task	5. Congruent-Accuracy	*r* *sig.*	-.044 .782
	6. Incongruent-Accuracy	*r* *sig.*	-.136 .389
	7. Simon effect-Accuracy	*r* *sig.*	-.275 .078
Go/NoGo	8. Go-Accuracy	*r* *sig.*	-.305 **.049***
	9. NoGo-Accuracy	*r* *sig*	-.153 .334
	10. d'	*r* *sig*	-.326 **.046***

Appendix K. N2 amplitude correlation matrices

Table 1. Younger adults. N2 correlations with age not controlled for (zero-order correlations). Significant at $p < .05$*, $p < .01$**, $p < .001$***.

Conditions and congruency effects			Simon Task			Go/NoGo			
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	-	**.832**	.101	.425	.279	-.161	.409
		sig.		**.000*****	.711	.101	.296	.552	.116
	2. Incongruent	*r*		-	**.635**	.446	.176	-.292	.373
		sig.			**.008****	.083	.514	.272	.154
	3. N2-effect	*r*			-	.208	-.072	-.301	.101
		sig.				.439	.791	.257	.711
Go/NoGo	4. Go	*r*				-	**.565**	-.475	.484
		sig.					**.023***	.063	.057
	5. NoGo	*r*					-	.458	.402
		sig						.074	.123
	6. N2-effect	*r*						-	-.093
		sig							.732

Table 2. Older adults. N2 amplitude cross-task zero-order correlations Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects			Simon Task		Go/NoGo				
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	-	**.912**	**-.801**	**.649**	**.692**	.089	-.209
		sig.		**.000**	**.000**	**.005**	**.002**	.735	.420
	2. Incongruent	*r*		-	**-.485**	**.629**	**.703**	.170	-.037
		sig.			**.049**	**.007**	**.002**	.514	.886
	3. N2-effect	*r*			-	-.464	-.450	.059	.391
		sig.				.061	.070	.822	.121
Go/NoGo	4. Go	*r*				-	**.934**	-.227	-.183
		sig.					**.000**	.381	.481
	5. NoGo	*r*					-	.136	-.222
		sig						.601	.392
	6. N2-effect	*r*						-	-.096
		sig							.713

Table 3. Older adults. N2 amplitude cross-task correlations. Significant at $p < .05$*, $p < .01$**, $p <.001$***. Partial correlation with age controlled for.

Conditions and congruency effects			Simon Task			Go/NoGo		
			1	2	3	4	5	6
Simon Task	1. Congruent	*r*	-	**.925**	**-.799**	**.635**	**.677**	.070
		sig.		**.000*** **	**.000*** **	**.008** **	**.004** **	.796
	2. Incongruent	*r*		-	**-.511**	**.634**	**.713**	.167
		sig.			**.043***	**.008** **	**.002** **	.536
	3. N2-effect	*r*			-	-.434	-.405	.105
		sig.				.093	.120	.697
Go/NoGo	4. Go	*r*				-	**.932**	-.250
		sig.					**.000*** **	.350
	5. NoGo	*r*					-	.119
		sig						.662
	6. N2-effect	*r*						-
		sig						

Appendix L. N2 latency correlation matrices

Table 1. Younger adults.N2 correlations with age not controlled for (zero-order correlations). Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects				Simon Task			Go/NoGo			
				1	2	3	4	5	6	Age
Simon Task	1.	Congruent	*r*	-	.406	-.655	-.371	-.508	-.237	.033
			sig.		.119	.006**	.157	.045*	.378	.902
	2.	Incongruent	*r*		-	.425	-.078	-.049	.049	-.154
			sig.			.101	.774	.857	.856	.569
	3.	N2-effect	*r*			-	.303	.462	.275	-.160
			sig.				.254	.071	.302	.553
Go/NoGo	4.	Go	*r*				-	.830	-.286	-.412
			sig.					.000***	.283	.113
	5.	NoGo	*r*					-	.297	-.425
			sig						.263	.101
	6.	N2-effect	*r*						-	-.024
			sig							.928

Table 2. Older adults. N2 correlations with age not controlled for (zero-order correlations). Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects			Simon Task			Go/NoGo			
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	**-**	**.725**	**-.732**	-.069	.311	.311	-.225
		sig.		**.001****	**.001****	.793	.225	.225	.385
	2. Incongruent	*r*		-	-.061	-.290	.116	.337	.023
		sig.			.815	.258	.657	.185	.931
	3. N2-effect	*r*			-	-.188	-.335	-.117	.349
		sig.				.471	.188	.656	.170
Go/NoGo	4. Go	*r*				-	.266	**-.619**	.158
		sig.					.302	**.008****	.544
	5. NoGo	*r*					-	**.593**	.384
		sig						**.012***	.128
	6. N2-effect	*r*						-	.181
		sig							.488

Appendix M. P3 amplitude correlation matrices

Table 1. Younger adults. P3 correlations with age not controlled for (zero-order correlations) for younger adults. Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects			Simon Task			Go/NoGo			
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	-	**.913**	-.211	**.639**	**.704**	**.538**	-.100
		sig.		**.000*****	.434	**.008****	**.002****	**.047***	.713
	2. Incongruent	*r*		-	**-.591**	**.637**	**.634**	**.549**	-.194
		sig.			**.016***	**.008****	**.008****	**.042***	.472
	3. P3-effect	*r*			-	-.264	-.128	-.223	.268
		sig.				.324	.638	.443	.316
Go/NoGo	4. Go	*r*				-	**.742**	**.935**	-.164
		sig.					**.001*****	**.000*****	.545
	5. NoGo	*r*					-	**.520**	-.030
		sig						**.046***	.911
	6. P3-effect	*r*						-	-.033
		sig							.912

Table 2. Older adults – P3 amplitude cross-task zero-order correlations. Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects			Simon Task			Go/NoGo			
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	-	**.946**	**.566**	**.784**	**.641**	.389	.133
		sig.		**.000*****	**.018***	**.000*****	**.006****	.123	.665
	2. Incongruent	*r*		-	**.267**	**.837**	**.704**	.330	.125
		sig.			**.300**	**.000*****	**.002****	.196	.633
	3. P3-effect	*r*			-	.203	.113	.316	.019
		sig.				.436	.667	.216	.943
Go/NoGo	4. Go	*r*				-	**.866**	**.471**	-.092
		sig.					**.000*****	**.056**	.725
	5. NoGo	*r*					-	-.004	-.070
		sig						.987	.791
	6. N2-effect	*r*						-	-.190
		sig							.466

Appendix N. P3 latency correlation matrices

Table 1. Younger adults.P3 correlations with age not controlled for (zero-order correlations). Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects				Simon Task			Go/NoGo			
				1	2	3	4	5	6	Age
Simon Task	1.	Congruent	*r*	-	.902	-.082	.341	.578	-.341	-.221
			sig.		.000***	.764	.197	.030	.197	.410
	2.									
	3.	Incongruent	*r*		-	-.505	.238	.468	-.289	-.294
			sig.			.046*	.375	.091	.278	.270
	4.	P3-effect	*r*			-	.132	.090	-.015	-.082
			sig.				.626	.760	.956	.764
Go/NoGo	5.	Go	*r*				-	.464	.228	.032
			sig.					.095	.396	.908
	6.	NoGo	*r*					-	-.270	-.329
			sig						.350	.251
	7.	P3-effect	*r*						-	-.199
			sig							.460

Table 2. Older adults. P3 correlations with age not controlled for (zero-order correlations). Significant at *p* < .05*, *p* < .01**, *p* <.001***.

Conditions and congruency effects			Simon Task			Go/NoGo			
			1	2	3	4	5	6	Age
Simon Task	1. Congruent	*r*	**-**	**.729**	.351	-.170	.437	-.200	-.083
		sig.		**.001*****	.167	.513	.079	.441	.750
	2. Incongruent	*r*		-	-.385	-.049	.437	-.200	-.006
		sig.			.127	.853	.079	.441	.983
	3. P3-effect	*r*			-	-.163	-.265	.115	-.105
		sig.				.532	.305	.659	.689
Go/NoGo	4. Go	*r*				-	.135	.431	.048
		sig.					.605	.084	.855
	5. NoGo	*r*					-	-.351	.088
		sig						.167	.736
	6. P3-effect	*r*						-	-.071
		sig							.785