The contribution of bilingualism to differences in brain structure and function in aging, mild cognitive impairment, and Alzheimer disease

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ABSTRACT

The contribution of bilingualism to differences in brain structure and function in aging, mild cognitive impairment, and Alzheimer disease

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This dissertation presents findings that address several questions with respect to research demonstrating protection from age-related cognitive decline and dementia in older bilinguals relative to monolinguals. Manuscript 1 (Chapter 4) reports research investigating the contribution of bilingualism to cognitive reserve by examining the clinical and neurophysiological manifestations of dementia in monolingual and multilingual patients with mild cognitive impairment (MCI) and Alzheimer disease (AD). Neuropsychological assessment data, demographic information, cortical thickness, and gray matter tissue density are compared between monolinguals and bilinguals. Results in AD patients indicated lower grey matter density in the posterior parahippocampal gyri (and similar directional trends for the rhinal cortices) for multilinguals compared to monolinguals, despite the fact that the groups were matched for functioning on two episodic memory tests. Results in both MCI and AD patients showed thicker cortex and greater tissue density in a number of regions related to bilingualism in multilinguals compared to monolingual. Additionally, this study also found significant correlations between brain regions related to language and cognitive control and episodic memory measures, for multilingual patients but no monolingual patients. This provides evidence towards our hypothesis that for multilingual patients, greater brain matter in cognitive control regions may form part of compensatory memory network.

Manuscript 2 (Chapter 5) reports research investigating functional differences in the brain activity of younger and older monolinguals and bilinguals while completing cognitive control tasks (i.e., Stroop, Simon, and Eriksen flanker tasks). Previously collected and published data (Kousaie & Phillips, 2012b; 2017) are re-analysed using novel electrophysiological measures to investigate whether bilingualism contributes to differences in brain responses between monolinguals and bilinguals, and whether these effects vary as a function of aging. As was seen in the previously published research, neither the younger nor the older participants show conflict-

specific language-group differences in behavioural results (with the exception of the Stroop task for the older adults). However, differences are seen in electrical brain activity between the four groups suggesting differences in cognitive control processing. Broadly, we found an overall age difference in power (with older adults lower higher power in the alpha and theta frequency bands, and more suppression in the beta frequency band than younger adults), and some evidence for conflict-specific language-group differences (with younger and older bilinguals showing larger conflict effects in power than their monolingual counterparts). We also found that induced activity was a better marker of conflict processing than evoked activity and that the locus of the conflict differed across the three tasks with respect to the manifestation of trial type differences in event-related power.

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CONTRIBUTION OF AUTHORS

The two studies included in this thesis were conceptualized by Hilary Duncan, with guidance from Dr. Natalie Phillips. For Manuscript 1 (Chapter 4), MRIs and neuropsychological evaluations were conducted at the Jewish General Hospital Memory Clinic as part of routine patient visits. Hilary Duncan designed the study and collected additional demographic data from patient files with the help of a research assistant. Hilary Duncan analysed demographic and neuropsychological data, and conducted group-level statistical analyses involving MRI structural data. Jim Nikelski ran linear regressions on structural MRI data. Hilary Duncan and Dr. Natalie Phillips interpreted the results collaboratively. For Manuscript 2 (Chapter 4), Shanna Kousaie conceived of the design of the tasks, created the stimuli, recruited and tested participants, and processed and analyzed behavioural data under the supervision of Dr. Natalie Phillips as part of her dissertation and an additional publication (Kousaie & Phillips, 2012b; 2017). Hilary Duncan analyzed the behavioural data with a larger sample size, and processed and analyzed the EEG time-frequency data, under the supervision of Dr. Natalie Phillips. The first draft of both manuscripts were written by Hilary Duncan and subsequently revised by Dr. Natalie Phillips. Note that throughout this dissertation "I" is used when referring to the dissertation, whereas "we" is used within and when referring to the manuscripts that comprise Chapters 4 and 5.

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1.0 Chapter 1: General Introduction and Organization of the Dissertation

The idea that healthy lifestyle variables and stimulating mental activity may have an impact on both the structure and functioning of the brain has a long history. The concept of neural plasticity, the brain's ability to reorganize by forming new neural connections, was introduced by Hebb in 1949, and famously summarized by Siegrid Löwel and Wolf Singer (Löwel & Singer, 1992) as, "neurons wire together if they fire together" (more commonly phrased as "cells that fire together, wire together"). Following this came the idea that mental stimulation could elicit plastic changes within the brain: in rats and monkeys environmental enrichment has been shown to lead to increased rates of neurogenesis and synaptogenesis, and relatedly, higher levels of brain activity (Altman & Das, 1964; Diamond, Krech, & Rosenzweig, 1964; Harlow, Rowland, & Griffin, 1964; Rosenzweig, Krech, Bennett, & Diamond, 1962). Research with humans suggests that extensive training or experience in a variety of activities leads to beneficial neuroplastic changes in brain structure, as has been seen in older adults trained on three-ball juggling (Driemeyer, Boyke, Gaser, Büchel, & May, 2008), London taxi drivers (Maguire et al., 2000), and professional musicians (Gaser & Schlaug, 2003). Relatedly, studies have shown that certain mentally-stimulating lifestyle variables, like having higher levels of education or participation in social activities, may protect against the cognitive decline typically seen in aging and forestall the cognitive and functional impacts of Alzheimer disease.

Recent years have seen a mounting interest in bilingualism and particularly in the non-linguistic cognitive effects that speaking more than one language may engender. This is unsurprising, given that the number of bilinguals in Canada, and worldwide, is steadily increasing. However, along with the current attention to bilingualism has come the mounting recognition that bilingualism is a multifaceted concept and more research is needed to explore its implications for cognitive functioning. It is clear that, for bilinguals, the cognitive system is implicated in the process of maintaining and controlling multiple language systems. What requires further study, however, is how, and under what circumstances, this unique requirement generalizes to non-linguistic cognitive functions. Further, there is an increasing need to explore the potential far-reaching consequences of bilingualism in terms of long-term cognitive consequences.

This thesis explores how speaking more than one language may result in functional and structural changes to the brain, and explores how those changes may mitigate the cognitive

decline often seen in aging and in dementia. The following introductory section of this dissertation is composed of two separate chapters. Chapter 2, which has been published as a book chapter elsewhere (Duncan & Phillips, 2016), examines the evidence for bilingualism as a potential cognitive reserve variable. It outlines: 1) key concepts in the areas of bilingualism and cognitive reserve, 2) the impact of bilingualism on language, cognition, and memory in healthy aging, and 3) the effects of bilingualism on the development of dementia. Chapter 3 focuses more specifically on how a hypothesized bilingual advantage in cognitive control may be the mechanism by which bilingualism contributes to cognitive reserve. To examine this topic, I will give a more in-depth review of the hypotheses for the bilingual advantage, and will review behavioural and neuroimaging studies of cognitive control in bilinguals. Following the two literature review chapters of the general introduction, I present two manuscripts. The first paper examines cortical thickness and tissue density in monolingual and multilingual patients with mild cognitive impairment (MCI) and Alzheimer disease (AD). The second paper examines electroencephalogram (EEG) activity of younger and older monolinguals and bilinguals during performance of three cognitive control tasks. Finally, the last chapter (Chapter 5, General Discussion) discusses the overalls results and implications of the two studies, outlines limitations, and presents directions for future research.

2.0 Chapter 2: The Contribution of Bilingualism to Cognitive Reserve in Healthy Aging and Dementia

This chapter, "The Contribution of Bilingualism to Cognitive Reserve in Healthy Aging and Dementia," by H. D. Duncan and N. A. Phillips, was originally printed in *Bilingualism Across the Lifespan: Factors Moderating Language Proficiency* (pp. 305–322), by E. Nicoladis and S. Montanari (Eds.), 2016, Washington, DC: American Psychological Association.

This chapter reviews how speaking more than one language may mitigate the cognitive decline often seen in aging, and possibly delay the onset of dementia. In Part One, we will review key concepts including cognitive reserve and the bilingual benefit and will outline the cognitive decline commonly seen in aging in a discussion about how the bilingual benefit may contribute to cognitive reserve to help offset age-related cognitive decline. In Part Two, which deals with bilingualism in healthy aging, we will review studies examining the differences in language, cognition, and memory between healthy older monolinguals and bilinguals. We will then outline the few studies that look at the potential neuroanatomical differences between older monolinguals and bilinguals, and large cohort studies of healthy older adults. In Part Three of the chapter, we will synthesize and analyze the research in a relatively new area of interest, namely the study of the effects of bilingualism on the development of dementia.

This chapter will demonstrate that the study of cognitive and brain differences between monolinguals and bilinguals contributes not only to our understanding of the mechanisms of the bilingual brain, but adds to our growing understanding of the concept of cognitive reserve, and how cognitive reserve might play a role in healthy and pathological aging. Additionally, as demonstrated in other chapters in this volume and by others (e.g., Luk & Bialystok, 2013), bilingualism is a multifaceted phenomenon that can be defined in many ways, and varies across individuals, groups, and cultures. As such, it is important to keep in mind when reviewing the following research that the studies vary in terms of the breadth and depth of their assessment of important language-related variables. This is a topic that will resurface in each part of the chapter. We will try to pay specific attention to how a number of variables are assessed, and whether they impact the overall pattern of results. One set of these variables is related to bilingualism and language group assessment. This includes factors like age of acquisition,

proficiency, time spent using the languages, and amount of switching between two languages. Another set consists of variables that have been shown to contribute to cognitive reserve, like education. Finally, we consider variables that are related to bilingualism, but not language *per se*, like immigration status or language context.

2.1 Part 1: Key Concepts

Cognitive Reserve

The concept of cognitive reserve arose after the repeated finding that the degree of damage to the brain does not always correlate with functional and cognitive abilities. In other words, two people with similar levels of brain damage or pathology do not necessarily function at the same level (e.g., Stern, 2009). For example, one study found that about 45% of older adults were found on autopsy to have evidence of Alzheimer disease pathology in their brains although they appeared to have had normal cognitive function while living (Schneider, Arvanitakis, Kelly, & Bennett, 2006). Briefly, the theory of cognitive reserve states that individuals with more cognitive reserve (e.g., people with higher IQ, more years of education, or those who participate in mentally or physically stimulating activities) are able to maintain the same level of functional or cognitive performance compared to those with less cognitive reserve, despite having greater amounts of brain pathology or age-related brain changes (Barulli & Stern, 2013). A number of activities appear to protect the brain against the effects of aging, including evidence for the benefits of late life recreational activity (e.g., Brewster et al., 2014), higher levels of education (e.g., Schneider, Wilson, Bienias, & Arnold, 2005), cognitively stimulating activities (e.g., Wilson et al., 2013), and social engagement (e.g., Engelhardt, Buber, Skirbekk, & Prskawetz, 2010).

There are two hypothesized ways in which cognitive reserve mechanisms might function, namely neural reserve and neural compensation (Stern, 2009). Neural reserve refers to the differences between healthy, non-impaired individuals in the strength or efficiency of the cognitive networks set up in their brain. Thus, activities contributing to cognitive reserve could train brain networks used for completing a task, making a network more efficient and effective (neural reserve). In contrast, neural compensation refers to how individuals use alternate brain networks to compensate when their brain is weakened by disease, such as Alzheimer disease. Thus, if one network sustains damage, then a network that has been strengthened through cognitive reserve could hypothetically be relied upon, allowing a person to use compensatory

mechanisms. Research has shown that, when matched on Clinical Dementia Rating scores, older adults with higher socioeconomic status (SES) have reduced brain volume and accelerated brain atrophy than those with lower SES (Fotenos, Mintun, Snyder, Morris, & Buckner, 2008). Although these results may seem initially counter-intuitive, they are in line with the cognitive reserve theory because they indicate that those persons with higher cognitive reserve (i.e., higher SES) are able to cope longer with brain pathology (i.e., greater brain atrophy) before they begin to show signs of cognitive deficit or succumb to dementia. The inverse of this hypothesis is also appears to be true; in a group of older adults matched on brain atrophy, those with higher cognitive reserve will have better cognitive and functional performance. For example, when balanced on brain atrophy, older adults with higher levels of education showed better memory performance, and older adults with higher occupational attainment showed better memory and reasoning performance (Staff, Murray, Deary, & Whalley, 2004).

The Theory of the Bilingual Benefit

How might being bilingual relate cognitive reserve? Speaking more than one language may be similar to other mentally stimulating activities, and therefore could be a contributor to cognitive reserve and protect against age-related decline and the onset of dementia. But what exactly is it about speaking two languages that might exercise the brain? As outlined in the companion chapter (Freeman, Shook, & Marian, 2016), research suggests that a bilingual's two languages are active when completing word recognition or language production tasks, even when only one language is required. The simultaneous activation of languages means that bilinguals will hold two lexical representations in mind and will require inhibitory or control mechanisms to manage the competition between their languages (e.g., Green, 1998). This is believed to benefit other aspects of cognition, particularly components of executive functioning known as attention control and inhibitory control.

Cognitive Reserve and Bilingualism in Aging

During normal aging, the brain is most vulnerable to atrophy of the prefrontal lobes (Good et al., 2001; N. Raz et al., 1997) which support executive functioning. Older adults perform more poorly than younger adults on many components of executive functioning, including tests of attention control and inhibition (e.g., Belleville, Rouleau, & Van der Linden, 2006; Sylvain-Roy & Belleville, 2014), planning (e.g., Sorel & Pennequin, 2008), and set-shifting (e.g., Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2000; Goffaux, Phillips, Sinai, & Pushkar, 2008). This

area is particularly important as executive functions predict functional living skills in both the cognitively healthy elderly and patients with dementia (Pereira, Yassuda, Oliveira, & Forlenza, 2008). Furthermore, good executive functioning can allow an older adult to remain independent even when suffering from other forms of cognitive loss (e.g., Cahn-Weiner, Malloy, Boyle, Marran, & Salloway, 2000). In relation to the cognitive reserve theory, this would mean that older bilinguals, who have spent years exercising these hypothesized control mechanisms, would build up neural reserve and demonstrate more preserved executive functioning than older monolinguals. Additionally, for older adults who develop dementia, their experience dealing with two languages could then be an example of neural compensation; that is, the brain areas and cognitive functions typically affected by dementia (i.e., hippocampus, temporal lobes, and memory functions) might be supported by their superior executive functioning capabilities.

2.2 Part Two: The Effects of Bilingualism on Aging

Attention and Executive Functioning

Attention control, inhibition, and other aspects of executive functioning have been the most studied areas with respect to the effects of bilingualism on cognitive functioning. Numerous studies have shown a bilingual advantage on executive control tasks (Bialystok, 1999; Bialystok & Martin, 2004; Costa, Hernandez, & Sebastián-Gallés, 2008) with the magnitude of the advantage increasing from adulthood into older age (Bialystok, Craik, & Ruocco, 2006a; Bialystok, Craik, & Ryan, 2006b; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Luk, 2008). Typically, executive control tasks examine reaction time and accuracy during tasks that contain "congruent" or low-conflict trials, and "incongruent", or high-conflict, trials. For example, the Stroop task participants are typically slower to name incongruent ink colours than congruent colours. Older bilinguals showed a smaller Stroop effect than their monolingual counterparts, supporting a bilingual advantage in executive control of attention (Bialystok et al., 2008). However, this finding has not always been replicated (Kousaie & Phillips, 2012a), and it has been suggested that the apparent bilingual advantage would be better termed a more general executive benefit, rather than a specific benefit on attention control or inhibition (see studies reviewed in Hilchey & Klein, 2011). A more recent study using multiple executive functioning tasks also found no reliable advantage for older bilinguals compared to older monolinguals, and suggested that discrepancy between studies in the field in terms of finding a bilingual advantage may be related to language variables outside of the dichotomous

monolingual versus bilingual classification (Kousaie, Sheppard, Lemieux, Monetta, & Taler, 2014).

As outlined in the introduction to this chapter, and as noted by Kousaie and Phillips (2012b), a number of issues remain in this field of research. For instance, it is not clear whether executive functioning advantages are confined to bilinguals with high levels of proficiency in both their languages, those with many years of speaking two languages, those who live in a context that requires them to switch between languages frequently, or those who speak specific languages that may increase the need for cognitive control. Furthermore, very few of the studies looking at cognitive control have addressed the many non-language variables that could be related to being bilingual, such as being an immigrant, one's level of social engagement, and participation in cultural life, and education. Note that these later factors could contribute more directly to cognitive reserve, independent of their relationship with being bilingual.

Memory

Surprisingly, given the significance of memory functions in aging and dementia, and its purported relationship with executive functioning (e.g., Troyer, Graves, & Cullum, 2007), there is a dearth of literature examining whether a bilingual advantage may be seen in episodic memory. Episodic memory is a type of long-term memory for past experiences that can be recalled as having occurred at a particular time and place. Impairment in this cognitive function is one of the hallmarks of Alzheimer's disease. Schroeder and Marian (2012) tested a group of older bilinguals from a variety of cultural backgrounds, and for whom the language of testing (English) was a second language. In a picture recall task, older bilinguals recalled more pictures than the older monolinguals, and those with an earlier age of second language acquisition and more experience with a second language had better recall. The bilingual participants in this study spoke a variety of native languages (e.g., Bengali, French, German, Gujarati), with the majority (72%) being more proficient in their first language; however, the majority also indicated that English was currently their most frequently used language. This study could provide evidence towards the theory that bilingualism contributes to cognitive reserve in the domain of memory for those who must frequently speak their less proficient language. Unfortunately, this study does not give information on the immigration status of the bilinguals, making it difficult to assess whether the results are a benefit from bilingualism, or instead immigration-related factors. A cross-sectional study by Ljunberg, Hassson, Andrés, Josefsson, and Nilsson (2013) using only

Swedish non-immigrants found that bilinguals had better verbal episodic memory than monolinguals in both middle adulthood and older age when all were tested in their first language. However, the difference between the two language groups did not increase in the older age groups. Unlike many other studies, the bilinguals in this group were culturally similar to their monolingual counterparts (all were born in Sweden). However, they also differed from bilinguals used in many other research studies in that they learned their second language through formal training, the majority spent only 0-2 hours a day on average using their second language, and most (64%) only spoke the second language when traveling (Ljunberg et al., 2013). Thus, the participants' level of second language proficiency and their use of their second language might have been low. As such, although the study addressed the potentially confounding issue of immigration, the definition of bilingualism differs from the majority of studies assessing the bilingual benefit, and would be more aptly categorized as a study assessing the benefits of learning a second language. Finally, Wodniecka, Craik, Luo, & Bialystok (2010) conducted two studies comparing groups of older, mostly immigrant, bilinguals with English as a second language, to older, non-immigrant English-speaking monolinguals on verbal and nonverbal memory tasks and found mixed results. In Study 1, they found moderate support for a bilingual advantage on recollection of faces, but a monolingual advantage for recollection of verbal material. Study 2 found no difference between a different group of monolinguals and bilinguals for recollection of abstract objects, and a bilingual advantage for recollection of verbal material. Notably, the bilinguals in Study 1 had significantly lower vocabulary scores than the monolinguals, and showed a disadvantage on the verbal memory task, whereas the bilinguals in Study 2 had higher vocabulary scores and scored better than monolinguals on the verbal memory task. As such, it is difficult to declare this study unequivocal evidence for a bilingual benefit in episodic memory, as it could be that those with higher vocabulary scores, regardless of their language group, demonstrate better verbal memory.

With such mixed results, and so few studies to draw from, it is not yet possible to conclude whether bilingualism confers an advantage on memory processing. Additionally, as with studies assessing the effects of bilingualism on cognition, it is difficult to untangle which aspects of bilingualism may contribute to any advantage (i.e., immigrations status, age of acquisition, time spent speaking a second language). However, given that episodic memory declines with age, and episodic memory impairment is the earliest and most significant change observed in early

Alzheimer disease, this area is an important one for future study.

Language

Bilingualism does not confer advantages in all cognitive abilities. Many studies of vocabulary knowledge report that bilinguals score lower in each of their languages than monolingual speakers of that language (e.g., Bialystok, Luk, Peets, & Yang, 2010). This deficit is found at all ages, including older adulthood (Bialystok & Luk, 2012). Older bilinguals, similar to younger bilinguals are also disadvantaged on naming tasks (Bialystok et al., 2008). When it comes to lexical access and retrieval, the impact of bilingualism appears to differ with age. For example, younger bilinguals generate fewer words in both phonemic and semantic fluency than younger monolinguals (Gollan, Montoya, & Werner, 2002), however older bilinguals generate fewer category words than older monolinguals, but performed similarly on letter fluency (Rosselli, Ardila, Araujo, & Weekes, 2000). Additionally, older monolinguals have significantly lower phonemic and semantic fluency scores than younger monolinguals, whereas older bilinguals have only lower semantic scores compared to their younger counterparts (Gollan et al., 2002).

Importantly, the degree of similarity between a bilingual's two languages could have an effect on lexical retrieval as phonologically similar words from the two languages interfere with each other. The majority of studies assessing verbal fluency or lexical access in bilinguals have been conducted with Spanish-English bilinguals (e.g., Gollan et al., 2002) or English monolinguals compared to mixed groups of second-language English bilinguals (e.g., Bialystok et al., 2008). A study examining level of bilingualism (as a ratio between native Marathi and second-language Hindi proficiency) indicated that a higher level of bilingualism was associated with better phonemic and semantic verbal fluency in Marathi (Kamat et al., 2012). The authors of this study suggest that the high level of cognates (words that have a common root or origin, like English "hospital" and French "hôpital") between the two languages may mediate the relationship between bilingualism and verbal fluency.

Neuroanatomical

Another avenue for investigating the potential impact of bilingualism on cognitive decline in aging is to directly examine brain structure to assess whether speaking a second language shapes the brain. A large area of research is devoted to analysing how bilinguals process language compared to monolinguals using brain imaging techniques such as fMRI (for reviews

see Luk, Green, Abutalebi, & Grady, 2012; Perani & Abutalebi, 2005); however there is less research examining brain differences in relation to cognitive abilities, and even fewer that look at the effect in the aging brain. A study examining white matter in older monolinguals and bilinguals found that lifelong bilinguals had higher white matter integrity than monolinguals in the corpus callosum which is an important structure for interhemispheric communication (Luk, Bialystok, Craik, & Grady, 2011a). The authors posited that being bilingual contributes to cognitive reserve by helping maintain white matter integrity in aging. However, another group of researchers found the exact opposite finding – older bilinguals had *lower* corpus callosum white matter integrity than a group of monolinguals matched on age and cognitive functioning (Gold, Johnson, & Powell, 2013a). The authors in this case posited that, in line with the cognitive reserve hypothesis, older bilinguals were able to perform at the same level as older monolinguals *despite* more age-related brain damage. There are multiple possibilities for the discrepancy between these two studies. For example, although both studies attempted to account for language variables such as proficiency (in fact, the studies used the same criteria to define bilingualism), only one of the studies gives information on immigration status. In the Luk et al. (2011) study over half of the bilingual group were immigrants, compared to 14% of the monolingual group, whereas this information is not given in the Gold et al. (2013) study. More importantly, however, the older adults in the Luk et al. (2011) study were significantly older than those examined by Gold et al. (2013). According to the cognitive reserve hypothesis, it is possible that the "younger" older bilingual adults tested by Gold et al. (2013) were demonstrating evidence of the structural effects of cognitive reserve, prior to the onset of significant age-related brain atrophy (i.e., neural reserve), whereas the "older" older bilingual adults in the Luk et al. (2011) study were demonstrating the protective effects of cognitive reserve (i.e., neural compensation), after the onset of significant age-related brain atrophy. Finally, Abutalebi, et al. (2014) found that older bilinguals had more grey matter volume than age-matched monolinguals in the left anterior temporal pole, an area that is hypothesized to be involved in lexical retrieval and is activated by both of a bilingual's languages. Unfortunately, the monolinguals in this study spoke Italian and were from Italy, whereas the bilinguals spoke English and Cantonese and were from Hong Kong, offering a number of other potential causes for the difference in grey matter (i.e., health behaviour, diet). They did, however, find that, within the bilingual group, grey matter volume was significantly associated with naming performance in the second language, suggesting that

the proficiency in a second language may be related to brain structure.

Cohort Studies

A cohort study is a type of longitudinal research that follows a large group of healthy people and uses correlational analyses to determine factors associated with particular outcomes. In the study of bilingualism, the benefit of a cohort study is that it often takes advantage of previously collected data being used for epidemiological purposes and allows one to examine a larger number of participants than would be possible with a typical experimental study. The difficulty with using cohort data is that, given the broad range of measures often collected, the measurement of any one variable may not be particularly in-depth (e.g., education, language proficiency, immigration status), and or variables are measured retrospectively, such as obtaining language-related information via self or caregiver report rather than objective assessment. Nonetheless, the data from two large-scale cohort studies can shed light on whether being bilingual affects cognitive decline in older adults. Kavé, Eyal, Shorek, and Cohen-Mansfield (2008) examined 814 older adults from a representative sample of the Israeli Jewish population. They found that the number of languages spoken correlated positively with cognitive screening test scores beyond the effect of other demographic variables, such as age, gender, place of birth, age at immigration, or education. However, this study did not contain any monolinguals; all participants spoke Hebrew and at least one other language; therefore, individuals who may have had particularly weak language abilities, having been unable to learn Hebrew in a Hebrew-dominant country, were excluded. Additionally, the authors were able to circumvent the potentially confounding effects of education by examining a sub-group of non-educated older adults, where they also found that the number of languages spoken predicted cognitive functioning. In this study, participants self-reported which languages they spoke, which ones they spoke at home, and which language they were most comfortable speaking; however, the amount of time speaking each language, age of acquisition, and proficiency were not assessed.

A cohort study by Bak, Nissan, Allerhand, and Deary (2014) assessed later-life cognition in 853 older English native speakers, 262 of whom reported speaking a second language. All participants were born and raised in Edinburgh, Scotland, eliminating any potential effects of immigration or cultural variables. This study found that older bilinguals outperformed age-matched monolinguals on general intelligence and reading. This finding differs from previously reviewed research, which has typically found any benefit to be in executive functioning and not

general intelligence, or language-related tasks. The bilinguals in this study, however, would not have met criteria for bilingualism in many of the previously reviewed studies. For example, the bilinguals were English native speakers born and living in an officially English-speaking country. One quarter of them did not learn their second language until after age of 18, and 65% were not using their second language in their everyday life. Similar to the Ljunberg et al. (2013) study reviewed in the memory section, this study appears to demonstrate that learning a second language (rather than being bilingual) could contribute to cognitive reserve in aging.

These three studies demonstrate the difficulties of conducting large-scale cohort studies to examine the effects of bilingualism on cognition in aging. Specifically, because it is not clear what particular aspect of bilingualism may contribute to the hypothesized benefit, it is important to attempt to assess a number of relevant variables (language proficiency, age of acquisition, etc.), and to take into account variables known to affect cognition (e.g., education). Furthermore, as the field advances, certain issues are arising that research indicates may be relevant (e.g., immigration status). Given that no individual study is capable of measuring every potentially relevant variable, we must be cautious when interpreting the findings of single studies. This issue is particularly relevant for the studies discussed in the following section (Part 3), those that examine the effects of bilingualism on dementia.

2.3 Part Three: The Benefits of Bilingualism in Dementia

Dementia is a general term for a decline in mental ability that is severe enough to interfere with daily life. Dementia is not a specific disease, but is a characteristic of a number of diseases and disorders. The most common form of dementia is Alzheimer disease, but other forms include frontotemporal dementia, Lewy Body dementia, and vascular dementia. Alzheimer disease is a progressive, late-life neurodegenerative disorder, characterized by problems with long-term memory, executive functions, attention, and behaviour. Given the aging population, Alzheimer disease is a significant health concern. An estimated 500,000 Canadians (Alzheimer Society of Canada, 2010), and 36 million people worldwide (Alzheimer's Disease International, 2010) currently have Alzheimer disease, and it is estimated that within a generation this number will more than triple, reaching 115 million people (Alzheimer's Disease International, 2010). There is currently no cure for Alzheimer disease; thus, most efforts focus on preventing or delaying the symptoms of the disease. Research has shown that those with greater cognitive reserve are likely to go more years without experiencing cognitive symptoms compared to patients with lower

cognitive reserve (e.g., Y. Liu, Cai, Xue, Zhou, & Wu, 2013; Querbes et al., 2009).

Recent research suggests that bilingualism may protect against the onset of dementia in Alzheimer disease and related disorders. The general outcome of this line of research is mixed, with some studies providing evidence for a positive impact of bilingualism on later life outcomes(e.g., Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007), some finding mixed results that depend specifically on immigrant status or the possible nature of the L1/L2 relationship (Chertkow et al., 2010) or education level (Gollan, Salmon, Montoya, & Galasko, 2011), and some studies finding no effect of language group (Brewster et al., 2014; Crane et al., 2009; Yeung, St John, Menec, & Tyas, 2014). A number of the studies will be reviewed in more detail, in order to illustrate for the reader some of the methods used and the challenges faced by researchers in this area. Some of the issues that will be discussed include the limited assessment of other variables that may be related to bilingualism (i.e., immigration status), the assessment of language group (e.g., self-report compared to objective testing of language ability), and the limitations imposed by retrospective versus prospective studies. These studies are broadly divided into 3 sections: 1) retrospective studies that look at the estimated age at onset of dementia symptoms and age at diagnosis in dementia patients, 2) studies that follow large cohorts of healthy older adults and document which language group has the highest rate of conversion to dementia, and 3) experimental studies comparing cognitive performance or neurophysiological measures of monolinguals and bilinguals with dementia.

The pioneering study on the effects of bilingualism on dementia was conducted by Bialystok et al. (2007) who examined the association between bilingualism and age at diagnosis of dementia. The monolingual and bilingual groups did not differ in terms of cognitive abilities (as assessed by a commonly-used short cognitive screening exam called the Mini-Mental State Examination, MMSE) and were matched on occupational status (as assessed by a five-point scale by Human Resources and Skills Development Canada). Bilingual patients had significantly fewer years of education (10.8 years vs. the monolingual group mean of 12.4 years). Finally, a panel of judges (with experience in bilingualism research) decided the language group to which each participant belonged. Importantly, results indicated that the bilingual dementia patients had an onset of symptoms 4.1 years later than the monolingual dementia patients, and visited the clinic for the first time 3.2 years later than the monolingual group. Although the patient group was mixed (i.e., composed of those with frontotemporal dementia, dementia with Lewy bodies,

etc), this major finding was also significant for the subset of patients with probable AD: bilingual AD patients had an age of onset of symptoms that was 4.3 years later than monolinguals (although information on MMSE, education, and occupational status for the AD subgroup is not given). This study provides an example of how difficult it is to parse out variables related to bilingualism – in this study, bilingual status was confounded with immigrant status, as 81/93 of the bilingual patients, (compared to 13/91 of the monolingual patients) were immigrants. As mentioned earlier in the chapter, it is possible that being an immigrant could contribute to cognitive reserve through a number of different manners (diet, health behaviours, etc). However, the study was the first of its kind (to explore a potential beneficial impact of bilingualism on dementia), and indicated that the issue certainly warranted further exploration.

Immigration

As discussed in an editorial by Fuller Thomson and Kuh (2014) there is an emerging body of evidence suggesting that immigrants have better health and cognitive outcomes than non-immigrants. In order to assess the possible influence of immigration status on dementia symptoms, or its interaction with bilingualism, Chertkow et al., (2010) examined the age at diagnosis of Alzheimer disease and age at symptom onset for a cohort of 632 monolingual, bilingual, and multilingual (3 or more languages) participants. This research took place in Montréal, Canada, where bilingualism and multilingualism is common. Residents can be bilingual for different reasons, with some being non-immigrant native Canadians speaking the two official languages of Canada, others being immigrants who have a native language and have learned English and/or French. According to this study, for the group as a whole, those who spoke three or more languages (but not bilinguals *per se*) experienced a protective effect in relation to age at diagnosis or age at symptom onset, but there was no significant effect of speaking only two languages (i.e., bilingualism). However, when the analyses were limited to the immigrant patients, being either bilingual or multilingual delayed the diagnosis of Alzheimer disease by almost 5 years. Interestingly, there was a trend toward the same effect in non-immigrant bilinguals whose first language was French, but not for those whose first language was English. Thus, this study showed that the relationship between the number of language spoken and its impact on the onset of symptoms is not straightforward and may interact with important factors such as immigration, or, in the case of the native French vs. native English analyses, perhaps culture-related or language-use variables.

One way to examine the effects of bilingualism on dementia without conflating it with immigration is to look at bilingualism in a group of non-immigrants. Crane and colleagues (2009) followed a large group of healthy Japanese-American men who were born in Hawaii and recorded who became diagnosed with dementia. Because all of the patients were second generation (i.e., it was their parents who had immigrated), it eliminates any possible direct effect of immigration status. Additionally, this large cohort study overcomes the downfalls of the previously reviewed retrospective chart studies, which relied on assessing age of symptom onset and age at diagnosis retrospectively. The sample of 2299 men were asked to rate their written and spoken Japanese abilities; all of them were fluent in English and their abilities in Japanese varied from none at all to completely fluent. The study showed that there was no significant difference in the prevalence of dementia (Alzheimer disease or vascular dementia) between monolinguals (English speakers) and bilinguals. Similarly, Sanders, Hall, Katz, and Lipton (2012) found no benefit of bilingualism in a large cohort of fluent English speakers for those with low (0-11years) or intermediate (12-15 years) levels of education.

Assessment of Language Group Variables

Studies of bilingualism in healthy aging tend to use experimental designs, and the assessment of the level or degree of bilingualism is often more thorough than in the large cohort studies reviewed here (i.e., Chertkow et al., 2010; Crane et al., 2009). Many of the papers discussed used self or caregiver report to assess bilingualism. Some of the studies did not collect any data on fluency, proficiency, or age of acquisition (e.g., Alladi et al., 2013; Chertkow et al., 2010), others collected data on language fluency, but do not report its effects on conversion to dementia (i.e., Bialystok et al., 2007; Ossher, Bialystok, Craik, Murphy, & Troyer, 2013; Yeung et al., 2014). Objective measures of bilingualism are a more accurate way to assess proficiency and to categorize participants into language groups. Gollan, Salmon, Montoya, and Galasko (2011) assessed the impact of degree of bilingualism (by comparing naming in a bilingual's first and second language) on age at onset of symptoms (assessed subjectively by family members) and age at diagnosis (taken from medical records). This study is the only study to date that directly assesses language dominance as a factor in cognitive reserve. They found that the degree of bilingualism was positively correlated with age at symptom onset and age at diagnosis only for Spanish-dominant bilinguals, and not English-dominant bilinguals. That is, for Spanish-dominant bilinguals, the more equally bilingual a person was, the later their age of onset and age

of diagnosis. Importantly, the outcome variables did not correlated with subjective measures of bilingualism, suggesting that use of self-report may not accurately reflect actual language proficiency or its relationship with cognitive outcomes.

Education

In the previously mentioned study by Gollan, and colleagues (2011), their finding of delayed age at symptom onset and age at diagnosis was found only in Spanish-dominant bilinguals (rather than English dominant bilinguals). The Spanish-dominant group had significantly lower levels of education, and statistical analyses showed that the benefit associated with bilingualism was robust only in bilinguals with low education level. The authors hypothesized that this is because those with higher levels of education hit a ceiling in cognitive reserve, and that bilingualism could not add any additional benefit. Other studies factoring in education have found mixed results. One study found no benefit for those with low to intermediate levels of education, and a reverse effect (bilinguals were more likely to convert to dementia) for those with higher levels of education (Sanders et al., 2012). However, others have found that a subset of non-educated and illiterate bilinguals showed a similar delay in onset of dementia (compared to monolinguals) as a larger, educated cohort of bilinguals (Alladi et al., 2013). Still others have found a delay in the onset of dementia symptoms in a group of bilinguals who were less educated than their monolingual counterparts (Bialystok et al., 2007). In that case, the authors suggested that the fewer years of education may be more reflective of a lack of access to education than a lack of ability, given that many of the bilinguals immigrated from Europe and would have had their adolescence and/or early adulthood disrupted by World War II (2007). Regardless, it appears that the impact of bilingualism on the expression of dementia may be moderated in a complex way by education and other factors that relate to cognitive reserve.

Neuroanatomical

In order to examine whether bilingualism might contribute to cognitive reserve by protecting against neuropathological changes, Schweizer, Ware, Fischer, Craik, & Bialystok (2012) assessed 20 monolingual and 20 bilingual probable AD patients and found that although the two groups were matched on cognitive ability, the bilinguals showed greater atrophy in AD-relevant brain areas compared to monolinguals. They concluded that bilingualism contributed to cognitive reserve, which delayed the onset of AD by requiring greater amounts of brain pathology before the disease clinically manifests, supporting the neural compensation hypothesis

of cognitive reserve.

Concluding Comments

The studies in this newly developing research area can mostly be divided into several types: experimental studies examining cognitive function with detailed tasks in older monolinguals and bilinguals (e.g., Bialystok et al., 2008), clinical studies that have retrospectively examined the language status and onset of dementia from medical files in already diagnosed dementia patients (e.g., Chertkow et al., 2010), and large cohort studies that have followed healthy older adults and have observed dementia prevalence or cognitive decline (e.g., Yeung et al., 2014). With the exception of the experimental studies, these latter studies were not initially designed to examine the impact of language status on later life outcomes. In both classes of studies, given their retrospective nature, the assessment of potentially important language variables, variables related to cognitive reserve, and/or culturally relevant variables like immigration status or the degree of assimilation or acculturation into a person's new environment can be cursory or missing altogether.

With regards to language-related variables, the studies we have reviewed have shown that the degree of bilingualism may have an impact, as well as age of acquisition, and amount of time spent speaking both languages. In fact, two of the studies provide evidence that learning a second language later in life (rather than being bilingual per se) could contribute to cognitive reserve (Bak et al., 2014; Ljuneberg et al., 2013). We would suggest that learning a second language later in life could reflect a general openness to stimulating cognitive challenges. Variables like education and occupational status were included in many of the studies in order to account for their potential impact on cognitive reserve. Unfortunately, the relationship between education, bilingualism, and cognitive reserve is unclear, with some showing a bilingual benefit in those with little or no education (e.g., Alladi et al., 2013; Kave et al., 2008), while others did not (e.g., Sanders at al., 2012). Finally, participation in social activities has been shown to contribute to cognitive reserve (Engelhardt et al., 2010). Depending on the country in question, and whether the person in question is an immigrant or native to the country, being multilingual could promote a person's ability to participate in either a majority culture (e.g., Chertkow et al. 2010) or reflect access to formal education and/or media (e.g., Alladi et al., 2013; Perquin et al., 2013).

As illustrated in this chapter, bilingualism is a multifaceted phenomenon that varies in important ways across individuals, groups, and cultures. Although promising, the current studies

indicate that much more research is needed to examine what aspect of "bilingualism" may lead to increased cognitive reserve – whether the hypothesized benefit comes from frequent switching between languages, from learning a second language within or outside of the language "critical period", or from variables related to the degree to which a person is integrated into his or her culture and thus has opportunities to engage in enriching activities. Future research will have to employ more in-depth measurement of relevant language behaviours to fully understand the impact language use has on brain plasticity. Regardless, if a clear relationship can be established between bilingualism and increased cognitive reserve, then effort put into clarifying how to take advantage of this benefit is warranted.

3.0 Chapter 3: The Bilingual Advantage in Cognitive Control

The previous chapter explored evidence for bilingualism's contribution to cognitive reserve. It established that there is currently preliminary evidence that speaking more than one language, like other enriching activities, contributes to cognitive reserve, delaying the cognitive impact of dementia. While certain topics were explored in-depth (e.g., the impact of bilingualism on dementia), other topics were only briefly reviewed or explored. As such, in Chapter 3 I will expand upon some of those topics, with a special interest in exploring the bilingual advantage in cognitive control as a potential mechanism for bilingualism's contribution to cognitive reserve. I will review the theory behind the bilingual benefit and summarize the language-group research on the three most used cognitive control tasks (the Stroop, Simon, and Eriksen tasks). I will then review evidence for language-group differences in neural activation during cognitive control tasks. Throughout, I will keep a special focus on how the effects of aging are manifested in bilinguals.

3.1 Theory of the bilingual benefit

Historically, studies hypothesizing a bilingual benefit surmised that such a benefit might come from a bilingual's lifelong need to manage two concurrently active languages (e.g., Bialystok et al., 2008; Costa, Hernandez, Costa-Faidella, & Sebastián-Gallés, 2009; Kroll, Bobb, Misra, & Guo, 2008). Indeed, research demonstrates that both of a bilingual's languages are active when completing word recognition or language production tasks, even in contexts requiring only one language (Francis, 1999; Hermans, Bongaerts, de Bot, & Schreuder, 1998; Pivneva, Mercier, & Titone, 2014; Van Heuven, Dijkstra, & Grainger, 1998). Green's (1998) Inhibitory Control (IC) model proposed that the simultaneous activation of languages means that bilinguals will hold two lexical representations in mind and will require inhibitory or control mechanisms to manage the competition between their languages. It was further hypothesized that constant exercise of these mechanisms benefited other aspects of cognition, particularly components of executive functioning known as attention control and inhibitory control. The IC model was later extended to become the Adaptive Control Hypothesis (ACH), (Abutalebi & Green, 2007; ABUTALEBI & Green, 2016; Abutalebi & Green, 2008; Green & Abutalebi, 2013). The ACH posits that language comprehension and production require the interaction of multiple discrete and overlapping control processes (e.g., goal maintenance, conflict monitoring) carried out by interconnected networks of brain regions, in all language speakers. However,

bilingual language functioning specifically results in adaptive changes in the recruitment of and interactions between these networks. In support of this, functional neuroimaging studies have demonstrated that the regions recruited by bilinguals in the hypothesized series of networks are indeed involved in language processing and/or cognitive control (for a review see, P. Li, Legault, & Litcofsky, 2014). The ACH further posits that bilinguals will experience better executive functioning because of the general control mechanism that they exercise during language processing.

3.2 Cognitive Control

Cognitive control is a complex set of processes (composed of many subcomponents) that allow flexible responding and adaptive goal-directed behaviour. Cognitive control processes are particularly important for correctly resolving conflicts between incompatible, irrelevant, or incongruent information. The process of successful conflict resolution involves a number of discrete steps, including detection of conflict, selection of appropriate information for processing, filtering out of irrelevant information, inhibition of prepotent responses, and appropriate response selection. Tasks used to examine cognitive control processes involved in conflict typically include two types of trials, each containing a relevant and irrelevant (in terms of task goal) piece of information. On congruent trials, the two pieces of information are compatible, or congruent, meaning that they lead to the same response. On incongruent trials, the relevant and irrelevant information are incompatible, or incongruent, and therefore lead to different responses (with the irrelevant information leading to an incorrect response). Incongruent trials contain conflict and require cognitive control. They typically take longer to respond to than neutral or congruent trials. Many tasks also contain neutral trials that do not contain conflict (where the relevant information is either presented alone or alongside additional irrelevant information that is not paired with any response.). The difference between incongruent and congruent trials (in either reaction time or accuracy) is known as the conflict effect. Some researchers also calculate the facilitation effect (congruent trials – neutral trials), and/or the interference effect (incongruent trials – neutral trials). To further explain this basic task design, I will outline the three most commonly used cognitive control tasks, as well as highlight important concepts (i.e., the locus of the conflict) concerning cognitive control tasks.

In the Stroop task (Stroop, 1935), participants must identifying a color word's ink color (by verbal response or pressing a button) and not respond to the word itself. On congruent trials, the

relevant information (ink colour) does not conflict with the irrelevant information (the color word) – for example, the word BLUE written in blue ink. On incongruent trials the relevant and irrelevant information are in conflict - -for example, the word BLUE written in red ink. Some forms of the Stroop task include neutral trials using a non-color word (e.g., a series of Xs written in red ink). This type of conflict is often referred to as stimulus-stimulus (S-S) conflict, as both the relevant and irrelevant information are present within the stimulus.

Although there are many versions of the Simon task (Simon & Rudell, 1967), in the traditional spatial Simon task participants are asked to indicate the colour of a stimulus (by pressing a key to indicate if the stimulus is RED or BLUE). The stimuli appear on the left or right side of the display screen, and the response keys are on the left and right side of the keyboard (and/or are pressed with the index fingers of the left and right hand). On congruent trials the relevant response (the response key to indicate the correct colour) is not in conflict with the irrelevant information (position of the stimulus on the screen) – for example a blue stimulus being presented on the left side of the screen when the BLUE response key is on the left side of the keyboard. On incongruent trials the relevant response and the irrelevant information are in conflict – for example a blue stimulus being presented on the right side of the screen when the BLUE response key is on the left side of the keyboard. On neutral trials, coloured squares are presented in the centre of the screen. In this design, the conflict occurs between the stimulus and response (the congruent or incongruent information is present in both the stimulus and the response) and is often referred to as stimulus-response (S-R) conflict.

In the Eriksen flanker task (B. A. Eriksen & Eriksen, 1974), participants must press a left or right key to indicate the identity of a central target stimulus flanked by irrelevant stimuli. A common variation to the Eriksen task requires participants to indicate the direction of a central arrow while ignoring information from the non-target arrows by which it is flanked. On congruent trials the relevant information (target arrow) is does not conflict with the irrelevant information (flanker arrows) as they point in the same direction as the target. On incongruent trials the relevant information and the irrelevant information are in conflict as the flankers point in the opposite direction of the target. Some versions of the Eriksen task include neutral trials where the target arrow is presented either alone, or is surrounded by non-directional flankers. Similar to the Stroop task, this design contains S-S conflict (the congruent or incongruent

information is present within the stimulus), although there are important differences between the two tasks, which will be discussed below.

These three commonly used cognitive control tasks have a number of differences, and have been shown to have little correlation behaviourally (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Keye, Wilhelm, Oberauer, & Ravenzwaaij, 2008; e.g., Kousaie & Phillips, 2012b), and to activate partially different neural networks (X. Liu, Banich, Jacobson, & Tanabe, 2004; Peterson et al., 2002; Wager et al., 2005), which may be due to different networks being recruited for S-S and S-R conflict (Egner, 2008; Egner, Delano, & Hirsch, 2007; Nee, Wager, & Jonides, 2007). Stroop conflict arises from the irrelevant written color word information conflicting with the relevant ink colour, the Simon conflict from the irrelevant spatial information in the stimulus conflicting with the spatial location of the response key, and the Eriksen conflict from the irrelevant direction of the flanker arrows conflicting with the relevant information of the target arrows. The Stroop task also differs from the Simon, Eriksen and other cognitive control tasks in that it involves linguistic stimuli and semantic processing, while most other cognitive control tasks are non-linguistic by design. Additionally, in the Stroop task, the relevant and irrelevant information are two different dimensions of the exact same stimulus (word form and ink colour) and therefore overlap spatially, whereas in other tasks with S-S conflict, like the Eriksen task, the relevant and irrelevant information are the same dimension (direction of arrows) but are spatially distinct from each other.

Taken together, this information suggests that the different sub-components of cognitive control required for resolving conflict (e.g., conflict monitoring, conflict detection) may come into play at different times and in different ways for these three tasks, yet these tasks are not often directly compared and contrasted within one study. These differences may become especially significant when comparing groups, like monolinguals and bilinguals. If bilingualism does indeed contribute to cognitive reserve in the form of neural reserve, this may not necessarily impact the different conflict-related neural networks to the same degree. Likewise, the effects of aging may result in differences in age-related impairment to the implicated neural networks. Further, any compensation-related activation differences between older bilinguals and older monolinguals may vary across the different conflict-related networks, and therefore across tasks. Taken together, this indicates that language-group and age group differences may vary across

tasks because of differences in neural reserve and neural compensation. These topics will be further explored within the separate sections below.

3.3 Bilingualism and Cognitive Control

There are now many studies examining cognitive control abilities of bilinguals compared to monolinguals using a variety of executive function tasks, including the three cognitive control tasks outlined above, and interpreting behavioural data. In general these studies have found that bilingual participants demonstrate better cognitive control abilities than monolinguals, as evidenced by smaller conflict effects in RT (incongruent RT – congruent RT), although some studies have found that bilingual participants are faster than monolingual participants on both congruent and incongruent trials (e.g., Costa et al., 2009), suggesting a more global than conflict-specific advantage for bilinguals. As is explored in Manuscript 2, other studies have failed to find-language group differences (Kousaie & Phillips, 2012a; e.g., 2012b), and some have suggested that a bilingual benefit in cognitive control may be difficult to measure in younger adults who are at their cognitive peak (Bialystok et al., 2008; Kousaie & Phillips, 2017). Consistent with this, research with older adults has more consistently found a bilingual benefit when examining RT and accuracy on cognitive control tasks. These results will be reviewed below.

In an examination of the Stroop effect in younger and older monolinguals and bilinguals, Bialystok and colleagues (2008) found that the Stroop effect (slower RT on incongruent than congruent trials) increased with age, and that bilinguals in both age groups had a smaller Stroop effect than their monolingual counterparts. They did not find that this bilingual advantage increased with age. Two studies using non-computerized verbal versions of the Stroop task found evidence for a bilingual advantage for older adults. Bialystok and colleagues found no bilingual advantage for younger adults, but older bilinguals were faster than older monolinguals on the interference condition the task (Bialystok, Poarch, Luo, & Craik, 2014b). Kousaie and colleagues (2014) found that both younger and older bilinguals showed a bilingual advantage in accuracy on a verbal Stroop task. Importantly, in all three of these studies, although older bilingual participants were fluent in both their languages, they were mostly performing the Stroop task in their second language (L2) (72% of the older bilinguals in Kousaie et al., 2014). Contrary to these findings, studies where bilinguals performed the Stroop task in their either their first language (L1), or where bilinguals and monolinguals are equally fluent on the language used for

the Stroop task, have failed to find a bilingual advantage in older adults (Antón, García, Carreiras, & Duñabeitia, 2016; Kousaie & Phillips, 2012a). However, even when older bilinguals perform in their L2 they do not always show a bilingual advantage (Billig & Scholl, 2011).

Within the Simon task, research on the bilingual advantage in older adults has been mixed. A study by Bialystok and colleagues (Bialystok et al., 2004) examined the bilingual benefit in middle aged (30-45) and older (60-88) monolinguals and bilinguals by comparing their performance on the Simon task. They found that both the younger adult and older bilinguals had smaller Simon effects (incongruent RT – congruent RT) than their monolingual counterparts, and further, that this advantage was even more pronounced for the older bilinguals. They also examined the Simon effect across a number of different age groups - children, young adults, middle-aged adults, and older adults (Bialystok, Martin, & Viswanathan, 2005b). Their results showed a global advantage (faster for both congruent and incongruent trials) for bilingual children compared to monolingual children, no language-group differences in RT for the younger adults, and a global advantage for both middle-aged and older adults. In another study, they found no language-group difference in Simon effect for younger adults (nor a global advantage), but found that older bilinguals had a significantly smaller Simon effect compared to older monolinguals (Bialystok et al., 2008). Similarly, Salvatierra and Roselli (2011) compared performance on the Simon task and found no difference between monolinguals and bilinguals in the Simon effect for younger adults, but older bilinguals had a smaller Simon effect than older monolinguals. It should be noted that in this case the smaller conflict effect for bilinguals compared to monolinguals appears to be driven by monolingual groups performing more quickly than bilinguals on congruent trials (thus resulting in a larger difference between their congruent and incongruent trials), rather than a difference between the language groups on incongruent trials. Other researchers have failed to find a bilingual advantage on the Simon task for older bilinguals (Billig & Scholl, 2011; de Bruin, Bak, & Sala, 2015; Gathercole et al., 2014; Grady, Luk, Craik, & Bialystok, 2015; Kirk, Fiala, Scott-Brown, & Kempe, 2014; Kousaie et al., 2014).

Abutalebi and colleagues (2015b) used the Flanker trials from the Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002), comparable to an Eriksen task, to examine the performance of older monolinguals and bilinguals. Although they found a global advantage for the older bilinguals (faster RT on all trials), there was no difference between the

language groups on the Eriksen effect. Interestingly, Ong and colleagues (Ong, Sewell, Weekes, McKague, & Abutalebi, 2016) re-analysed this data using a diffusion model approach and found that older bilinguals differed from older monolinguals in a measure called "non-decision time", but not on "drift effect". This suggests that older bilinguals may have better attentional control than older monolinguals, which allows them to process stimuli more efficiently, but that the two groups perform equivalently at suppressing conflicting information.

To date, only one study has compared the performance of older monolinguals and bilinguals on all three tasks of cognitive control (Kousaie:2016uz, for a comparisons across the three tasks in younger bilinguals see, Kousaie & Phillips, 2012b). As this study also used neuroimaging methods (and was derived from the same recording session as the data reported in Manuscript 2), it will be discussed in greater detail in a later section, however, it can be noted here that that evidence for a bilingual advantage was seen on the Stroop task (with no difference in RT for older monolinguals and older bilinguals on congruent trials, but significantly faster RT for older bilinguals compared to older monolinguals on incongruent trials), but not on the Simon or Eriksen tasks.

3.4 Neuroimaging Studies of the Bilingual Benefit in Aging

It is clear that studies using behavioural data to examine cognitive control in younger and older monolinguals and bilinguals do not consistently show language group differences. One explanation put forward to explain the inconsistency in findings is that behavioural results are not sensitive enough to capture language-group differences, especially in younger adults who may be functioning at their cognitive peak and performing at ceiling (Bialystok et al., 2008; Kousaie & Phillips, 2012b). Given the seemingly subtle nature of the bilingual advantage, recent studies have turned to using neuroimaging measures to examine whether processing differences exist between younger and older monolinguals and bilinguals during cognitive control tasks. These results will be explored in more depth below.

Evidence from studies employing fMRI has provided support for the idea that bilinguals recruit a different neural network than monolinguals while completing cognitive control tasks, even when the two groups do not differ behaviourally. In an fMRI study examining the effect of bilingualism on brain functioning during cognitive control tasks, Luk, Anderson, Craik, Grady and Bialystok (2010) used an adaptation of the Eriksen flanker task (containing no-go trials) to examine response to S-R conflict (which they called interference suppression) as well as

response inhibition (to no-go trials) in a group of monolingual and bilingual adults. They did not find language-group differences in RT on any of the Flanker trial types (congruent, incongruent, neutral). Results from the fMRI analysis showed that bilinguals recruited a much more widespread network to deal with conflict (incongruent trials compared to congruent trials) than did monolinguals. Specifically, monolinguals recruited the left temporal pole and superior parietal cortex when presented with conflict, whereas bilinguals recruited significantly more regions including subcortical regions, fusiform gyrus, inferior frontal gyri (IFG), supplementary motor area (SMA), and inferior parietal regions for incongruent but not congruent trials. In contrast, Coderre and colleagues (2015) found no differences in behavioural results, nor in neural activation, between monolinguals and bilinguals during an Eriksen task. Interestingly, however, when comparing within-group overlap in activated brain regions across three different tasks (the Eriksen, a linguistic version of the Eriksen, and a semantic categorization task), they found subtle language-group differences. Results showed that monolinguals had no significant areas of overlap across the three tasks, whereas bilinguals showed significant overlap in the left IFG.

Using magneto-encephalography (MEG) Bialystok and colleagues (Bialystok et al., 2005a), examined the performance of younger monolinguals (English) and two groups of bilinguals (French-English and Cantonese-English) on the Simon task. Although they found no differences in behavioural measures of the Simon effect, nor in pattern of activation, the relationship between RT and brain activity differed across the groups. Specifically, the two bilingual groups showed a relationship between faster RT and greater alpha activity in superior and middle temporal, cingulate, and superior and inferior regions, occurring mostly in the left hemisphere. In contrast, the monolingual group showed a relationship between faster RT and activation in middle frontal regions.

Rodríguez-Pujadas and colleagues (Rodriguez-Pujadas et al., 2014) used a switching task to compare behavioural and neural differences between monolinguals and bilinguals when processing conflict. While switching tasks differ in a number of ways from the three cognitive control tasks reviewed here, critically, they contain conflict. Each trial in a switching task contains S-S conflict (e.g., a coloured shape where either the colour or the shape is the currently relevant information), which is highest on switch trials, as the previous trial has primed the currently irrelevant information (for more detail on switching tasks see Rogers & Monsell, 1995). Researchers found that while the two groups showed equivalent switch costs (switch RT –

repeat RT), bilingual participants recruited a more extensive network compared to monolinguals for switch trials. Additionally, bilinguals showed higher levels of activation than monolinguals in a number of areas associated with bilingual language control, such as the left IFG and left anterior cingulate cortex (ACC). Garbin and colleagues (Garbin et al., 2010) used a switching task to examine the neural basis of cognitive control in monolinguals and bilinguals. Results showed a language-group difference in behavioural measures: while monolinguals showed the expected switch cost (longer RT on switch trials than repeat trials, akin to having a higher conflict effect), bilingual participants did not show any effect of conflict (similar RTs on switch and repeat trials). In terms of neural recruitment, examination of fMRI data indicated that for switch trials (compared to repeat trials) monolinguals activated a network commonly recruit during non-verbal switch tasks: areas in the right IFG, the ACC, and the left inferior parietal lobe (IPL) for switch trials but not non-switch trials. In contrast, bilingual participants activated regions more commonly associated with language control: the left IFG/insula. The ACC, the right IFG, and the left IPL were not associated with switching for the bilingual group.

Taken together these studies indicated that younger monolinguals and bilinguals recruit both unique and overlapping regions during cognitive control tasks involving conflict. Bilinguals tend to recruit more extensive networks and these networks often overlap with those shown to be used for bilingual language control (Abutalebi & Green, 2008; De Baene, Duyck, Brass, & Carreiras, 2015; Green & Abutalebi, 2013). This suggests that speaking more than one language results in reorganization, and perhaps strengthening, of neural networks. Further, it provides preliminary evidence for the mechanism by which bilingualism may contribute to cognitive reserve – enhanced executive functioning systems. How language-group differences in neural activation might vary as a function of age is another important question. Aging adults experience slow and progressive declines in cognitive functioning related to cell death. A substantial body of research has examined how older adults with more cognitive reserve (i.e., higher levels of education, higher SES) manage to compensate and outperform peers with less cognitive reserve. To date, fewer studies have examined this with bilingualism as the proxy for cognitive reserve.

For example, Ansaldo, Ghazi-Saidi, & Adrover-Roig (2015) found that while older monolinguals and bilinguals did not differ in terms of RT on a Simon task, older bilinguals showed a different pattern of neural recruitment than older monolinguals on incongruent trials. Older monolinguals showed an age-related pattern of recruitment (consistent with the posterior-

anterior shift in aging; PASA), with activation in the right middle frontal gyrus. Older bilinguals did not show a PASA effect, and instead showed activation in the left IPL, an area implicated in bilingual language processing and cognitive control (Abutalebi & Green, 2007). As a follow-up to this study, Berroir and colleagues (Berroir, Ghazi-Saidi, Dash, & Adrover-Roig, 2016) analysed the fMRI data using graph theory analysis with small-world network properties to examine the neurofunctional networks involved. Their results showed that the older monolinguals showed a brain network containing a larger set of connected areas than the older bilinguals. The network used by the older bilinguals had only one brain region with higher connectivity values when compared to the same area in the older monolingual group - the left inferior temporal sulcus, whereas the brain network used by the older monolingual group had multiple areas that showed higher connectivity values compared to those same areas in the older bilingual group - the left superior frontal gyrus, the left lateral orbital sulcus, the right inferior opercular frontal gyrus, the right medial lingual occipito-temporal gyrus, and the right parieto-occipital sulcus.

Gold, Kim, Johnson, Kryscio and Smith (2013b) compared younger and older monolinguals and bilinguals in a task-switching paradigm. Behavioural results showed no difference in proportional RT switch cost (switch RT – nonswitch RT/nonswitch RT X 100) between younger monolinguals and younger bilinguals, but there was a non-significant trend for a smaller switch cost in older bilinguals compared to older monolinguals. Results showed that brain activation in response to conflict (switch trials compared to non-switch trials) was observed for all groups in the bilateral dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), supramarginal gyrus and ACC, however, older monolinguals showed age-related increases in activity in the left DLPFC, left VLPFC, and ACC (suggestive of compensatory over-recruitment), whereas older bilinguals did not differ from younger bilinguals.

Another method to examine the brain activity underlying cognitive control is electroencephalographic (EEG) recording. To date only four EEG studies have compared brain activity of monolinguals and bilinguals during cognitive control tasks (Coderre & van Heuven, 2014; Heidlmayr, Hemforth, Moutier, & Isel, 2015; Kousaie & Phillips, 2012b; 2017), and have found evidence to support both conflict-specific and global language-group differences in neurophysiological activity. With regards to stimulus-related ERPs, these papers have looked at the fronto-central N200 (or N2) which is thought to be related to conflict monitoring, the centro-

parietal Ninc (sometimes referred to as the N400), which is thought to reflect the higher cognitive cost of responding to incongruent stimuli, the P300 (or P3), thought to reflect resource allocation, and the LPC (late positive component), which occurs approximately 600-900ms following the stimulus and is thought to reflect conflict resolution or response selection. Although beyond the scope of this paper, it is important to note that within the cognitive control literature there is also interest in response-related ERPs, such as the ERN (Kousaie & Phillips, 2012b).

Heidlmayr and colleagues (2015) found conflict-specific language group differences in processing even in the absence of behavioural differences The researchers tested highly proficient, but non-balanced, French-German bilinguals and French monolinguals on a modified Stroop task. They found no evidence of a bilingual advantage in the behavioural results: RTs were longer for the incongruent than both the congruent and neutral trials. Bilinguals did not show a larger RT conflict effect, nor were they faster overall than monolinguals. In contrast, the researchers found clear evidence of a language-group difference in the ERP results, with an ERP conflict effect for monolinguals (more negative amplitude on incongruent trials compared to congruent trials) in both the N400 (400-500ms) and the late sustained negative-going potential (540-700ms) time periods, but no difference in the amplitudes between the two trial types for bilinguals. They did not find trial type or language group differences in the N2.

Coderre and van Heuven (2014) also found a conflict-specific language group processing difference, with evidence to suggest that bilinguals showed smaller conflict effects in ERP components than monolinguals. Using a modified Stroop task, the researchers examined the performance of Chinese-English bilinguals and English monolinguals on neutral, congruent, and incongruent trials. It is important to note that the modification included the addition of several stimulus onset asynchronies (SOAs), meaning that unlike the classic Stroop paradigm, colour words were not presented in congruent and incongruent colour ink. Instead, colour words were presented in a white font and surrounded by a congruently or incongruently coloured rectangle. The colour word was presented at either -400ms or 0ms compared to the colour rectangle. Additionally, bilingual participants completed the Stroop task in their L1 (Mandarin) and L2 (English). Here, we discuss the results of the 0ms SOA, as this most closely parallels the classic Stroop task. Analysis of the RT conflict effect and the RT interference effect (incongruent - neutral) demonstrated no difference between monolinguals and bilingual L1, but showed a larger

RT interference effect in the monolinguals compared to the bilinguals in their less dominant L2. Analysis of the neutral trials indicated monolinguals took significantly longer to respond than bilinguals performing in either their L1 or L2. Analyses on the Ninc were conducted on the difference waves (incongruent-congruent; i.e., the ERP conflict effect). Similar to the conflict-specific language group differences found by Heidlmayr and colleagues (2014), they found that bilinguals showed a trend towards a smaller Ninc than monolinguals (notably this was only in their L2, bilinguals did not differ from monolinguals when performing in their L1).

Research from our group (Kousaie & Phillips, 2012b) compared the performance of English-French bilinguals and English monolinguals on a Stroop, Simon, and flanker task, each with neutral, congruent, and incongruent trials. These results are reviewed in greater detail in Manuscript 2, as they are derived from the same recording session as the data in that manuscript. The researchers found that although there was no difference between monolinguals and bilinguals in the behavioural results, the two groups processed conflict differently on a neurophysiological basis as measured by the N2 and P3. The N2 results in the Stroop task, and the P3 results in the Stroop and Simon task indicate a global language group processing difference (as bilinguals differed from monolinguals on congruent and incongruent trials). The results from the Eriksen task do suggest a conflict-specific language-group difference, with the difference (in terms of P3 latency) between congruent and incongruent trials being smaller for bilinguals than monolinguals. Additionally, the results indicated that although all three tasks involve cognitive control, they did not engender similar ERP results. When looking at the data collapsed across the two language groups, they found an N2 conflict effect for the Eriksen only, P3 conflict effects for the Stroop and Simon when measuring amplitude, and the Simon and the Eriksen when measuring latency. This indicates that differences between tasks (in terms of locus of the conflict - the Stroop and Eriksen tasks contained S-S conflict, while the Simon task contained S-R conflict - and whether stimuli are linguistic or not) can result in differences in the timing and nature of the neural processes subserving cognitive control.

Recently, Kousaie and Phillips (2017) examined behavioural and ERP results in older monolingual and bilingual participants using the same methodology as their 2012 study (Kousaie & Phillips, 2012b). They found behavioural evidence for a bilingual benefit in the Stroop task, with no difference between RT for monolinguals and bilinguals on congruent trials, and significantly faster RTs for bilinguals compared to monolinguals on incongruent trials. They did

not find any RT or accuracy differences between the language groups on the Simon or Eriksen tasks. For the ERP data, results varied by component and task. Conflict-specific language group differences were seen in all three tasks when measuring the N2, but only on the Stroop task for the P3. In line with the previous research, the direction of these language group differences are that bilinguals show smaller (or no) differences between congruent and incongruent trials than monolinguals. Notably, when looking at the data collapsed across the two language groups, the locus of the conflict differed across tasks. Results showed that for the N2, congruent and incongruent trials were not significantly different on any ERP measure for the Stroop task, but were significantly different when measuring peak amplitude and latency in the Simon task, and mean and peak amplitude for the Eriksen task. For the P3, congruent and incongruent trials differed in the Stroop task when measuring mean and peak amplitude, and on the Simon and Eriksen tasks when measuring peak latency. Again, these findings demonstrate that variability between tasks can result in differences in the locus of the ERP manifestation of the conflict effect.

It is clear from the review of the preceding studies that ERP analyses add important information to our understanding of the locus of differences in cognitive control processing between monolinguals and bilinguals. Essentially, ERP analysis have shown us that in certain situations bilingual participants process conflict in a manner different from their monolingual counterparts, even if there is no difference in behavioural measures, and that often bilinguals show smaller differences between congruent and incongruent trials compared to monolinguals.

Taken together, Chapters 2 and 3 indicate that there is mounting evidence for bilingualism's contribution to cognitive reserve, as evidenced by a delay in cognitive decline in in dementia patients, enhanced cognitive control abilities in aging, and language-group specific neural networks supporting cognitive control processing. However, these two chapters also make clear that language-group differences can be subtle, and it is not yet well understood what variables may interact with or mediate any bilingual advantage. Chapter 2 touched upon the importance of measuring/balancing variables related to participants (e.g., language proficiency, level of education, immigration status), while Chapter 3 discussed important task-related variables (e.g., locus of the conflict, linguistic/non-linguistic stimuli). What is clear is that each of these avenues of study merit further attention.

3.5 Overview of the current project

The studies included in this thesis were designed to extend the literature reviewed in Chapters 2 and 3. The goal of Manuscript 1 was to examine structural brain differences between monolingual and multilingual patients with MCI and AD. By measuring cortical thickness and grey matter density in medial temporal regions we were able to test predictions made by the cognitive reserve hypothesis, when multilingualism is used as proxy for reserve. Additionally, by comparing neurophysiological measures in areas related to bilingualism and cognitive control, we were able to examine whether neuroplastic changes related to bilingualism found in younger and older adults were also visible in MCI and AD patients. The goal of Manuscript 2 was to examine functional brain differences between younger and older monolinguals and bilinguals. By using time-frequency analyses of EEG data recorded during three cognitive control tasks we were able to examine whether any language-group differences in neural oscillations varied as a function of age group. The following two manuscripts provide a detailed description of these studies.

Chapter 4: Manuscript 1:

Structural brain differences between monolingual and multilingual patients with mild cognitive impairment and Alzheimer disease: Evidence for cognitive reserve?

To be submitted to *Neuropsychologia*

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4.1 Abstract

Two independent lines of research provide evidence that speaking more than one language 1) contributes to greater grey matter in healthy younger and older adults and 2) delays cognitive symptoms in mild cognitive impairment (MCI) or Alzheimer disease (AD). We examine cortical thickness and tissue density in monolingual and multilingual MCI and AD patients matched (within patient groups) on demographic and cognitive variables. In cognitive control regions, multilingual MCI and AD patients had thicker cortex than the monolinguals. In areas related to MCI and AD pathology, we found higher tissue density in multilingual MCIs versus monolingual MCIs, but similar or lower tissue density in multilingual AD versus monolingual AD. Results were largely replicated in our native-born Canadian MCI participants, ruling out immigration as a potential confound. Finally, multilingual patients showed a correlation between cortical thickness in language and cognitive control regions and performance on episodic memory tasks. Given that multilinguals and monolinguals were matched on memory functioning, this suggests that greater gray matter in these regions may mediate their memory function. Our results suggest that being multilingual may delay the cognitive effects of disease-related atrophy and may also contribute to increased brain matter in areas related to cognitive control and language.

Keywords: Bilingualism, Cognitive Reserve, Brain Reserve, Mild Cognitive Impairment, Alzheimer Disease.

Structural brain differences between monolingual and multilingual patients with mild cognitive impairment and Alzheimer disease: Evidence for cognitive reserve?

4.2 Introduction

Two independent lines of research provide evidence for bilingualism's impact on the brain. Research with healthy younger and older adults suggests that speaking more than one language may increase gray matter in areas related to language and cognitive control (e.g., D. Klein, Mok, Chen, & Watkins, 2014). Research with patients with Alzheimer disease (AD) and mild cognitive impairment (MCI) suggests that bilingualism may contribute to cognitive reserve (CR), similar to other enriching lifestyle variables (Alladi et al., 2013; Bialystok, Craik, Binns, Ossher, & Freedman, 2014a), and moderate the relationship between brain integrity and cognitive functioning (Schweizer et al., 2012). Further, it has recently been proposed that the greater gray matter seen in older bilinguals may represent the neural underpinnings of the CR seen in bilingual dementia patients (Gold, 2016). The current study seeks to examine this proposal by bringing these two lines of evidence together. The current study compares cortical thickness and tissue density in a sample of monolingual and multilingual MCI and AD patients matched (within patient group) on cognitive functioning in areas related to language and cognitive control and regions known to atrophy in MCI and AD. Although bilingualism is commonly defined as speaking more than one language (with most studies reporting participants who speak two languages), we use the term multilingualism when referring to our sample, as approximately half of our multilingual patients speak more than two languages.

Research over the last decade suggests that speaking more than one language may provide cognitive benefits, specifically in executive functions like cognitive control (for a review see Dong & Li, 2015). Studies have shown that bilingual participants are less affected by irrelevant or competing stimuli (Bialystok et al., 2008; e.g., Bialystok & Martin, 2004), are better able to switch between two tasks (Garbin et al., 2010; Prior & Gollan, 2011) and are better able to inhibit pre-potent responses (Costa et al., 2009; Luk, De Sa, & Bialystok, 2011b) compared to monolinguals. Further, this language-group difference tends to become more pronounced in old age, such that the disparity in performance between monolinguals and bilinguals is larger in older adults than in younger adults (Bialystok et al., 2004). Although the claim of a bilingual advantage has been the topic of much debate (e.g., Hilchey & Klein, 2011; Paap, Johnson, & Sawi, 2015), discussion of this controversy is beyond the scope of this paper. Instead, we aim to

contribute to the literature examining whether bilingualism contributes to gray matter differences, and whether these structural differences may be linked to cognitive reserve.

Results from studies that have focused on healthy younger and older adults have demonstrated that speaking more than one language may cause neuroplastic changes to brain structure. Researchers have found language group differences in grey matter in a number of areas related to language and cognitive control, with greater brain matter for bilinguals compared to monolinguals. For younger adults these regions include the left inferior frontal gyrus (D. Klein et al., 2014), the left Heschl's gyrus (Ressel et al., 2012), the left putamen (Abutalebi et al., 2013), the right and left supramarginal gyri (Grogan et al., 2012), and the left and right cerebellum (Pliatsikas, Johnstone, & Marinis, 2014). For older adults, these brain areas include the left anterior inferior temporal gyrus (Abutalebi et al., 2014), the left and right inferior parietal lobe (Abutalebi, Canini, Rosa, Green, & Weekes, 2015a), and the left and right anterior cingulate cortex (Abutalebi, Guidi, Borsa, Canini, Rosa, Parris, et al., 2015b). It has been suggested that the lack of consistency in findings may be due to variability between studies in terms of analysis methods used and sample selection (for comprehensive reviews see García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2015; P. Li et al., 2014). Other studies have failed to find language group differences in older participants using whole-brain VBM analyses (Gold, Kim, Johnson, Kryscio, & Smith, 2013b), or in ROI analyses of the hippocampus, entorhinal cortex, or temporal pole (Olsen et al., 2015). Thus, there is accruing, but variable, evidence that, in healthy adults, being bilingual leads to greater tissue density and thicker cortex compared to being monolinguals.

Research comparing monolingual and bilingual dementia patients comes from the CR perspective. The CR hypothesis was originally proposed to explain non-systematic differences in the association between degree of brain damage and its outcome (Stern, 2002). The theory posits that participation in cognitively stimulating life experiences contributes to CR (Sattler, Toro, Schönknecht, & Schröder, 2012; Verghese et al., 2006; Wilson et al., 2013; Wilson & Bennett, 2003), which affords an individual more flexible and/or efficient cognitive processing. This in turn allows an individual to function at a level higher than would be predicted based on their level of neuropathology. In general, studies exploring whether bilingualism may be a contributor to CR in the context of dementia tend to compare variables such as age of symptom onset and/or age of clinical diagnosis between monolinguals and bilinguals, but do not include structural brain

measures. Although the findings are mixed, there is some evidence to support a delay in the symptoms or diagnosis of dementia for bilinguals as compared to monolinguals (for a review see, Guzmán-Vélez & Tranel, 2015). Recent research has also found a delay in symptom onset and diagnosis for bilingual patients with MCI compared to matched monolinguals (Bialystok, Craik, Binns, Ossher, & Freedman, 2014a; Ossher et al., 2013). Only one study to date has matched monolingual and bilingual AD patients on cognitive performance and then measured differences in neuropathology. Schweizer and colleagues (2012) found that bilinguals showed greater atrophy in AD-relevant brain areas (i.e., showed less brain matter) than monolinguals when measuring the radial width of the temporal horn and temporal horn ratio from CT scans, despite being matched on age, education, and cognitive performance.

In summary, these two families of findings may appear contradictory- research with healthy younger and older adults suggest that bilinguals have *thicker* cortex/higher tissue density compared to monolinguals, while the CR research hypothesizes that bilinguals would have *less* brain matter than their monolingual peers. The critical difference between these literatures is the brain regions of interest. In the healthy adult literature, bilingualism is conceptualized as an enriching exercise that contributes to neuroplasticity. As such these studies have directly measured brain areas thought to be affected by bilingualism. In comparison, within the CR literature, bilingualism is viewed as a contributor to cognitive reserve, which is only indirectly measured by quantifying the discrepancy between disease progression (or brain atrophy) and cognitive functioning. As such, the brain regions being measured are those affected by MCI and AD (Schweizer et al., 2012). We further propose that the greater gray matter previously found in areas related to language and cognitive control may represent, or be related to, the neural mechanism supporting bilingualism's contribution to CR. In other words, a bilingual's ability to maintain memory functioning in the face of disease-relevant neuropathology could be *dependent* on greater grey matter in brain areas related to bilingualism. In a review of bilingualism's contribution to CR, Gold (2016) makes a similar proposal, that bilinguals may experience a delay in dementia symptoms because they are able to compensate by relying more on enhanced executive control abilities. If this were the case, one might expect a correlation between grey matter in brain areas related to bilingualism and disease-relevant cognitive performance (i.e., episodic memory). As such, enriching lifestyle factors like bilingualism could contribute to both functional reorganization (CR) and structural changes in the brain.

The issue of immigration has a potentially important mediating or moderating effect on bilingualism's relationship with cognitive functioning (Bak & Alladi, 2014; Chertkow et al., 2010; Perani & Abutalebi, 2015; Schweizer, Craik, & Bialystok, 2013). Being bilingual is often, though not always, associated with being an immigrant and, depending on one's geographical location, it can be difficult to find sizable research samples of either immigrant monolinguals or non-immigrant bilinguals. As such, many studies have collapsed native-born and immigrant bilinguals together, or have compared mostly immigrant bilinguals to mostly native-born monolinguals. Immigration is related to a number of health and cognitive outcomes (e.g., Fuller-Thomson, Nuru-Jeter, Richardson, Raza, & Minkler, 2013) and may be associated with other CR variables like occupation and leisure activity (Mondini et al., 2014). Thus, it is a crucial variable to control.

Taken together, there is a growing body of research from healthy adults, MCI patients, and AD patients that examines the effects of bilingualism on the brain. The current research bridges the gaps between the bodies of literature in several important ways.

In summary:

1) Preliminary evidence exists that bilingualism results in thicker cortex in brain areas related to language switching and/or cognitive control. The current study extends this research to examine whether the differences seen in healthy younger and older adults will be present in multilingual MCI and AD patients.

2) Only one study has examined neuroanatomical differences in AD patients (Schweizer et al., 2012) and no work has been done in MCI patients. We match multilingual and monolingual MCI and AD patients on disease-relevant cognitive performance (episodic memory) and examine brain regions implicated in MCI and AD (medial temporal lobe areas).

3) We will examine whether language switching and cognitive control related brain regions help to support or contribute to the hypothesized CR in multilinguals. To examine this question, we tested whether there is a relationship between the brain areas related to bilingualism and measures of episodic memory.

4) Given the potential confound of immigration on the effects of bilingualism, we repeated our analyses in a sub-group of non-immigrant monolingual and multilingual MCI patients.

4.3 Materials and Methods

4.3.1 Participants

We employed the database of the Memory Clinic of the Jewish General Hospital in Montréal, Canada, a tertiary care referral clinic. Patients consented to analysis of their MRI data for research purposes, as reviewed by the Research Ethics Board of the Jewish General Hospital. The current sample was restricted to individuals who had MRI scans conducted beginning November 2002, as significant upgrades were made to the scanner earlier that year. Table 1 provides information for demographic and neuropsychological variables for each group.

Patient groups

Patients in the current study were diagnosed with MCI or AD. MCI subjects included in this study were clinically classified as "amnestic" or "amnestic plus" MCI, since memory was the major complaint, memory impairment was the main objective finding, and other cognitive domains were largely preserved on clinical evaluation. MCI diagnosis was carried out by trained neurologists or geriatricians using standardized criteria (as reviewed in Gauthier et al., 2006; and adapted from Petersen et al., 2001). AD was diagnosed by a neurologist or geriatrician in consultation with other Memory Clinic physicians, nurses, and neuropsychologists, using National Institute of Neurological and Communicative Disorders and Stroke- the Alzheimer's disease and Related Disorders Association criteria (McKhann, Drachman, Folstein, & Katzman, 1984).

We excluded patients who identified as left-handed and those where there was evidence to believe that their cognitive function reverted to "normal" at some point following their initial MCI diagnosis. For a number of patients, an initial scan at the time of diagnosis was conducted prior to 2002 (and therefore on a different MRI machine); as such, the second scan was used for 24 MCI and 5 AD patients, and the third scan for 2 MCI patients. The finalized database analyzed here consists of 94 patients, 68 with MCI and 26 with AD.

Language groups

Our sample had 34 monolingual MCI patients, 34 multilingual MCI patients, 13 monolingual AD patients, and 13 multilingual AD patients. Multilingualism was defined according to the criterion set out by Bialystok and colleagues (Bialystok et al., 2007) for bilingualism, namely that the majority of the participant's life was spent regularly using at least

Table 1.

Group means, standard errors, F-values, and *p*-values for demographic and neuropsychological variables.

	MCI						AD					
	Mono (n=34)		Multi (n=34)				Mono (n=13)		Multi (n=13)			
	M	SE	M	SE	F	*p*	M	SE	M	SE	F	*p*
Age at scan	73.6	0.9	73.7	1.0	0.01	*.95*	78.5	1.5	78.0	1.5	0.06	*.81*
MMSE at scan	26.7	0.4	27.6	0.3	2.16	*.15*	22.5	0.9	22.5	1.0	0.00	*1.00*
Scan to test (days)	-18.5	12.3	10.7	25.4	0.36	*.55*	160.1	104.7	90.3	83.1	0.77	*.38*
Education (years)	12.5	0.7	12.3	0.7	0.05	*.83*	12.7	1.0	12.1	1.1	0.17	*.68*
Age at onset[1]	68	1.1	67.8	1.3	0.02	*.90*	74.3	1.5	72.6	1.6	0.44	*.51*
Age at diagnosis	71.5	0.9	72.2	1.0	0.28	*.60*	77.1	1.6	76.7	1.3	0.04	*.84*
	N	%	N	%			N	%	N	%		
Women	17	50	15	41			8	62	3	23		
Immigrant	7	21	20	59			2	15	7	54		
Bilingual	-	-	18	53			-	-	9	69		

[1] Age of symptom onset information was assessed via family interviews in which an estimate of the year and month of onset of memory complaints was determined by the question, ‘‘Can you give the month and year when you first noticed memory problems (in the patient)?’’

Table 1. cont.

	MCI						AD					
	Mono (n=34)		Multi (n=34)				Mono (n=13)		Multi (n=13)			
	M	SE	M	SE	F	*p*	M	SE	M	SE	F	*p*
Short delay verbal recall (%)	52.1	2.7	48.5	2.6	1.0	*.32*	33.8	3.4	32.5	3.0	0.1	*.82*
Long delay verbal recall (%)	25.5	3.1	22.7	3.5	0.5	*.49*	6.0	1.7	5.3	2.3	<0.1	*.92*
Immediate visual recall	56.1	3.1	54.1	2.9	0.2	*.64*	30.0	4.5	30.9	6.9	<0.1	*.91*
Delayed visual recall	21.8	3.4	22.9	3.3	0.1	*.80*	5.1	2.5	8.1	3.5	0.1	*.71*
Stroop Words (s)	38.7	2.2	36.3	2.0	0.2	*.63*	65.0	13.7	64.3	7.5	<0.1	*.94*
Stroop Interference	2.3	0.2	2.1	0.1	0.4	*.51*	3.2	0.9	2.5	0.3	1.5	*.23*
Spatial Span total (/)	11.6	0.5	10.1	0.4	4.7	*.03*	8.8	0.7	9.2	1.3	0.1	*.72*
Block Design (/68)	27.0	1.8	25.8	1.3	0.3	*.61*	18.8	1.8	20.7	3.1	0.3	*.60*
Trail A (s)	52.0	3.4	48.0	2.9	3.3	*.57*	83.2	11.7	86.3	14.0	0.1	*.78*
Orientation (%)	93.5	1.8	94.7	1.5	2.0	*.66*	81.2	3.5	78.9	3.3	3.2	*.57*
Clock (/10)	8.3	0.3	7.8	0.3	1.7	*.20*	6.77	0.48	6.3	0.6	0.5	*.50*

two languages, and was based upon chart information derived from a neuropsychological interview. Information regarding age of acquisition and proficiency was not reliably available in all patients. Monolingual participants spoke only one language, and multilingual participants were defined as speaking two or more languages. Monolingual patients were either English or French speakers. Within the multilingual group, just over half were bilingual, with the majority (%) being English/French or French/English bilinguals. Similarly, for those who spoke three or more languages, all but one spoke English, French, and one of a variety of other languages (e.g., Yiddish, Hebrew, Greek, Arabic, etc). Immigration status was determined by place of birth; however, we did not control specifically for the age at which the patient immigrated to Canada. Numbers in the AD group were too small to achieve statistical power; therefore, data from only non-immigrant MCI patients were analysed (27 monolinguals and 14 multilinguals).

Matching variables

We matched each language group (monolingual or multilingual) within each patient group (MCI or AD) on a number of measures of clinical severity and cognitive functioning: years of education, age at time of scan, time from neuropsychological assessment to scan, Mini Mental Status Examination (MMSE) score, and two tests of episodic memory (all $p > .15$). Episodic memory tests included: percentage of words recalled (short delay and long delay verbal recall score) from either the California Verbal Learning Test - Second edition (CVLT-II; Delis, Kramer, Kaplan, & Ober, 2000)or the Rey Auditory Verbal Learning Test (RAVLT; Spreen & Strauss, 1998), and raw immediate and delayed recall score from the Wechsler Memory Scale - III Visual Reproduction subtest (WMS III; Wechsler, 1997b).

4.3.2 Cognitive functioning

Additional data from the neuropsychological assessments were analyzed to examine whether the language groups differ from each other in other cognitive domains. Scores were derived from standardized neuropsychological tests administered during a clinical assessment session. The six measures included: The Victoria Stroop Task (Stroop, 1935), the Spatial Span subtest from the WMS III; Block Design from the Wechsler Adult Intelligence Scale third edition (WAIS III; Wechsler, 1997a); Trails A (Reitan, 1958), orientation, and clock design (Rouleau, Salmon, Butters, & Kennedy, 1992).

4.3.3 MRI acquisition and pre-processing

High-resolution (1-mm isotropic) T1-weighted sagittal images were acquired on a Siemens SonataVision 1.5 T scanner (TR=22, TE=9.2) Brain Imaging Center, Montreal Neurological Institute (MNI), in Montreal, Quebec. Structural images were submitted to the CIVET pipeline (version 1.1.11; http://wiki.bic.mni.mcgill.ca/index.php/CIVET) developed at the MNI for fully automated structural image analysis (Ad-Dab'bagh et al., 2006), whose steps are detailed elsewhere (Karama et al., 2009). Cortical thickness analyses were conducted on brain areas on or close to the cortical surface (e.g., inferior frontal gyrus, pre-supplementary motor area), whereas voxel-based morphometry was used for medial structures (e.g., hippocampus, rhinal sulcus). For the VBM analyses, grey and white matter volumes derived from the tissue classification stage (step 3 of the process) were convolved with an 8-mm full-width at half-maximum (FWHM) 3D Gaussian blurring kernel, and then entered into the regression analyses.

4.3.4 Regions of interest

Two families of hypothesis-driven regions of interest (ROIs) were selected based on: 1) areas implicated in language and cognitive control and 2) areas known to atrophy in MCI and AD. Within each ROI, the specific vertex or voxel analysed was chosen based on either the specific coordinates given in relevant publications (when available) or the general functional or anatomical brain region, and was then refined by the results of our global regression analyses. The latter allowed us to account for individual variability in the location of functional substrates, subtle differences in coordinate systems, and differences that could have been introduced by image pre-processing and template registration. As such, we were able to analyze the vertex or voxel with the strongest effect in our data, while remaining within a given ROI as guided by our *a priori* hypotheses. For example, Abutalebi et al. (2014) found decreased grey matter volume (using VBM) in the left anterior temporal lobe at the MNI space x, y, z coordinates: [-45, -4, -36]. We investigated the left anterior temporal lobe ROI at [-51, -10, -40], as this location showed the largest effect in our global regression analysis. ROIs that did not contain significant vertices/voxels in the global regression analysis were not further analysed. See Table A.1 in Supplementary Materials for the coordinates of ROIs used in our study.

4.3.5 Statistical analyses

Demographic and neuropsychological variables were assessed with ANOVAs. Planned comparisons were conducted to examine the effects of language group within each patient group.

Statistical analyses were carried out in a similar manner for both the cortical thickness and VBM analyses, with the dependent variable (DV) being native-space, vertex-level cortical thickness (measured in millimeters) for the cortical thickness analyses, and voxel-level, grey matter tissue density for the VBM analyses. Two regression equations were run at each vertex and voxel of interest, one to examine the effects of Language Group (Figure 1A) and another to test for a significant interaction between Language Group and Patient Group (Figure 1 B). In both cases, the DV was regressed onto age (at time of the scan), Language Group (monolingual or multilingual), and Patient Group (MCI or AD). These statistical analyses were performed using the R software package (Team, 2016). In the interest of thoroughness, results are initially presented uncorrected for multiple comparisons, then presented with correction for multiple comparisons within each family of ROIs. In the case of a significant interaction between Language Group and Patient Group, ANCOVAs (using age as a covariate) were run to examine planned comparisons between monolinguals and multilinguals within each patient group.

4.4 Results

4.4.1 Cognitive functioning results

See Table 1 for means and standard errors of neuropsychological variables, and F- and *p*-values from planned comparisons of language groups within each patient group. There was a main effect of Patient Group (all $p < .001$) for all neuropsychological variables, with MCI patients outperforming AD patients. No main effect of Language Group was found for any other neuropsychological variables, (all $p > .207$).

4.4.2 Structural measure results

Results are presented by ROI family. See Table 2 for t- and *p*-values from the regression analyses, and Table A.2 (Appendix A) for the mean (and standard error) cortical thickness and tissue density for monolingual and multilingual MCI and AD patients, separated by analysis method (including one post-hoc finding that survived a threshold of $p < .01$ in the global analysis).

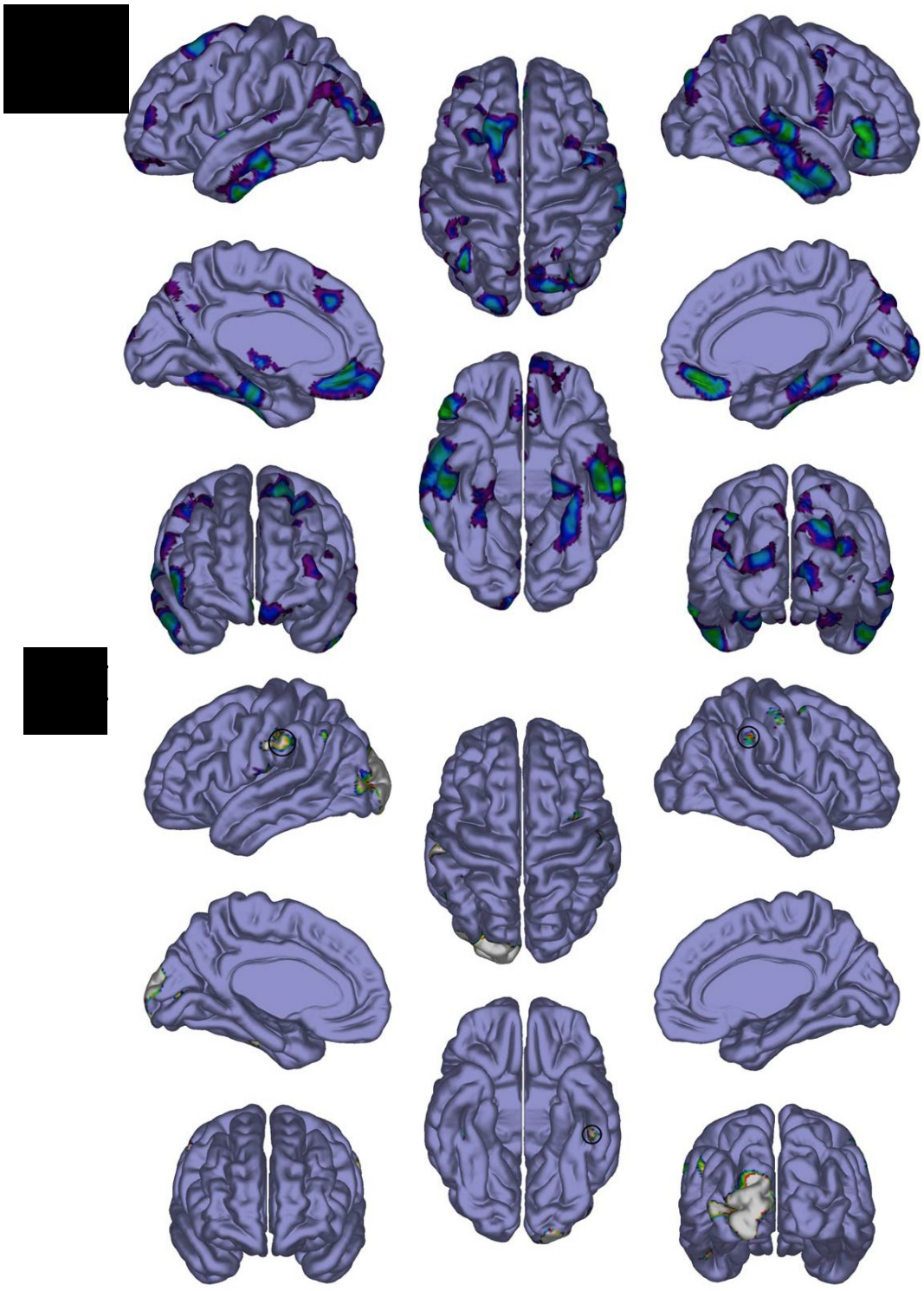

Figure 1. A. Significance of the Languages term alone, using an uncorrected threshold of p =.05, rendered onto an average elderly surface. T-statistic colour mapping values range between 2.00 and 4.00. B.

Table 2.

T- and *p*-values for regression analyses of Family 1 and Family 2 ROIs and post-hoc finding.

Family 1. Language Group and Patient Group Main Effects				
	Language Group		Patient Group	
	t	*p*	t	*p*
L iFG^{CT}	2.27	*.026*	-0.57	*.571*
R iFG^{CT}	3.26	*.002*	0.35	*.729*
L mSFG^{CT}	2.67	*.009*	0.45	*.651*
R vmPFC^{CT}	3.28	*.001*	-1.11	*.270*
L aTG^{CT}	2.98	*.004*	-1.74	*.086*
R aTG^{CT}	2.72	*.008*	-1.57	*.120*
L iPL^{CT}	2.98	*.004*	-1.19	*.239*
L Cer^{VBM}	2.95	*.004*	-1.49	*.140*
R Cer^{VBM}	3.15	*.002*	-1.8	*.075*
R cerTon^{VBM}	4.61	*.001*	1.64	*.105*

Family 1. Language Group, Patient Group, and Interaction Effects						
	Language Group		Patient Group		Interaction	
	t	*p*	t	*p*	t	*p*
L SMG ^{CT}	2.61	*.010*	1.86	*.066*	-2.51	*.014*
R SMG^{CT}	1.65	*.103*	1.13	*.263*	-2.24	*.027*

Table 2. con't.

Family 2. Language Group and Patient Group Main Effects				
	Language Group		Patient Group	
	t	*p*	t	*p*
L Hippo^{VBM}	2.70	*.008*	-2.65	*.009*
R Hippo^{VBM}	2.69	*.008*	-3.44	*.001*

Family 2. Language Group, Patient Group, and Interaction Effects						
	Language Group		Patient Group		Interaction	
	t	*p*	t	*p*	t	*p*
L Rhin^{VBM}	2.21	*.029*	1.80	*.075*	-2.45	*.016*
R Rhin^{VBM}	1.12	*.265*	1.07	*.289*	-2.07	*.041*
R pPHC^{VBM}	1.72	*.089*	1.30	*.195*	-3.13	*.002*
L pHC^{VBM}	1.62	*.110*	1.46	*.148*	-2.7	*.008*
	Language Group		Diagnostic Group		Interaction	
	t	*p*	t	*p*	t	*p*
Left visual association cortex^{CT}	3.46	*.001*	1.86	*.067*	-3.16	*.002*

Notes: aTG = anterior temporal gyrus; Cer = cerebellum; cerTon = cerebellar tonsil; Hippo = hippocampus; IFG = inferior frontal gyrus; IPL = inferior parietal lobule; L = Left; mSFG = medial superior frontal gyrus; pPHC = posterior parahippocampal cortex; Rhin = rhinal; R = Right; SMG = supramarginal gyrus; vmPFC = ventromedial prefrontal cortex

Family 1 – Language and cognitive control areas

Language group effects. As can be seen in Figures 2a and 2b, there was a main effect of language group in nearly all of the Family 1 ROIs (all $p < .024$), with the exception of the putamen and Heschl's gyrus which did not exceed a threshold of $t > 2.00$ in the global regression analyses. For the ROIs showing a significant effect, the pattern was greater cortical thickness for multilinguals compared to monolinguals. After controlling for Family-wise Type I error, the right inferior frontal gyrus, right ventromedial prefrontal cortex, right cerebellum, and right cerebellar tonsil remained significant. None of the regions showed a reliable effect of Patient Group (all p's>.075).

Interaction effects. Figure 2c shows the ROIs for which there was a reliable interaction between Language Group and Patient Group. Both the left and right supramarginal gyri show an interaction between Language Group and Patient Group ($p = .014$ and $p = .027$, respectively), although this does not remain significant after controlling for multiple comparisons.

Family 2 ROIs – Disease-relevant areas

Language group effects. As seen in Figure 3a, greater tissue density was found in the multilingual group compared to the monolingual group in the left and right hippocampi (all *p*s < 0.009). Both regions remain significant after correcting for multiple comparisons. These regions also showed a significant effect of Patient Group, with higher tissue density for MCI than AD patients (all $p < 0.01$).

Interaction effects. As seen in Figure 3b, a similar pattern is observed across the four regions, with the overall trend towards higher tissue density in the multilingual MCIs compared to the monolinguals and the reverse pattern (i.e., lower tissue density in the multilinguals compared to monolinguals) in the AD patients. This was supported by a reliable Language Group by Patient Group interaction for the left and right parahippocampal gyri ($p = .008$ and $p = .002$ respectively), and left and right rhinal sulci ($p = .016$ and $p = .041$). Note that the latter pair did not survive correction for Family-wise Type I error. Planned comparisons indicated that multilingual MCI patients had higher tissue density than monolingual MCI patients in the right parahippocampal gyrus, while the opposite pattern was found in the AD patients (i.e., lower tissue density for multilinguals compared to monolinguals) in the left and right parahippocampal gyri.

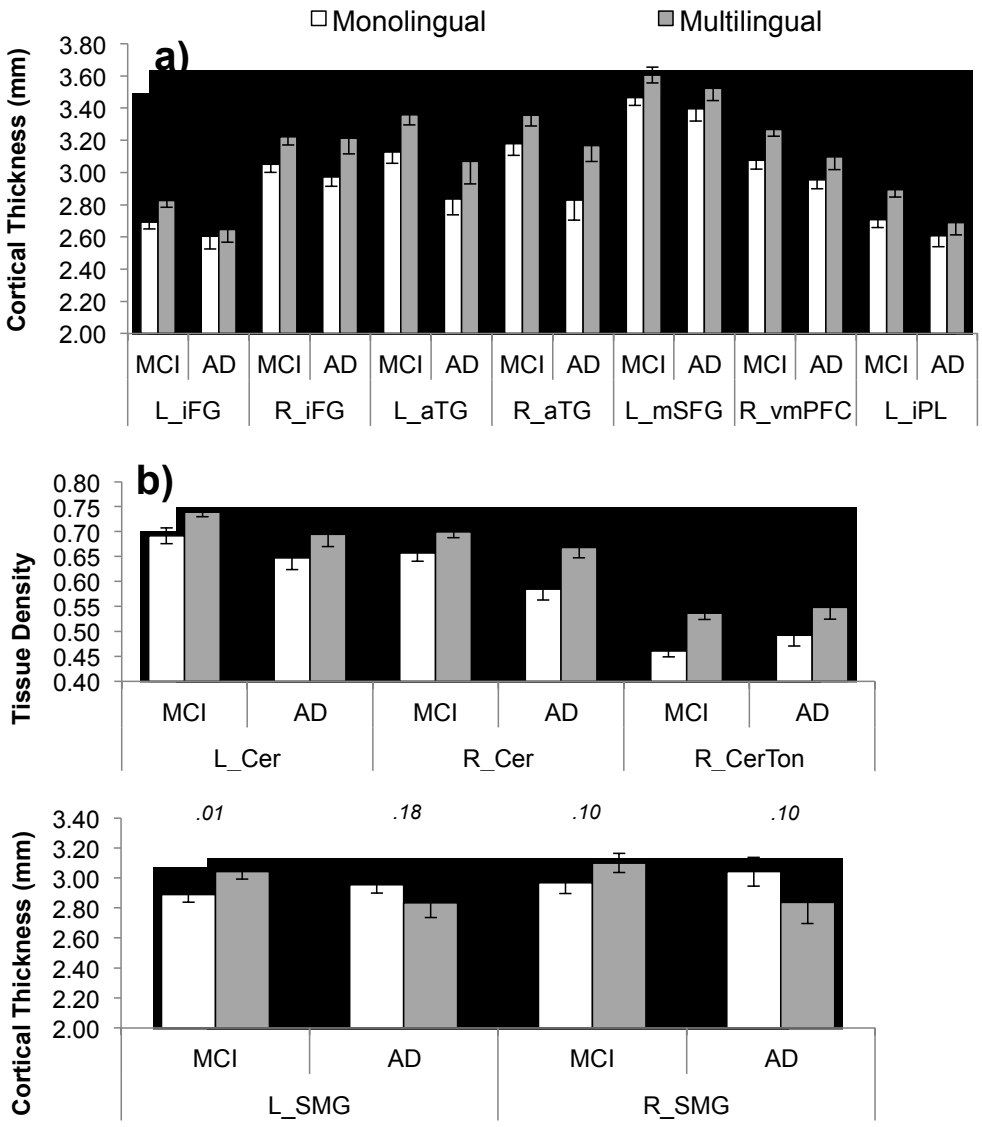

Figure 2. aTG = anterior temporal gyrus; Cer = cerebellum; cerTon = cerebellar tonsil; iFG = inferior frontal gyrus; iPL = inferior parietal lobule; L = Left; mSFG = medial superior frontal gyrus; R = Right; SMG = supramarginal gyrus; vmPFC = ventromedial prefrontal cortex. a) Cortical thickness (mm) of monolingual and multilingual MCI and AD patients in Family 1 ROIs showing an additive effect. b) Tissue density of monolingual and multilingual MCI and AD patients in Family 1 ROIs showing an additive effect. c) Cortical thickness (mm) of monolingual and multilingual MCI and AD patients in Family 1 ROIs showing an interaction effect. Italicized numbers are p-values from planned comparisons.

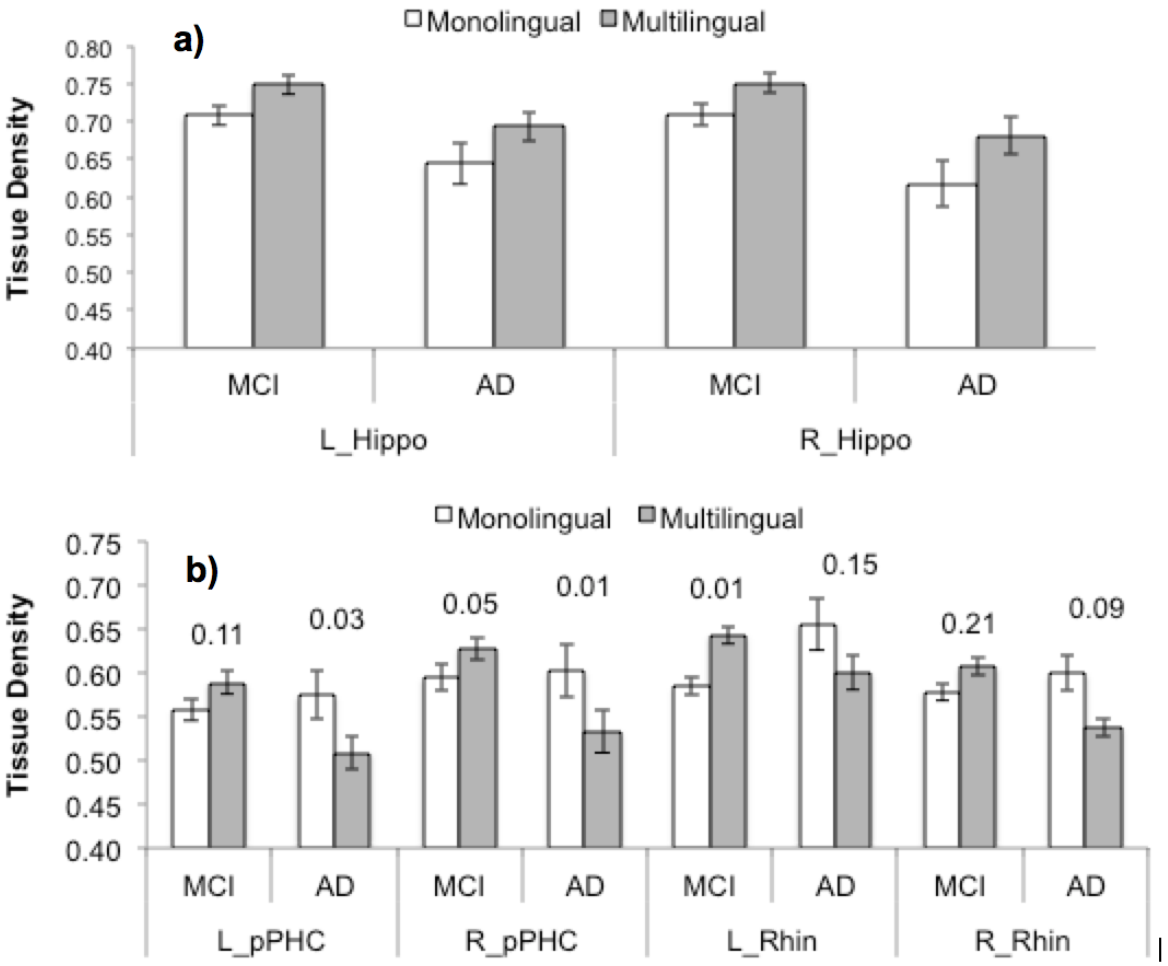

Figure 3. Hippo = hippocampus; L = Left; pPHC = posterior parahippocampal cortex; Rhin = rhinal; R = Right. a) Tissue density of monolingual and multilingual MCI and AD patients in Family 2 ROIs showing an additive effect. b) Tissue density of monolingual and multilingual MCI and AD patients in Family 2 ROIs showing an interaction effect. Italicized numbers are p-values from planned comparisons.

MCI conversion. Recall that within a group of MCI patients, some will likely progress to AD, whereas others will not. To explore whether these potential subgroups differed in the pattern of findings, we divided our monolingual and multilingual MCI groups by whether or not the patient has since been diagnosed with AD. The average follow-up period was 8.5 years, with 12 of the non-converted MCI patients having been followed for less than 5 years. A Language Group by Conversion Group ANOVA indicated that amongst the MCI patients who as yet had not converted to AD, multilingual MCIs showed a pattern of thicker cortex and higher tissue density in both Family 1 (areas related to language and cognitive control) and Family 2 (disease-relevant) ROIs compared to monolingual MCIs. In contrast there were no Language Group differences among those MCIs who later converted to AD. See Table 3 for group means, standard errors, F-values, and *p*-values for monolingual and multilingual MCI converters and non-converters.

Table 3.

Group means, standard errors, F-values, and *p*-values for monolingual and multilingual MCI converters and non-converters.

	Non-Converted						Converted					
	Mono (n=23)		Multi (n=28)				Mono (n=11)		Multi (n=6)			
	M	SE	M	SE	F	*p*	M	SE	M	SE	F	*p*
L iFG	2.67	0.06	2.83	0.05	4.6	*.04*	2.73	0.06	2.82	0.13	0.5	*.48*
R iFG	3.01	0.06	3.25	0.06	8.6	*.01*	3.14	0.1	3.10	0.11	0.1	*.77*
L mSFG	3.45	0.06	3.63	0.05	5.1	*.03*	3.49	0.09	3.48	0.16	0.0	*.95*
R vmPF	3.06	0.07	3.28	0.04	7.3	*.01*	3.11	0.09	3.21	0.15	0.5	*.49*
L aTG	3.07	0.09	3.40	0.06	8.8	*<.04*	3.25	0.12	3.18	0.22	0.1	*.73*
R aTG	3.19	0.09	3.42	0.07	4.1	*.05*	3.16	0.14	3.05	0.19	0.3	*.58*
L iPL	2.71	0.05	2.90	0.05	5.8	*.02*	2.70	0.1	2.87	0.11	1.5	*.23*
L Cer	0.70	0.02	0.74	0.01	3.6	*.06*	0.68	0.03	0.74	0.03	2.5	*.12*
R Cer	0.65	0.02	0.71	0.01	5.9	*.02*	0.68	0.03	0.67	0.03	0.1	*.81*
R cerTon	0.47	0.02	0.54	0.01	13.3	*<.01*	0.44	0.02	0.50	0.04	3.0	*.09*
L SMG	2.82	0.05	3.07	0.06	10.7	*<.01*	3.03	0.06	2.92	0.13	0.7	*.41*
R SMG	2.93	0.07	3.08	0.05	3.0	*.09*	3.04	0.08	3.19	0.12	0.9	*.48*
L Hippo	0.71	0.02	0.75	0.01	4.5	*.04*	0.71	0.03	0.73	0.03	0.3	*.57*
R Hippo	0.71	0.02	0.76	0.01	4.1	*.05*	0.71	0.02	0.72	0.05	0.2	*.68*
L Rhin	0.58	0.02	0.65	0.02	5.5	*.02*	0.59	0.02	0.62	0.03	0.5	*.50*
R Rhin	0.58	0.02	0.61	0.02	1.4	*.25*	0.58	0.02	0.59	0.04	0.0	*.87*
L pPHC	0.56	0.02	0.60	0.01	2.2	*.14*	0.55	0.02	0.56	0.05	0.0	*.88*
R pPHC	0.59	0.02	0.64	0.01	4.9	*.03*	0.60	0.02	0.59	0.04	0.2	*.69*

Notes: aTG = anterior temporal gyrus; Cer = cerebellum; cerTon = cerebellar tonsil; Hippo = hippocampus; IFG = inferior frontal gyrus; IPL = inferior parietal lobule; L = Left; mSFG = medial superior frontal gyrus; pPHC = posterior parahippocampal cortex; Rhin = rhinal; R = Right; SMG = supramarginal gyrus; vmPFC = ventromedial prefrontal cortex

4.4.3 Correlational results

Bivariate correlations were used to examine the relationship between memory and cortical thickness of Family 1 ROIs, within each group. See Figure 4 for representative scatterplots and Table 4 for Pearson's r and *p* values. For the monolingual MCI patients, there were no significant correlations. Correlations were found for the multilingual MCI patients between the long delay verbal recall score and the left inferior frontal gyrus, left pre-supplementary motor area, left anterior temporal gyrus, and left supramarginal gyrus, and between the delayed visual recall score and the left anterior temporal gyrus and right cerebellum. For the AD patients, we looked only at the short delay verbal and immediate visual recall scores, as many patients scored at floor on the long delay measures. For the monolingual AD patients, a correlation was found between the immediate visual recall score and the left inferior parietal lobule. For the multilingual AD patients, correlations were seen between the short delay verbal recall score and the left inferior frontal gyrus, right inferior frontal gyrus, and left supramarginal gyrus.

4.4.4 Immigration group analyses

To examine the potential influence of immigration, we repeated our regression analyses on a sub-sample of non-immigrant patients. The groups did not differ on demographic variables (all $p > .09$) and the same set of neuropsychological variables as the larger sample ($p > .155$). ROIs were based on those used in the entire sample, but adjusted to the location of the largest t-statistic within the general functional region. Refer to Table 5 for demographic information, coordinates, mean cortical thickness/grey matter density, and t and *p* values. With regards to disease-relevant brain areas, multilinguals had higher values in the left and right entorhinal and perirhinal cortices; however, these were subtle and did not survive correction for multiple comparisons. No differences were found in the left or right hippocampi. With regards to brain areas related to language and cognitive control, these results largely confirmed those found with the whole sample, showing a thicker cortex in the multilingual group than in the monolingual group, which includes the left and right inferior frontal gyri, left and right anterior temporal gyri, left inferior parietal lobule, and the right cerebellar tonsil. Results were more reliable in the right hemisphere than the left. Only the right anterior temporal gyrus, left inferior parietal lobule, and the right cerebellar tonsil survived correction for multiple comparisons. No differences were seen in the anterior cingulate cortex, putamen, or the medial frontal cortex.

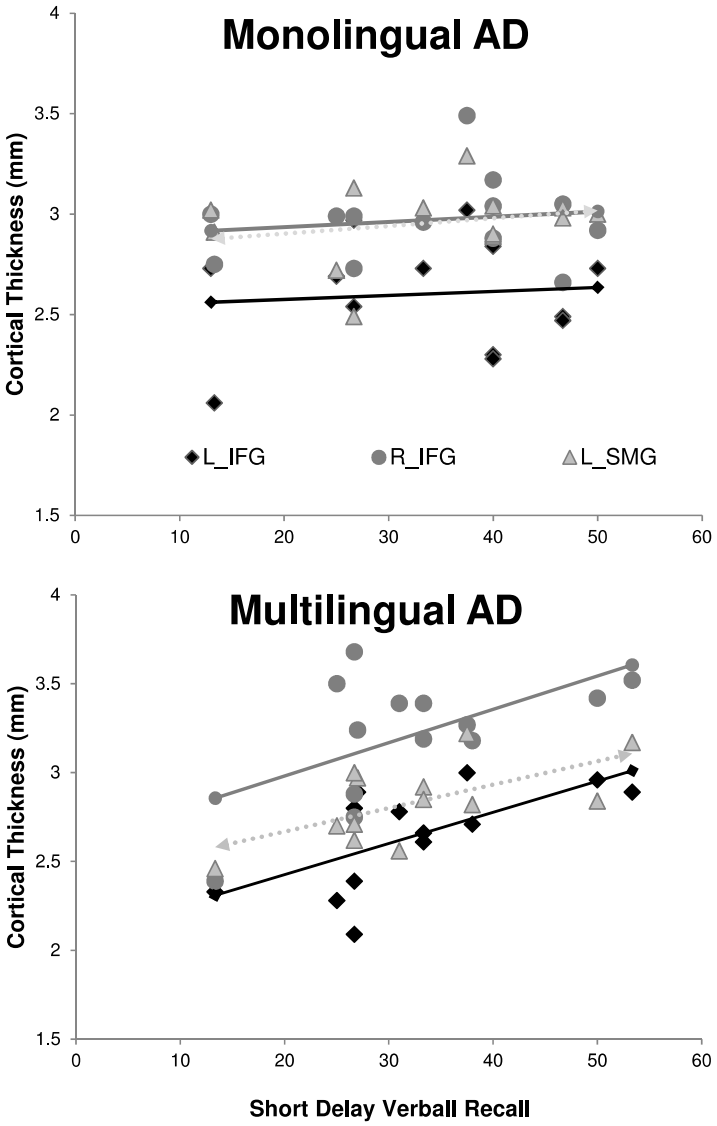

Figure 4. IFG = inferior frontal gyrus ; L = Left; R = Right. SMG = supramarginal gyrus. Scatterplot of correlation between Short Delay Verbal Recall score (%) and cortical thickness (mm) of the left inferior frontal gyrus, right inferior frontal gyrus, and left supramarginal gyrus, for monolingual and multilingual AD patients.

Table 4

Correlation results between brain regions associated with bilingualism and episodic memory scores

	MCI							
	Delayed Verbal Recall				Delayed Visual Recall			
	Monolingual		Multilingual		Monolingual		Multilingual	
	r	*p*	r	*p*	r	*p*	r	*p*
Left inferior frontal gyrus	0.03	*.86*	0.39	*.02**	0.07	*.68*	0.18	*.32*
Right inferior frontal gyrus	0.00	*.99*	0.24	*.18*	-0.02	*.92*	0.19	*.30*
Left medial superior frontal gyrus	0.21	*.23*	0.42	*.02**	-0.10	*.59*	0.27	*.12*
Right ventromedial prefrontal cortex	0.18	*.32*	0.25	*.15*	0.00	*1.00*	0.25	*.17*
Left anterior temporal gyrus	0.08	*.65*	0.37	*.03**	0.12	*.50*	0.40	*.02**
Right anterior temporal gyrus	0.24	*.18*	0.19	*.28*	0.18	*.31*	0.29	*.11*
Left inferior parietal lobule	0.14	*.44*	0.20	*.25*	0.16	*.35*	0.27	*.13*
Left supramarginal gyrus	-0.03	*.87*	0.36	*.04**	-0.03	*.89*	0.20	*.27*
Right supramarginal gyrus	0.04	*.83*	0.18	*.31*	0.05	*.79*	0.30	*.10*
Left cerebellum	0.11	*.54*	-0.01	*.96*	0.23	*.20*	-0.05	*.79*
Right cerebellum	-0.10	*.58*	0.00	*.99*	-0.10	*.58*	0.37	*.04**
Right cerebellar tonsil	0.17	*.35*	-0.05	*.78*	0.12	*.51*	0.17	.35
	AD							
	Immediate Verbal Recall				Immediate Visual Recall			
	Monolingual		Multilingual		Monolingual		Multilingual	
	r	*p*	r	*p*	r	*p*	r	*p*
Left inferior frontal gyrus	0.08	*.79*	0.65	*.02**	-0.23	*0.56*	0.09	*.81*
Right inferior frontal gyrus	0.14	*.64*	0.56	*.05**	-0.01	*0.98*	0.31	*.39*
Left medial superior frontal gyrus	0.24	*.44*	0.41	*.17*	0.02	*0.96*	0.20	*.59*
Right ventromedial prefrontal cortex	0.04	*.91*	0.16	*.61*	-0.01	*0.98*	0.29	*.41*
Left anterior temporal gyrus	-0.16	*.59*	0.55	*.05**	0.16	*0.69*	0.04	*.91*
Right anterior temporal gyrus	0.17	*.58*	0.44	*.13*	0.00	*1.00*	0.12	*.74*
Left inferior parietal lobule	-0.36	*.22*	0.40	*.18*	0.70	*0.04**	0.23	*.52*
Left supramarginal gyrus	0.23	*.44*	0.62	*.02**	-0.17	*0.66*	0.25	*.48*
Right supramarginal gyrus	0.01	*.99*	0.25	*.41*	-0.10	*0.80*	0.34	*.34*
Left cerebellum	0.18	*.55*	0.50	*.08*	0.38	*0.32*	0.02	*.95*
Right cerebellum	-0.24	*.43*	0.43	*.14*	0.46	*0.22*	0.12	*.74*
Right Cerebellar Tonsil	0.20	*.51*	-0.07	*.83*	-0.36	*0.35*	0.55	*.10*

Table 5.

Demographic, neuropsychological, and cortical thickness data for non-immigrant MCI patients.

		Monolingual (n=27)		Multilingual (n=14)			
		M	*SE*	M	*SE*	t	*p*
Age at symptom onset		68.00	*1.10*	68.80	*1.80*	-0.39	*.70*
Age at scan		73.50	*1.00*	72.50	*1.70*	0.57	*.58*
MMSE at scan		26.60	*0.50*	27.90	*0.50*	-1.74	*.09*
Education		12.40	*0.80*	12.60	*1.00*	-0.13	*.90*
Block design		28.78	*2.05*	27.69	*2.00*	0.33	*.74*
Immediate verbal recall		0.51	*0.03*	0.44	*0.03*	1.45	*.16*
Delayed verbal recall		0.25	*0.04*	0.18	*0.06*	1.04	*.31*
Delayed visual reproduction		22.37	*3.92*	20.14	*4.91*	0.34	*.73*
Clock (/10)		8.56	*0.30*	7.93	*0.40*	1.26	*.22*
Stroop Interference		2.36	*0.20*	1.97	*0.11*	1.41	*.17*
Orientation (%)		93.20	*2.15*	91.56	*3.08*	0.44	*.66*
Trail A		48.90	*3.65*	44.11	*4.45*	0.80	*.43*
Spatial span total		12.16	*0.55*	10.43	*0.62*	2.00	*.05*
		Cortical Thickness in mm					
		Monolingual (n=27)		Multilingual (n=14)			
	Coordinates	M	SE	M	SE	t	*p*
L iFG	-53, 16, 25	2.81	*0.05*	3.00	*0.06*	2.38	*.023*
R iFG	50, 32, -22	3.30	*0.06*	3.57	*0.08*	2.76	*.009*
R vmPFC	1, 45, -20	3.22	*0.07*	3.43	*0.07*	1.90	*.064*
L iTG	-50, -27, -29	2.54	*0.05*	2.77	*0.08*	2.63	*.012*
R mTG	64, -48, -3	3.10	*0.01*	3.46	*0.02*	3.98	*.000*
L iPL	-40, -78, 25	3.00	*0.02*	3.28	*0.03*	3.37	*.002*
L eRhin	-20, -21, -25	2.99	*0.04*	3.17	*0.09*	2.17	*.036*

Table 5. con't.

		Grey Matter Density Values					
		Monolingual (n=27)		Multilingual (n=14)			
	Coordinates	M	SE	M	SE	t	*p*
R cerTon	8, -52, -55	0.46	0.01	0.57	0.02	4.23	*.0001*
L eRhin	-25, -17, -22	0.66	0.02	0.75	0.02	2.73	*.010*
R eRhin	27, -19, -20	0.68	0.02	0.75	0.02	2.39	*.022*
L pRhin	-39, -20, -29	0.58	0.02	0.67	0.04	2.12	*.041*
R pRhin	38, -23, -23	0.58	0.02	0.64	0.02	1.94	*.058*

Notes: cerTon = cerebellar tonsil; eRhin = entorhinal cortex; iFG = inferior frontal gyrus; iPL = inferior parietal lobule; L = Left; mTG = medial temporal gyrus; pRhin = perirhinal cortex; PHC = posterior parahippocampal cortex; R = Right; SMG = supramarginal gyrus; vmPFC = ventromedial prefrontal cortex

4.5 Discussion

The aim of the present study was to investigate whether a history of speaking more than one language contributes to structural brain differences in MCI and AD patients. Specifically, cortical thickness and grey matter density were measured in monolingual and multilingual groups of MCI and AD patients, who were (within each patient group) matched on episodic memory functioning, MMSE, age (at time of scan), and education. We found 1) multilingual MCI and AD patients showed greater brain matter in the form of thicker cortex and higher grey matter density compared to matched monolinguals in brain areas related to language and cognitive control, 2) partial evidence for the contribution of bilingualism to CR in AD patients, but not MCI patients, 3) both AD and MCI multilinguals show positive correlations between episodic memory scores and certain brain regions outside of the medial temporal region, suggesting that multilinguals may have access to a compensatory network that offsets medial temporal lobe changes and helps maintain some degree of memory functioning, and finally, 4) we largely replicated the language and cognitive control area results within a group of non-immigrant MCI patients, indicating that the results were not likely due to any potential influence of immigration. We will explore each of these results below.

4.5.1 Brain areas related to bilingualism

Turning to the other major finding of the current study, namely the evidence for contribution of bilingualism to structural brain differences in areas related to language and cognitive control, multilingual MCI and AD patients showed thicker cortex and greater tissue density in some of the ROIs compared to monolingual counterparts. We found greater grey matter in multilinguals (both MCI and AD) as compared to monolinguals in left and right inferior frontal gyri, left medial superior frontal gyrus, right ventromedial prefrontal cortex, left and right anterior temporal gyri, left parietal lobule, left and right cerebellum, and right cerebellar tonsil, with the most reliable results in the right frontal ROIs (inferior frontal gyrus and ventromedial prefrontal cortex) and the right cerebellum (posterior lobe and tonsil).

Previous research has found neuroanatomical differences between monolinguals and bilinguals and has posited that the differences in brain structure seen between the language groups represent neuroplastic changes brought about by the experience of speaking more than one language (for reviews see García-Pentón et al., 2015; P. Li et al., 2014). The adaptive control hypothesis (Green & Abutalebi, 2013) posits that language comprehension and production

require the interaction of multiple discrete and overlapping control processes (e.g., goal maintenance, conflict monitoring) carried out by interconnected networks of brain regions and furthermore, that bilingual language functioning results in adaptive changes in the recruitment of and interactions between these networks. Functional neuroimaging studies have demonstrated that the regions recruited by bilinguals in the hypothesized series of networks are indeed involved in language processing and/or cognitive control (for a review see P. Li et al., 2014). Our data contribute to the hypothesis that having two languages "exercises" specific brain regions implicated in various control processes, inducing neural changes that can be seen at the level of greater cortical thickness and grey matter density, and further, that these structural differences can be seen in the brains of multilingual MCI and AD patients.

4.5.2 Cognitive reserve

CR in AD patients

We found that multilingual AD patients showed thinner cortex and lower tissue density in the posterior parahippocampal gyri and the rhinal sulci compared to their monolingual counterparts, suggesting more AD neuropathology. This suggests that their greater CR (gained from a history of managing two languages) allowed them to perform at the level of their monolingual peers on several episodic memory tasks, despite having sustained more atrophy in areas related to memory processing. This is the second study to use neuroanatomical measures to examine the impact of speaking more than one language in AD patients who are balanced on clinical severity/cognitive performance. Schweizer and colleagues (2012) found that bilingual AD patients showed greater medial temporal atrophy (as measured by several estimates of brain volume derived from CT scans) compared to a group of monolingual AD patients matched on age, education, and cognitive functioning. Importantly, our results extend these findings by enabling the precise measurement of cortical thickness and tissue density within specific medial temporal lobe structures. Our results indicate that, in the early stages of AD, multilinguals were able to tolerate more atrophy in the posterior parahippocampal gyri and rhinal sulci than monolinguals, while maintaining a comparable cognitive level. Moreover, we were able to demonstrate that multilingual patients with MCI did not show similar decreases in medial temporal cortex relative to their peers; in fact, they showed the opposite pattern.

Interestingly, the results seen in the hippocampi proper are not in line with predictions made by the CR hypothesis. Specifically, we would have expected to see decreased grey matter

density in the left and right hippocampi in multilingual AD patients compared to monolingual AD patients, as we saw for the parahippocampal gyri. Instead, the hippocampi showed a main effect of Language Group suggesting greater hippocampal volumes for the multilinguals compared to the monolinguals, regardless of Patient Group. The lack of a CR-congruent pattern in the left and right hippocampi, although puzzling, may simply be due to the fact that our AD sample consists of mostly early-AD patients. Recent research shows that neurodegeneration often occurs in the parahippocampal gyrus before the hippocampus (e.g., Desikan et al., 2009; Echávarri et al., 2010). As such, the AD patients in this sample may not have experienced significant enough neurodegeneration in the hippocampus proper for the multilinguals to demonstrate CR. The AD patients in our study did, however, show reliably smaller hippocampi compared to the MCI participants, which is a predictable pattern of results and indicates that our patient groups conform to this often-replicated pattern.

CR in MCI patients

The current study is the first to use neuroanatomical measures to examine the impact of multilingualism in MCI patients who are balanced on disease-specific cognitive functioning. We hypothesized that the multilingual MCI patients would not differ from monolingual MCI patients in disease-relevant areas as they have not begun to experience substantial AD atrophy. Unlike our multilingual AD patients, who showed evidence of CR (thinner cortex and decreased grey matter density compared to monolingual AD patients in disease-related areas), the multilingual MCI patients did not. They showed either thicker cortex/higher grey matter density or did not differ reliably from the monolingual MCIs. Our sample was composed of MCI patients whose primary deficits were in the memory domain, and these are the individuals who are more likely to convert to AD (Albert et al., 2011). Although the sample sizes were small, our results indicated that among the MCI patients who had as of yet not converted to AD, multilingual MCIs showed a pattern of thicker cortex and higher tissue density in both Family 1 (areas related to language and cognitive control) and Family 2 (disease-relevant) ROIs compared to monolingual MCIs, whereas there were no Language Group differences between monolingual and multilingual MCI patients that had converted to AD. Based on this pattern, it is possible that there is heterogeneity in the extent to which neuroplastic changes are expressed in multilinguals, with those who show evidence of it perhaps being delayed in their development of AD, or may not develop the disease at all. Those MCI patients who show lesser amounts of experience-

induced structural neuroplasticity appear more likely to decline to dementia in the future.

4.5.3 Correlational Results

In order to explore how patients could demonstrate equivalent performance on memory tests, despite evidence of reduced medial temporal matter, we examined the potential relationship between brain areas related to bilingualism and performance on memory tests. Interestingly, we found that multilingual patients showed significant correlations between episodic memory measures and a number of brain regions typically associated with language and cognitive control, while monolingual patients did not. It has been previously suggested that greater white matter density in older bilinguals compared to monolinguals may form the neural basis for bilingualism's contribution to CR (Luk et al., 2011a). Similarly, we suggest that the CR experienced by our multilingual AD patients may be made possible by the thicker cortex in frontal and parietal cognitive control areas. In other words, we take the correlation between cognitive control regions and episodic memory performance as evidence towards the hypothesis that multilingual patients are able to utilize alternate networks (i.e., the neural compensation subtype of CR) for memory processing and that they are able to do so because of their greater grey matter in brain regions exercised by being bilingual. However, these results are based on post-hoc correlational analyses and should be interpreted with caution.

A stronger test of this hypothesis would be to examine white matter tracts and functional connectivity between these regions, which is an area of future research for us.

4.5.4 Non-immigrant MCI sub-sample

Another unique strength of the current study is that we found similar results with a subgroup of non-immigrant MCI patients. Given the potential confounding effect of immigration with bilingualism, we conducted our analyses with a monolingual and multilingual non-immigrant subgroup of MCI patients. Disease-relevant ROI results show that monolingual and multilingual MCI patients do not differ significantly in these regions. The pattern of results from the ROIs related to language and cognitive control largely mirror those seen with the overall sample: multilingual patients show reliably thicker cortex in frontal, temporal, parietal, and cerebellar regions. Results for the medial frontal lobe (pre-supplementary motor/ventromedial prefrontal areas) and the supramarginal gyri were in the same direction but were found to be non-reliable differences, likely due to the lower statistical power in this subgroup analysis. Unfortunately, we were not able to conduct similar analyses for the AD participants due to the

smaller sample sizes. Nevertheless, if we were to extrapolate from our findings with the MCI participants, our results generally suggest that the important confound of immigration may not be playing a role in our BR results.

4.5.5 Limitations

This study has its limitations. Firstly, as data in this study were gathered retrospectively, the information that we had on language history and use was limited. As noted in recent reviews (e.g., Calvo, García, Manoiloff, & Ibáñez, 2016; Duncan & Phillips, 2016) important variables related to bilingualism (e.g., age of acquisition, degree of proficiency, contextual uses of language) may have an influence in the contribution to CR expression. Secondly, this study was limited by a lack of data from healthy older adults that could have provided appropriate baselines to compare the level of neurodegeneration in the patient groups. Relatedly, larger sample size would allow us the ability to split our multilingual group into bilinguals and multilinguals to determine whether there is any linear or dose-response to speaking multiple languages. This is important given that previous research suggests that the two groups may differ in terms of the cognitive impact of AD neuropathology (Chertkow et al., 2010).

4.5.6 Summary

Our data contribute to the growing literature that there may be subtle differences in brain structure related to multilingualism. These results add new information to the individual and intersecting bodies of literature on the hypothesized protective effect of bilingualism against the cognitive effects of dementia (CR) and neuroplasticity associated with bilingualism (where past studies have typically been limited to healthy young and old adults). Ours is the first study to use structural MRI data to examine CR in MCI and AD patients, the first to assess structure in language and cognitive control regions in MCI and AD patients, and the first to control for immigration status in these groups. Overall, our results contribute to the research findings that indicate that speaking more than one language is one of a number of lifestyle factors that contributes to reserve and supports the notion that multilingualism and its associated cognitive and sociocultural benefits are associated with brain plasticity.

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Chapter 5: Manuscript 2:

Does bilingualism contribute to cognitive reserve in aging: An electrophysiological study of evoked and induced event-related oscillations during cognitive control tasks

To be submitted to *Bilingualism: Language and Cognition*

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5.1 Abstract

Previous research investigating the bilingual advantage on non-linguistic cognitive control tasks has resulted in mixed findings. Some reasons for the inconsistencies across studies could be due to the potentially subtle nature of a bilingual advantage (making it difficult to detect and measure in younger adults or in behavioural measures) or due to the significant differences between cognitive control tasks in terms of locus of conflict (that may not engender language group differences in the same manner or to the same degree). We used time-frequency analysis to examine evoked and induced oscillatory activity of electrophysiological recordings from younger and older monolinguals and bilinguals during performance of three cognitive control tasks. Briefly, behavioural results show a bilingual advantage for older adults only, and only in the Stroop task. Conflict-related language group differences were seen in the Eriksen task in evoked power for younger adults and in the Stroop and Simon tasks in evoked power for the older adults. More generally, we also found that older adults showed lower alpha and theta power and more beta suppression than younger adults, that differences between the two trial types (i.e., conflict effect) were mostly observed in induced activity and not evoked, and that the cognitive control tasks differed in terms of the locus of the conflict with respect to neural oscillations.

An Electrophysiological Investigation of Cognitive Control in Bilingualism and Aging

5.2 Introduction

Research on the hypothesized cognitive advantages of bilingualism now spans close to two decades (for recent reviews see Adesope, Lavin, Thompson, & Ungerleider, 2010; R. Klein, 2015; Paap, Johnson, & Sawi, 2014). This area has garnered much attention and also much debate. For example, there is speculation that positive results may be affected by variables that co-vary with bilingualism, such as socioeconomic status or immigration, (Bastian, Souza, & Gade, 2016; Duncan & Phillips, 2016; Paap et al., 2015), or by specific linguistic circumstances/contexts (Qu, Low, Zhang, Zelazo, & Li, 2015; Singh & Mishra, 2015; Valian, 2015; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2015). Currently, there is some agreement that if bilingualism does indeed engender a benefit to executive functioning, it may not always be observable in end-product behavioural measures like reaction time (RT) and accuracy, it might not be elicited similarly by different cognitive control tasks (given the multifaceted nature of the construct of EF and the differences between tasks), and it may not always be observable in younger, healthy adults, who are presumed to be at their "cognitive peak" (Bialystok & Poarch, 2014; Kousaie & Phillips, 2017). Unfortunately, very little research exists using more sensitive measures, such as electroencephalogram (EEG), to examine whether monolinguals and bilinguals perform differently on cognitive control tasks (Coderre & van Heuven, 2014; Hanslmayr et al., 2008; Kousaie & Phillips, 2012b), and only one has examined these processes across a variety of cognitive control tasks and in older adults (Kousaie & Phillips, 2017). The goal of the current paper is to examine whether younger and older monolinguals and bilinguals differ in their performance of executive functioning tasks, and whether these differences are specific to, or generalize across different measures of cognitive control. To do so we examined evoked and induced EEG activity in younger and older monolinguals and bilinguals during three computerized tasks of cognitive control.

5.2.1 Cognitive Control

Broadly speaking, cognitive control refers to the ability to flexibly and variably adapt information processing and behaviour to effectively meet the requirements of a dynamic environment. Cognitive control is required in situations when there may be a conflict between task-relevant and task-irrelevant information. In situations where there is conflict the brain must monitor for and detect the conflict, resolve the conflict by suppressing irrelevant or interfering

information, respond appropriately, and monitor for post-response information. Three commonly used tasks to study cognitive control are the Stroop task (Stroop, 1935), the Simon task (Simon & Rudell, 1967), and the Eriksen (or flanker) task (B. A. Eriksen & Eriksen, 1974). Importantly, each task contains congruent trials (where the relevant and irrelevant information corresponds), and incongruent trials (where there is conflict between the relevant and irrelevant information). Responding to incongruent trials typically takes more time than responding to congruent trials, as the conflicting, or irrelevant, information must be suppressed/filtered and the conflicting/irrelevant response must be inhibited. The reaction time (RT) difference between incongruent and congruent trials is known generally as the conflict effect, although it often carries the name of the relevant task (i.e., the Stroop effect, the Simon effect). Importantly, the locus of the conflict differs across tasks, as will be explained further below.

In the Stroop task (Stroop, 1935), participants are tasked with identifying a color word's ink color while ignoring the word itself. On congruent trials, the ink and the color word are the same (e.g., the word BLUE written in blue ink). On incongruent trials the ink and the color word are different (e.g., the word BLUE written in red ink). In a commonly used version of the spatial Simon task (Simon & Rudell, 1967), participants are asked to indicate the colour of a stimulus. On congruent trials the response key to indicate the correct colour is on the same side as the position of the stimulus (e.g., the left response key indicates blue and a blue stimulus is presented on the left side of the screen). On incongruent trials the correct response key is on the opposite side from where the stimulus is presented (e.g., the left response key indicates blue and a blue square is presented to the right side of the screen). In the Eriksen flanker task (B. A. Eriksen & Eriksen, 1974), participants are required to indicate the identity of a central target stimulus flanked by irrelevant stimuli. On congruent trials the flanking stimuli point in the same direction as the target, while on incongruent trials the flankers point in the opposite direction.

Although these three tasks are frequently discussed together with the implied assumption that they measure equivalent aspects of cognitive control, they differ with regard to the locus of the conflict. The Stroop task contains stimulus-stimulus (S-S) conflict (with the written information conflicting with the ink colour), the Simon task contains stimulus-response (S-R) conflict (with the spatial information in the stimulus conflicting with the spatial location of the response key), and the flanker Eriksen task contains S-S conflict (the direction of the flanker arrows conflicting with the information of the target arrows). Additionally, despite both having

S-S conflict, the Stroop and Eriksen tasks differ in that the Stroop task requires linguistic processing, as the conflicting information (the colour word) requires reading and semantic processing, whereas the Eriksen is non-linguistic. Indeed, when examined behaviorally, there seems to be little correlation in performance between the three tasks (Fan et al., 2003; Keye et al., 2008; Kousaie & Phillips, 2012b), and their neural mechanisms appear to involve both overlapping and unique regions/networks (X. Liu et al., 2004; Peterson et al., 2002; Wager et al., 2005). Taken together, this information suggests that the different sub-components of cognitive control required for resolving conflict (e.g., conflict monitoring, conflict detection) may come into play at different times and in different ways for these three tasks.

5.2.2 The Bilingual Benefit

Research over the last few decades suggests that speaking more than one language may provide cognitive benefits (for a review see Dong & Li, 2015). It has been hypothesized that the need to manage competition between two languages exercises cognitive control mechanisms, creating a benefit that extends to non-linguistic tasks involving conflict (Abutalebi & Green, 2007; Baum & Titone, 2014; Green, 1986; Green & Abutalebi, 2013). Younger adult bilinguals have been shown to perform better than their monolingual counterparts on a number of tasks, including the Stroop, Simon, and Eriksen tasks (e.g., Bialystok et al., 2004; 2006b; Costa et al., 2008; 2009; Emmorey, Luk, & Pyers, 2008; Qu et al., 2015). Further, this language-group difference tends to becomes more pronounced in old age such that the disparity in performance between monolinguals and bilinguals tends to be larger in older adults than in younger adults (Bialystok et al., 2004; Salvatierra & Rosselli, 2011). It has been proposed that a language-group difference may be more easily observable in older adults, due to the expected age-related decline in cognitive abilities, than in younger adults who exhibit more efficient cognitive control (Kousaie & Phillips, 2017). Older bilinguals have been shown to outperform older monolinguals on a variety of tasks requiring cognitive control (e.g., Abutalebi, Guidi, Borsa, Canini, Rosa, Parris, et al., 2015b; Bialystok et al., 2004; 2008; Houtzager, Lowie, Sprenger, & de Bot, 2015; Salvatierra & Rosselli, 2011; Wiseheart, Viswanathan, & Bialystok, 2014). However, there are inconsistencies in the literature (for reviews see, Hilchey & Klein, 2011; Hilchey, Saint-Aubin, & Klein, 2015). A number of recent studies have failed to find language-group differences: between younger monolinguals and bilinguals adults on a Stroop task (Kousaie & Phillips, 2012a), between younger monolinguals and bilinguals on both a Simon and an Eriksen flanker

task (Paap & Greenberg, 2013), between monolinguals and bilinguals ranging from 3 to 60 years of age on a Simon task (Gathercole et al., 2014), between younger or older monolinguals and bilinguals on a Simon task (Kousaie et al., 2014), and between older monolinguals and bilinguals on a Simon task (Kirk et al., 2014). It has been suggested that being bilingual may not necessarily result in a performance benefit (e.g., faster or more accurate performance) on cognitive tasks (at least not reliably) and may instead result in a difference in processing which, under some circumstances, may result in a benefit for bilinguals (Hilchey et al., 2015; Kousaie & Phillips, 2012b; 2017). Relatedly, some researchers have noted that bilinguals often perform better than monolinguals on both congruent and incongruent trials of cognitive control tasks (Hilchey & Klein, 2011). This has led to the usage of the terms bilingual inhibitory control advantage (BICA) and bilingual executive processing advantage (BEPA). A BEPA occurs when bilinguals outperform monolinguals on both congruent and incongruent trials, whereas a bilingual inhibitory control advantage (BICA) describes when bilinguals and monolinguals perform similarly on congruent trials, and bilinguals outperform monolinguals on incongruent trials.

5.2.3 ERP Measures

Within the literature there are times when a bilingual benefit is not seen in RT or accuracy, yet brain imaging measures demonstrate differences in neural processing between monolinguals and bilinguals on cognitive control tasks. To date, only four EEG studies have investigated the electrophysiological indices of bilingual cognitive control processing (Coderre & van Heuven, 2014; Heidlmayr et al., 2015; Kousaie & Phillips, 2012b; 2017).

Coderre & van Heuven (2014) found that a group of Chinese-English bilinguals showed smaller conflict effects in ERP results than a group of English monolinguals on a modified Stroop task (with different stimulus onset asynchronies between the colour and the colour word). Bilingual participants completed the Stroop task in their first language (L1; Mandarin) and second language (L2; English). There was no evidence of a bilingual benefit in the behavioural results (on trials wherein the colour and the colour word were presented simultaneously) for bilinguals performing the Stroop task in their L1, but they showed a bilingual advantage performing in their L2. For the ERP results, when performing in their L2, bilinguals showed a smaller N400 conflict effect in amplitude (i.e., the differences between the negative peak amplitudes for incongruent compared to congruent trials was smaller) than monolinguals. The

N400 is thought to reflect processing of stimulus conflict (Bruchmann, Herper, Konrad, Pantev, & Huster, 2010; Caldas, Machado-Pinheiro, Souza, Motta-Ribeiro, & David, 2012). They did not find a conflict effect for either language group when examining the N200, which is thought to be related to conflict and error monitoring (Pires, Leitão, Guerrini, & Simões, 2014). In sum, their results demonstrated that when performing in their L1, bilinguals did not differ from monolinguals. However, when performing in their L2, bilingual participants show a smaller conflict effect in RT (a smaller difference between congruent and incongruent trials) and in the N400 (less neural differentiation between the two trial types) compared to monolinguals.

Heidlmayr and colleagues (2015) also found evidence of conflict-specific language group processing differences. Their results were also in the same direction as the L2 results of Coderre and van Heuven (2014): bilinguals showed smaller conflict effects in ERP components compared to monolinguals. They tested highly proficient, but non-balanced, French-German bilinguals and French monolinguals on a modified Stroop task. They found no evidence of a bilingual benefit in the behavioural results. However, there was clear evidence of a language group processing difference. Monolinguals showed a conflict effect (more negative amplitudes on incongruent trials compared to congruent trials) for the N400 and the late sustained negative-going potential (which is thought to reflect engagement of executive processes or response selection, Hanslmayr et al., 2008; Naylor, Stanley, & Wicha, 2012), whereas bilinguals showed no difference between trial types.

Kousaie & Phillips (2012) compared the performance of English-French bilinguals and English monolinguals on a Stroop, Simon, and an Eriksen flanker task. These results will be reviewed in some detail as they are derived from the same recording session as the data reported here. Although a bilingual advantage was not seen in the behavioural results, EEG data showed that monolinguals and bilinguals processed conflict differently on a neurophysiological basis, with ERP components being smaller and/or earlier for bilinguals compared to monolinguals. Consistent with Coderre and van Heuven (2014) and Heidlmayr and colleagues (2015), the results showed evidence for a conflict-specific language group difference, with bilinguals showing a smaller conflict effect than monolinguals. This was seen on the P3 component in the Eriksen task, where the difference between congruent and incongruent trials was larger for the monolinguals than bilinguals. However, unlike the results of the other two studies, Kousaie and Phillips (2012) found stronger evidence for non-conflict specific (or global) language group

processing differences. Specifically, on the Stroop task, bilinguals exhibited smaller N2s (no language group differences were seen in the Simon and Eriksen tasks) and earlier P3 (which is thought to reflect stimulus categorization and updating of information in working memory, Fjell, Walhovd, Fischl, & Reinvang, 2007; Pires et al., 2014) peak latencies than monolinguals all on trial types, and on the Simon task the had smaller P3 amplitudes than monolinguals on all trial types. The finding of language-group differences on *both* congruent and incongruent trials, suggests that bilinguals required less active conflict monitoring than monolinguals throughout the task (i.e., regardless of the level of conflict present on the current trial) in order to achieve similar behavioural performance. In sum, the N2 results in the Stroop task and the P3 results in the Stroop and Simon task point towards a difference between monolinguals and bilinguals on *all* trial types within the cognitive control tasks, while the P3 results in the Eriksen task are consistent with the previous research and indicate a larger conflict effect for monolinguals compared to bilinguals.

Taken together, these three studies provide evidence that bilinguals and monolinguals do not process conflict in the same manner, even if they perform similarly on a behavioural level. The three studies found evidence for conflict-specific language group processing differences, with bilinguals generally showing smaller conflict effects than monolinguals. Coderre and van Heuven (2014) and Heidlmayr and colleagues (2015) found this effect in the N400 on modified Stroop tasks, while Kousaie and Phillips (2012) found this effect in the P3 on an Eriksen flanker task. Kousaie & Phillips (2012) also found evidence for global language group processing differences on the N2 and P3 components. The other two studies did not find trial type differences or language group findings in the N2 component.

Recently, our group (Kousaie & Phillips, 2017) examined behavioural and ERP results in older monolingual and bilingual participants using the same methodology as our 2012 study (Kousaie & Phillips, 2012b). In examining the behavioural data, they found evidence of a bilingual benefit on the Stroop task, with a larger conflict effect for monolinguals compared to bilinguals, but no RT or accuracy differences between the language groups on the Simon or Eriksen tasks. Similar to the findings with younger adults, the presence of language group processing differences in the ERP was not dependent on finding language group differences in the behavioural measures, and varied by component and task. Additionally, older monolinguals tended to show larger conflict effects in neurophysiological results compared to older bilinguals,

consistent with the findings of other research groups (Coderre & van Heuven, 2014; Heidlmayer et al., 2015). Specifically, with regards to the N2, conflict-specific language group differences were seen on the Simon task in peak amplitude: monolinguals had larger peak amplitude on incongruent trials compared to congruent trials, while bilinguals showed no trial type difference. However, in contrast to this, older bilinguals had earlier peak latencies on congruent trials compared to incongruent trials, while monolinguals showed no trial type difference. On the Eriksen task, older monolinguals had larger amplitudes for incongruent compared to congruent trials while older bilinguals showed no trial type difference. For the P3, our group found language group differences in the conflict effect on the Stroop task when measuring mean amplitude: older monolinguals showed larger mean P3 amplitudes on congruent trials than incongruent, while there was no trial type difference for older bilinguals. There were no conflict-specific language group processing differences on any P3 measures in the Simon or Eriksen tasks.

Comparison of the two studies allows us to gain an understanding of how language group differences may vary by age group. Firstly, there were no differences found between monolinguals and bilinguals in the younger study using behavioural measures, while the study with older adults found evidence for a bilingual benefit in the Stroop task (but not the Simon or Eriksen tasks), indicating that being bilingual may act as a buffer against age-related cognitive decline and protect cognitive control abilities in certain situations/contexts. Both studies found language group differences in brain processing, and comparison of the language group differences across studies indicates both unique and overlapping findings. For example, in the younger adult study there were no conflict-specific language group differences in the N2, on any of the three tasks, while for the older adults, conflict-specific language group differences in the N2 were seen in the peak amplitude and peak latency for the Simon task, and in mean and peak amplitude for the Eriksen task, with smaller conflict effects for bilinguals than monolinguals. In both age groups, bilinguals showed a smaller conflict effect than monolinguals in the P3, but for younger adults this was in the Eriksen task and for older adults was found in the Stroop task.

Taken together, these four studies suggest that bilinguals are able to perform at the same level of monolinguals while showing reduced demands on the neurophysiological mechanisms thought to be associated with conflict processing. These results also touch on several important and interrelated issues: 1) that electrophysiological measures may show language group

differences not seen in behavioural measures, 2) that classic cognitive control tasks differ from each other, and may therefore produce different results, including in electrophysiological findings, and that 3) language group differences that are not seen in younger adults may be found in older adults. However, while ERPs have provided useful insights into the timing and nature of neuronal events that subserve cognitive processes, additional information can be gleaned from the EEG signal, as will be outlined in the following section.

5.2.4 Time-Frequency Decomposition

EEG data are made up of rhythmic activity that reflects fluctuations in the excitability of populations of neurons, also known as neural oscillations. Oscillations can be described by three variables: power (or magnitude, which is the amount of energy in the signal, and is measured by the amplitude of the oscillation), phase (which is the position along the sine wave at any given point in time and is measured in radians or degrees), and frequency (which refers to the speed of the oscillations and is measured in hertz (Hz)). Recently, the study of cognitive control processes has turned to time-frequency decomposition, which allows for the EEG signal to be decomposed in a way that provides information on power and phase within each frequency band, over time. Time-frequency decomposition affords two major benefits over traditional ERP analysis. First, time-frequency decomposition allows for examination of both evoked activity (activity that is both time- and phase-locked to the onset of a stimulus) and induced activity (activity that is time-locked but not-phase-locked to the onset of a stimulus). Due to the averaging process required to generate ERP components, they contain only evoked stimulus driven activity, while non-phase locked, or induced, activity is cancelled out (for in-depth discussions of evoked vs induced activity see Herrmann, Rach, Vosskuhl, & Strüber, 2014; Roach & Mathalon, 2008). This is especially important as recent research suggests that induced activity may convey important information about cognitive processing (Makeig, Debener, Onton, & Delorme, 2004), may better reflect processing of conflict (Cavanagh, Zambrano-Vazquez, & Allen, 2011), and may better correlate with behavioural measures (Cohen & Donner, 2013) than evoked activity. The second major benefit of time-frequency decomposition is that it provides important information about neural activity within the different EEG frequency bands. This allows for exploration of neural processes that may be co-occurring or interacting at different frequency bands during the same time period. For example, research suggests that activity in the alpha band responds to novel stimuli, may be strongly correlated to working memory (Başar, Basar-Eroglu, Karakaş, &

Schürmann, 2001), and may be involved in inhibition (Knyazev, 2007). Moreover theta activity may be closely related to executive functioning, selective attention and cognitive control (Klimesch, Sauseng, & Hanslmayr, 2007; Sauseng & Klimesch, 2008) .

5.2.5 Time-Frequency Analysis of Cognitive Control

Currently, only a handful of studies have used time-frequency decomposition to examine the modulation of oscillatory power in response to conflict in cognitive control tasks (e.g., Brittain et al., 2012; Hanslmayr et al., 2008; Nigbur, Cohen, Ridderinkhof, & Stürmer, 2012; Tang, Hu, & Chen, 2013; J. Zhao et al., 2015). Here we will review results from studies that used Stroop, Simon, and Eriksen/flanker tasks. It should be noted that currently, the majority of the studies presented below look at total oscillatory power, sometimes referred to as event-related spectral perturbation; ERSP (Cavanagh et al., 2011; Jiang, Zhang, & Van Gaal, 2015b; Q. Li et al., 2015; K. Wang, Li, Zheng, Wang, & Liu, 2014; J. Zhao et al., 2015; Y. Zhao et al., 2014). Total oscillatory power contains both phase-locked and non-phase-locked activity and it is not possible to differentiate what activity is evoked and what is induced. To date, few papers examine the unique contribution of induced activity to cognitive control (Cohen & Donner, 2013).

Theta. There is significant agreement across studies that both S-S and S-R conflict elicits increases in power in the theta frequency band, with most studies focusing on medial frontal regions (Brittain et al., 2012; Cavanagh et al., 2011; Cohen & Donner, 2013; Ergen et al., 2014; Hanslmayr et al., 2008; Jiang, Zhang, & Van Gaal, 2015a; Q. Li et al., 2015; Nigbur et al., 2012; Nigbur, Ivanova, & Stürmer, 2011; Tang et al., 2013; van Steenbergen, Band, & Hommel, 2012; K. Wang et al., 2014; J. Zhao et al., 2015; Y. Zhao et al., 2014). Importantly, when analysing time-frequency data from two versions of the Simon task, Cohen and Donner (2013) found that greater than 80% of theta power modulations in the mid-frontal cortex were time-locked, but not phase-locked to the stimuli (i.e., represented induced activity). They also found that this induced activity better correlated with reaction time compared to evoked activity, and that the induced activity better differentiated congruent and incongruent trial types compared to the evoked activity.

Alpha. Conflict-related increases in power (also called event-related synchronization or ERS) in the alpha frequency band are thought to reflect top-down inhibitory control processing, whereas decreases in power (event-related desynchronization; ERD) are thought to reflect the

suppression of ongoing neural activity (Klimesch et al., 2007; Tang et al., 2013). Three Stroop tasks have found increases in alpha frequency band power for S-S conflict (Ergen et al., 2014; Hanslmayr et al., 2008; Tang et al., 2013), and two studies using stimulus-response compatibility tasks (a combination of a Simon and Stroop task) found alpha ERS for both S-S and S-R conflict (Q. Li et al., 2015; K. Wang et al., 2014) . Only study found conflict-related alpha ERD; however this occurred later in the segment, during the inter-trial interval (van Driel, Swart, Egner, Ridderinkhof, & Cohen, 2015).

Beta. Findings within the beta frequency band mostly show a conflict-related ERD, with a larger decrease for incongruent trials compared to congruent trials (Q. Li et al., 2015; J. Zhao et al., 2015). Beta suppression is thought to be related to motor response (Brittain et al., 2012; J. Zhao et al., 2015). Out of three studies that used tasks containing both S-S and S-R conflict, one found beta suppression related to S-R conflict only (J. Zhao et al., 2015), one found beta suppression related to both types of conflict (K. Wang et al., 2014), and finally one study found enhanced conflict-related beta power for S-S conflict (Q. Li et al., 2015).

5.3 Current study

The primary goal of the present investigation was to compare the conflict-related evoked and induced power modulations in the neural activity of younger and older monolinguals and bilinguals when performing the Stroop, Simon, and Eriksen flanker tasks. Behavioural and ERP results from the same group of participants (with slight variation, due to technical issues for some participants) have already been examined (Kousaie & Phillips, 2012b; 2017), as such we expected our behavioural results to parallel those seen in the previous two studies, with no difference in conflict effects between younger monolinguals and bilinguals on any task, and a larger conflict effect for older monolinguals compared to older bilinguals (i.e., a bilingual benefit) for the Stroop task only. In terms of the time-frequency analyses, based on our group's ERP findings we expected to see larger conflict effects for the younger monolinguals compared to the younger bilinguals in the Eriksen task, and for the older monolinguals compared to the older bilinguals on all three tasks. However, due to the dearth of research using time-frequency analyses to examine cognitive control, we did not make predictions about how language-group differences in the conflict effect would vary across frequency bands, nor about whether they would appear in evoked or induced activity. Based on the reviewed time-frequency literature we predicted that we would see conflict-related activity in the theta and alpha bands, with more

activity on incongruent than congruent trials, and conflict-related beta suppression, with more beta suppression on incongruent than congruent trials.

5.4 Methods

5.4.1 Participants

Table 1 provides demographic information for each participant group. The younger adult group was composed of 51 participants, ranging in age from 18-35 years (Kousaie & Phillips, 2012). Of this group, 26 were English/French bilinguals (17 females; mean age = 24.50, SD = 3.434.15) and 25 were English monolinguals (15 females; mean age = 23.76, SD = 4.75). The older adult group was composed of 35 older adults, ranging in age from 60- 83years. (Kousaie & Phillips, 2017). Of this group, 18 were English/French bilinguals (12 females; mean age =68.89, SD = 5.50) and 17 were English monolinguals (14 females; mean age = 71.94, SD = 6.85). Further inclusion criteria for all participants included self-reported good health, no prior history of head injury, and no chronic use of medication that might affect cognitive functioning. Within each age group, language groups were matched on age, years of education, and cognitive functioning (as measured by the Montreal Cognitive Assessment; MoCA; Nasreddine et al., 2005). Due to poor quality EEG recording, three older monolinguals were removed from the Stroop task, one younger monolingual was removed from
the Simon task, one younger and one older monolingual were removed from the Eriksen task. For the Simon and Eriksen tasks, the language groups remained matched on demographic variables; however for the Stroop task an additional four participants were removed in order to balance the monolingual and bilingual older adults on age (see Table A Supplementary materials for demographic information broken down by task).

Language-related inclusion criteria for bilinguals required moderate to high proficiency in L2 and high proficiency in L1, measured using self-report, and a computerized animacy judgment task (administered during the testing session, see Kousaie & Phillips, 2017 for task description). Twenty-two younger bilinguals reported English as their native language, and four reported French as their native language. All younger bilinguals had learned their second language before the age of 10 (mean age of acquisition = 3.48, SD =2.73). Eleven older bilinguals reported English as their native language and 7 reported French as their native language. All older bilinguals had learned the second language before the age of 18 (mean age of

acquisition =5.36, SD = 5.38). All bilinguals reported actively using French in at least one area of their life (i.e., at work, in the home or with friends).

Participants were paid CAD$10/hour or received partial credit for course fulfillment for taking part. Younger participants were recruited from Concordia University and McGill University and older participants were recruited from a database within the Cognition, Aging, and Psychophysiology (CAP) Laboratory at Concordia University. Ethical approval for this study was obtained from the Concordia University Human Research Ethics Committee.

Table 1.

Demographic Information for Participant Groups

	Younger Monolinguals (n = 26)	Younger Bilinguals (n = 25)	Older Monolinguals (n = 18)	Older Bilinguals (n = 17)
	M *(SD)*	M *(SD)*	M *(SD)*	M *(SD)*
Age (in years)	22.5 *(4.5)*	23.7 *(4.0)*	68.9 *(6.5)*	71.9 *(5.9)*
Education (in years)	15.1 *(1.7)*	15.5 *(1.3)*	13.9 *(2.0)*	15.9 *(2.8)*
MoCA	28.6 *(1.3)*	27.8 *(1.7)*	26.8 *(2.0)*	26.6 *(2.0)*
L1 self-reported language proficiency	5.0 *(0.0)*	4.9 *(0.3)*	5.0 *(0.0)*	4.9 *(0.2)*
L2 self-reported language proficiency	n/a	4.2 *(0.6)*	n/a	4.6 *(0.6)*
Coefficient of variability L1	n/a	.24 *(.09)*	n/a	.23 *(.11)*
Coefficient of variability L2	n/a	.26 *(.09)*	n/a	.22 *(.07)*

5.4.2 Materials and Apparatus

The three cognitive control tasks were performed while EEG was recorded. These tasks included a modified Stroop task (Stroop, 1935), a modified Simon task (Simon & Rudell, 1967), and a modified Eriksen flanker task (Eriksen & Eriksen, 1974). All stimuli were presented using Inquisit version 2.0 (Millisecond Software, Seattle, WA) on a Dell precision 370 desktop with a Pentium 4 processor and Windows XP operating system on a 16 inch Compaq monitor. See Appendix B for a representation of the three cognitive control tasks. Each task contained a block of 36 practice trials (which was repeated until accuracy reached 80%) and 10 blocks of 72 trials. Each trial comprised: a blank screen lasting 500 ms; a fixation cross lasting 250 ms; and the stimulus, which stayed on screen until detected or a specified timeout was reached. For the Simon and Eriksen tasks, the timeout was 750 ms. A longer response interval was used for the Stroop task, 1250 ms, given its greater demand on working memory (i.e., four response keys to choose from, versus two for the Simon and Eriksen tasks). Trials were presented in a pseudorandom order so that there were an equal number of neutral, congruent, and incongruent trials, and no more than three trials of the same type were presented consecutively.

Stroop. Stimuli were presented at the center of the monitor in bold 27 point Arial font on a black background and were green (RGB: 0, 255, 0), red (RGB: 255, 0, 0), yellow (RGB: 255, 255, 0), or blue (RGB: 0, 0, 255). Neutral trials consisted of a series of "x"s , with the number of "x"s corresponded to the number of letters in the colour word name (e.g., "xxxx" printed in blue). Congruent trials contained one of the colour words *green*, *yellow*, *red*, or *blue* printed in the corresponding colour. Incongruent trials contained the same colour words printed in one of the alternate three colours (e.g., the word *red* printed in blue). The participant responded using the index and middle finger on each hand to respond using the computer keyboard. The letter "z" corresponded to yellow, the letter "x" to green, the symbol "," to red, and the symbol "." to blue. Coloured stickers were used to mark the keyboard keys. Participants performed a key acquisition task prior to the practice block. The key acquisition task was comprised of 80 trials where the participants were asked to identify the colour of green, yellow, red, or blue circles.

Simon. Red and blue squares (100 x 100 pixels) were presented at the center of the monitor on a black background. Red stimuli required a left key press (i.e., the letter "x" on the keyboard) and blue stimuli required a right key press (i.e., the symbol "." on the keyboard). For neutral trials the stimulus was presented in the center of the background, for congruent trials the

stimulus and correct response were on the same side (e.g., a red stimulus presented on the left of the monitor), and for incongruent trials the stimulus and the correct response were on opposite sides (e.g., a red stimulus presented on the right of the monitor).

Eriksen. Stimuli were comprised of arrowheads presented at the center of the monitor in white bold 36 point Arial font on a black background. Neutral stimuli were a single arrowhead (e.g., <); congruent stimuli consisted of a central arrowhead flanked by three arrowheads on each side pointing in the same direction as the target (e.g., <<<<<<<); and incongruent stimuli consisted of a central arrowhead flanked on either side by three arrowheads pointing in the opposite direction of the target (e.g., <<<>><<<). Participants responded to the direction of the central arrowhead by pressing a left key (i.e., the letter "x" on the keyboard) or a right key (i.e., the symbol "." on the keyboard).

5.4.3. Procedure

Testing sessions consisted of approximately 20 minutes for informed consent and neuropsychological testing, approximately 20 minutes of EEG set-up time, and 60 minutes of EEG recording during the experimental tasks. Participants were seated in a comfortable chair and informed consent was obtained at the beginning of the testing session (see Appendix C for consent form). The MoCA and neuropsychological testing were completed, followed by the animacy judgement task for younger and older bilingual participants and older monolinguals. Once the EEG set-up was complete the Stroop task was performed, followed by the Simon and Eriksen flanker tasks in counterbalanced order. The Stroop task was completed first due to its greater complexity relative to the other two experimental tasks (i.e., greater demands on working memory). At the end of the session, participants were debriefed and compensated for their time (course credit or $10 CAD per hour of participation).

5.4.3.1 EEG recording. The continuous EEG was recorded using an ActiveTwo nylon cap (BioSemi, Amsterdam, NL), from 64 scalp locations using Ag-AgCl electrodes placed according to the international 10-20 system. Eight additional electrodes were used: as references for offline processing of the data, one was placed on each earlobe; to record electro-oculogram (EOG), electrodes were placed above and below the left eye; to record the horizontal EOG, electrodes were places on the outer canthi of each eye; and two were placed corresponding to sites FT9 and FT10 according to the international 10-20 system of electrode placement. The EEG was recorded relative to Common Mode Sense and Driven Right Leg (CMS/DRL) electrodes placed at the

back of the head (to the left and the right of electrode POz, respectively) and was amplified using ActiveTwo amplifiers (BioSemi, Amsterdam, NL). The EEG was acquired using ActiView version 6.05 software (BioSemi, Amsterdam, NL), and sampled at a rate of 512 Hz in a 104 Hz bandwidth. The continuous EEG was converted from BioSemi Data Format (.BDF) to continuous file format (.CNT) using Polygraphic Recording Data Exchange version 1.2 (PolyRex; Kayser, 2003), it was also re-referenced to linked ears and a fixed gain of .5 was applied.

5.4.3.2 EEG offline processing. Offline processing was conducted using BrainVision Analyzer 2.0 (Brain Products GmbH, Munich) and was performed separately for each of the three tasks.

Pre-processing consisted of applying a low pass 100 Hz filter, a high pass 0.01 Hz filter, and a DC drift correction. Manual screening was conducted to remove exceptionally large artifacts and the EEG during breaks. Individual channels with bad connections were removed from further processing; however, electrodes with bad connections that were required for the formation of spatial regions of interest (S-ROIs), were interpolated using the Topographic Interpolation solution. Topographic interpolation was never required for more than two electrodes in any S-ROI. Vertical and horizontal ocular artifacts were removed using the Ocular Correction Independent Components Analysis (ICA) transformation. The recommended standard values were used (number of ICA steps: 512; ICA algorithm: Infomax Restricted). The blink and horizontal ocular activity were found by means of the relative EOG variance. EEG for all three tasks was segmented into continuous segments (1500 ms for the Simon and Eriksen tasks, and 2000 ms for the Stroop task), containing pre-stimulus windows of 750 ms. Semi-automatic artifact rejection was then conducted according to the following criteria: the absolute difference between two neighbouring sampling points could not exceed 50 microvolts, the difference between the maximum and minimum voltage within a segment could not exceed 200 microvolts, and activity could not fall below 0.5 microvolts. Segments were then split by trial type (neutral, congruent, and incongruent), and incorrect trials, and trials with RTs under 200 ms or 3 standard deviations above the individual's mean were omitted. Neutral trials were not analysed. Segments were averaged together for each participant, for each trial type (congruent and incongruent) separately.

For time–frequency decomposition, complex Morlet wavelet transformations were applied. We calculated wavelet coefficients for frequencies between 1 and 40Hz (Morlet parameter c4⁄40, linear frequency steps) with 40 frequency steps. To examine evoked activity (i.e., oscillatory activity that is phase-locked to the stimulus onset), the wavelet transform was computed on the averages of the segments (separately for congruent and incongruent). Induced activity (i.e., non-phase locked oscillatory activity) was calculated by subtracting the evoked activity from the total activity (computing the wavelet transform on individual trials and then obtaining the congruent and incongruent averages). Both evoked and induced activity were baseline corrected from -550ms to -250ms using the Percent Change solution (Brain Products GmbH, Munich). Based on previous research (Jiang, Zhang, & Van Gaal, 2015b; Y. Zhao et al., 2014) and visual inspection, we created three spatial regions of interest (S-ROIs): frontocentral (FC) - Fz, FCz, Cz, left centroparietal (LCP) – CP1, CP3, CP5, and right centroparietal (RCP) – CP2, CP4, CP6. Selection of time-frequency regions of interest (TF-ROIs) was guided by past research and refined based on visual inspection of the time-frequency representations of the individual trial types and contrast maps depicting the conflict effect (incongruent – congruent for each participant group). See Table 2 for a summary of S-ROIs and TF-ROIs. The normalized cumulative sum of the power within a TF-ROI was then exported using BrainVision's Wavelet Data Export solution (Brain Products GmbH, Munich). All power values were normalized using the formula: log[Power ÷ (1 - Power)] (Gasser, Bächer, & Möcks, 1982).

Table 2

Time-Frequency Regions of Interest (TF-ROIs) for Evoked and Induced Analyses of the Three Cognitive Control Tasks

Task	Theta (3.5-7.5 Hz)	Alpha (8.0-11.7 Hz)	Beta (14.1-30.0 Hz)
Stroop			
Evoked	100-300 ms	100-300 ms	-
Induced	400-600 ms	-	400-800 ms
Simon			
Evoked	100-300 ms	0-200 ms	
Induced	200-400 ms	-	400-600 ms
Erikson			
Evoked	100-300 ms	0-200 ms	
Induced	-	-	400-600 ms

5.5 Results

Statistical analyses were conducted using the statistical software package SPSS v. 22 (SPSS Inc., Chicago, IL, USA). Behavioural results will be reported first, followed by electrophysiological results. The sample size of participants varies by task due to technical issues concerning the electrophysiological recordings for a handful of participants for specific tasks.

5.5.1 Behavioural Results

We conducted Language Group (monolingual, bilingual) x Age Group (younger, older) x Trial Type (congruent, incongruent) mixed ANOVAs for the dependent variables RT and accuracy, separately for each of the three tasks. Results will be reported for RT and then accuracy. Reported effects were significant at an alpha level of .05. Results of main effects are presented regardless of their significance; however, in the interest of concision, only significant interactions are presented. All planned comparisons were subjected to Bonferroni correction and were conducted to examine the simple effects of Language Group in each task in order to examine whether monolinguals differed from bilinguals in each of the age groups, on either of the trial types. Table 3 shows means and standard deviations by trial type for RT and accuracy for the three tasks.

RT. A main effect of Age Group was found for all three tasks, indicating that younger adults performed faster than older adults (all *p*'s <.001). There was no main effect of Language Group for any of the tasks (all *p*s > .38), nor any interaction between Age Group and Language Group (although there was a trend towards significance for the Stroop task, p=.056). A main effect of Trial Type was found for all three tasks, indicating that participants had higher RTs on incongruent than congruent trials (all *p*s <.001). The three-way interaction between Age Group, Language Group and Trial Type was significant for the Stroop task, F (1,75), = 10.363, *p* =.002, but not the Simon, F (1, 78), = .242, *p* =.624, nor the Eriksen, F (1,80), = .019, *p* =.892.

Briefly, planned comparisons to examine Language Group showed that older bilinguals were faster than older monolinguals on incongruent trials in the Stroop task (*p* =.017), and younger monolinguals were faster than younger bilinguals on both types of trial in the Simon task (congruent *p* =.055; incongruent *p* = .050). There were no simple effects of Language Group on the Eriksen task (all *p* >.504).

Planned comparisons to examine the simple effects of Age Group indicated that both groups of younger adults were faster than their older counterparts in the Stroop task and the

Table 3

Means and Standard Deviations by Trial Type for RT and Accuracy for the Three Cognitive Control Tasks

	Younger Monolinguals	Younger Bilinguals	Older Monolinguals	Older Bilinguals
	M *(SD)*	M *(SD)*	M *(SD)*	M *(SD)*
			Stroop	
	(n = 25)	(n = 26)	(n = 14)	(n = 14)
RT				
Congruent	822.13 *(12.3)*	841.39 *(13.9)*	1002.94 *(30.6)*	981.01 *(13.4)*
Incongruent	874.00 *(14.1)*	896.65 *(14.1)*	1138.59 *(28.8)*	1067.09 *(16.0)*
Accuracy				
Congruent	94.81 *(0.8)*	94.23 *(0.8)*	95.41 *(1.5)*	94.62 *(1.4)*
Incongruent	91.84 *(1.1)*	92.05 *(1.5)*	82.54 *(2.2)*	87.45 *(3.5)*
			Simon	
	(n = 24)	(n = 26)	(n = 17)	(n = 18)
RT				
Congruent	614.09 *(8.4)*	650.65 *(18.1)*	704.38 *(16.6)*	689.2 *(9.3)*
Incongruent	651.33 *(9.4)*	690.33 *(19.4)*	747.65 *(15.7)*	728.12 *(9.5)*
Accuracy				
Congruent	96.75 *(0.5)*	95.07 *(1.9)*	94.54 *(1.7)*	95.76 *(1.9)*
Incongruent	89.50 *(1.3)*	90.60 *(1.9)*	89.83 *(1.9)*	90.95 *(2.0)*
			Eriksen	
	(n = 24)	(n = 26)	(n = 16)	(n = 18)
RT				
Congruent	655.64 *(7.2)*	664.07 *(6.2)*	780.55 *(18.8)*	775.05 *(7.9)*
Incongruent	722.36 *(8.6)*	730.36 *(7.9)*	825.04 *(18.8)*	820.93 *(7.5)*
Accuracy				
Congruent	96.20 *(1.2)*	97.40 *(0.6)*	89.16 *(2.9)*	93.19 *(2.9)*
Incongruent	86.36 *(1.9)*	89.04 *(1.6)*	70.85 *(5.4)*	76.17 *(5.1)*

Eriksen task (all $p < .001$). In the Simon task, both younger groups were faster than their older counterparts, but this difference was larger in the monolingual group (congruent = a difference of 90.3 ms, $p < .001$; incongruent = difference of 96.3 ms; $p < .001$) than the bilingual group (congruent = difference of 38.5 ms; $p = .063$; incongruent = difference of 47.8 ms; p .028).

In summary, within the RT data from all three tasks, there is evidence for a bilingual advantage for the older bilinguals on the Stroop task and what seems like a bilingual advantage for the older bilinguals (in that they differ less from their younger counterparts than the older monolinguals) on the Simon task, but may be better interpreted as a global speed advantage for the younger monolinguals.

Accuracy. Main effects of Age Group indicated that younger adults had higher accuracy than older adults, on the Stroop task ($p = .030$) and the Eriksen task ($p < .001$), but did not differ on the Simon task ($p = .899$). There was no main effect of Language Group on any of the tasks (all ps $> .192$), nor any interaction between Age Group and Language Group (all ps $> .445$). A main effect of Trial Type in all three tasks indicated that participants had higher accuracy on congruent than incongruent trials on all three tasks (all $p < .001$).

Planned comparisons indicated that there were no simple effects of Language Group on either trial type, on any of the three tasks (all ps $> .126$).

Planned comparisons of the simple effects of Age Group indicated that for the Stroop task, older monolinguals were significantly less accurate than younger monolinguals on incongruent trials (congruent: $p = .691$; incongruent: $p = .001$), while younger bilinguals and older bilinguals did not differ on either trial type (congruent: $p = .800$; incongruent: $p = .102$). In the Simon task, there were no Age Group differences for either of the Language groups (all $p > .348$). For the Eriksen task, older monolinguals were significantly less accurate than younger monolinguals (congruent: $p = .011$; incongruent: $p = .002$), older bilinguals were as accurate as younger bilinguals on congruent trials (congruent: $p = .105$; incongruent: $p = .007$).

In summary, within the accuracy data from all three tasks, there is evidence for a bilingual advantage for the older bilinguals on incongruent trials of the Stroop task in that they are as accurate as the younger bilinguals, whereas the older monolinguals are significantly less accurate than their younger counterparts. There is also some evidence for a bilingual advantage in the Eriksen task, although it is on the congruent trials – both older monolinguals and bilinguals are less accurate than the younger adults on incongruent trials; however, older bilinguals do not

differ from younger bilinguals on congruent trials, while older monolinguals are less accurate than younger monolinguals on congruent trials.

5.5.2 Time-frequency Wavelet Results

We conducted an Age Group (younger, older) x Language Group (monolingual, bilingual) x Trial Type (congruent, incongruent) x S-ROI (FC, LCP, RCP) mixed ANOVA on the exported power values, separately for each TF-ROI, for each task (ANOVA results are presented in Appendix B, Tables B.2.-B.7.). As this generates a substantial volume of data (11 mixed factor ANOVAs), we present the results in several different ways, with the goal of facilitating interpretation. We will outline the presentation sequence of the results section below.

Evoked and induced analyses are presented in separate sections. Each of the two sections begins with *highlights* giving an overview of the most important findings. Following this, the three tasks are presented separately. Each of the three task presentations includes a representative *time-frequency figure* (Figures 1-3, 5-7) and a paragraph outlining the *ANOVA results* for each TF-ROI[2]. Finally, each section contains a *summary* paragraph - that compares the results between the three tasks - and an accompanying *data interpretation grid* (Figures 4 and 8) to further aid in interpretation. Figures 4 (evoked activity) and 8 (induced activity) present the *p* values for the planned comparisons, and contain coloured squares depicting comparisons significant at $p < .05$.

5.5.2.1 Analysis of evoked activity.

Highlights

An overall inspection of the time-frequency representations of the evoked activity in the three tasks (Figures 1-3) show that activity in the alpha and theta bands is always red, indicating increased activity relative to baseline. Purple dashed boxes indicated the theta TF-ROIs, and black boxes indicate the alpha TF-ROIs. Within all three figures, pre-stimulus activity can be seen occurring from approximately -200 ms to 0 ms, which is due to the presentation of the cue. Highlights of the following analyses are: 1) younger participants seem to show higher power

[2] Within the descriptions of each ANOVA, the main effects of Language Group, Age Group, and Trial Type are presented when significant, as are the results of any significant interactions. Given that we are explicitly interested in the differences between Language Groups as a function of Age Group, we reported the results of planned comparisons (with Bonferroni correction) of the simple effects of Language Group computed at the level of the four-way interaction (e.g., the comparison between older monolinguals and older bilinguals on each trial type, at each S-ROI). Additionally, as no study to date has used time-frequency analyses to examine the bilingual benefit in aging, we also report the simple effects of Age Group and of Trial Type (using planned comparisons with Bonferroni correction). Effects reported as significant are all $p < .05$.

than older participants in both TF-ROIs, with some variation in topography and variation across the tasks, 2) there is a subtle pattern of Language Group effects which seems to be driven by the older monolinguals having lower power than the other three groups, and 3) in general there are no significant differences in evoked power between congruent and incongruent trials, suggesting that evoked activity in these TF-ROIs do not capture the conflict effect. These will be examined in more detail in the following paragraphs and in the evoked section summary.

Evoked power in the Stroop task.

Theta 100-300. A main effect of Age Group indicated that younger adults showed higher power than older adults. A main effect of Trial Type indicated significantly increased power during congruent trials compared to incongruent. Planned comparisons of Age Group indicated that younger monolinguals showed higher power than older monolinguals on congruent trials and incongruent trials at LCP and that younger bilinguals showed higher power than older bilinguals on congruent and incongruent trials at LCP and RCP, and on incongruent trials at FC. Planned comparisons of Trial Type indicated that older bilinguals had higher power on incongruent trials compared to congruent trials at FC.

Alpha 100-300. A main effect of Age Group indicated that younger adults showed higher power than older adults. Planned comparisons of Age Group indicated that both of the younger groups showed higher power than their older counterparts, on both Trial Types, at all S-ROIs. Planned comparisons of Language Group showed older bilinguals had higher power than older monolinguals on incongruent trials at LCP.

Evoked power in the Simon task.

Theta 100-300. A main effect of Age Group indicated that young adults had higher power than older adults. Planned comparisons of Age Group indicated that younger monolinguals had higher power than the older monolinguals on both trial types at LCP and RCP, and that younger bilinguals had higher power than the older bilinguals on both trial types at LCP and on congruent trials at FC.

Alpha 0-200. A main effect of Age Group indicated that younger adults showed higher power than older adults. A main effect of Trial Type indicated higher power on incongruent trials compared to congruent trials. Planned comparisons of Age Group indicated that younger monolinguals had higher power than older monolinguals on both trial types at FC and LCP, and that younger and older bilinguals did not differ from each other for either trial type, at any S-

ROI. Planned comparisons of Language Group indicated that older bilinguals had higher power than older monolinguals on incongruent trials RCP, with a non-significant trend at LCP (p =.063). Planned comparisons of Trial Type indicated that older bilinguals had higher power on incongruent trials than congruent trials at LCP and RCP.

Evoked power in the Eriksen task.

Theta 100-300. A main effect of Age Group indicates that younger adults showed higher power than older adults. The four-way interaction reached significance. Planned comparisons of Age Group indicated that both of the younger groups had higher power than their older counterparts on both trial types at LCP, but not FC or RCP. Planned comparisons of Language Group indicated that younger bilinguals showed higher power than younger monolinguals on incongruent trials at FC, with a non-significant trend at RCP (p =.063). Planned comparisons of Trial Type indicated that younger bilinguals showed higher power for incongruent trials than congruent trials at FC.

Alpha 0-200. There was a non-significant trend towards a main effect of Age Group in which younger adults had higher power than older adults. Planned comparisons of Age Group indicated that younger monolinguals had higher power than older monolinguals on incongruent trials at LCP, whereas the younger and older bilinguals did not differ from each other.

Figure 1. Time-frequency representations of evoked power at the left centroparietal S-ROI on the Stroop task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Figure 2. Time-frequency representations of evoked power at the right centroparietal S-ROI on the Simon task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Figure 3. Time-frequency representations of evoked power at the frontocentral S-ROI on the Eriksen task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Summary of evoked activity. In summary, there was no meaningful pattern of Trial Type effects in the evoked activity. There was subtle evidence for a language group processing difference for the older adults when examining the simple effects of Language Group (seen as blue squares in Figure 7, parts B and E). In the Stroop and Simon tasks older bilinguals showed higher power than older monolinguals on incongruent trials, but not congruent trials.

The most salient finding for evoked activity was an effect of Age Group, which varied depending on the TF-ROI, S-ROI, and task (seen as purple squares in Figure 7, parts A and D), and some evidence for a language group processing difference in the older adults. For the theta frequency band, younger participants showed higher power than older participants in all three tasks, on both types of trial. For the alpha frequency band, we found this same pattern in the Stroop task - younger participants showed higher power than older participants for both trial types. We did not see this pattern in the alpha band for the Simon task or the Eriksen task. Instead, in the Simon task we found that only the monolinguals showed an Age effect – younger and older bilinguals did not differ on either congruent or incongruent trials (This can also be seen in the time frequency representation depicted in Figure 3, where the older monolinguals show visibly less “red” than the other three groups). This indicates a more global language group processing difference for the older adults.

Figure 4. Data grid representing the planned comparisons from the four-way interaction for the theta band (Age Group (A), Language group (B), and Trial Type (C)) and alpha band ((Age Group (D), Language group (E), and Trial Type (F)), for evoked activity in the three tasks. Coloured squares indicate significant comparisons ($p < .05$), light coloured squares indicate values that approach significance.

5.5.2.2 Analysis of induced activity.

Highlights

An overall inspection of the time-frequency representations of the induced activity in the three tasks (Figures 5-7) shows red activity in the theta band, indicating increased activity relative to baseline. Activity in the beta band is blue, indicating decreased activity relative to baseline, known as suppression. Purple dashed boxes indicated the beta TF-ROIs, and black boxes indicate the theta TF-ROIs. Within all three figures, pre-stimulus activity can be seen occurring from approximately -200 ms to 0 ms, which is due to the presentation of the cue. Border effects (spectral distortion at the segment borders) can also be seen as blue at the bottom and red at the right of the figures. It was not possible to distinguish oscillatory activity from red, right-sided border effects in the theta band for the Eriksen, therefore that TF-ROI was not analysed. Highlights of the following analyses are: 1) An Age Group effect is seen in each task for both Language Groups - younger participants showed higher power in the theta band in the Stroop and Simon tasks, and less suppression in the beta band in the Simon and Eriksen tasks, compared to their older counterparts, 2) unlike the evoked activity, there are no Language Group effects and 3) we see significant differences in induced power between congruent and incongruent trials, suggesting that induced activity in these TF-ROIs captures the conflict effect. These will be examined in more detail in the following paragraphs and in the induced section summary.

Induced activity in the Stroop task.

Theta 400-600. A main effect of Age Group indicated that younger adults had higher power than older adults. A main effect of Trial Type indicated that incongruent trials had higher power compared to congruent trials. Planned comparisons of Age Group indicated that younger monolinguals had higher power compared to older monolinguals in the congruent and incongruent trials at FC and LCP, and that the younger and older bilinguals differed at all three S-ROIs. Planned comparisons of Trial Type indicated that younger monolinguals showed higher power on incongruent trials compared to congruent trials at all S-ROIs. Younger bilinguals showed higher power on incongruent trials compared to congruent trials at FC, but not LCP or RCP. There was no difference between trial types for older monolinguals at any S-ROI. Older bilinguals had higher power for the incongruent trials compared to congruent trials at LCP, with a trend at RCP.

Beta 400-800. A main effect of Trial Type indicated more beta suppression on incongruent trials compared to congruent trials. Planned comparisons of Trial Type indicated stronger beta suppression on incongruent trials compared to congruent trials for younger monolinguals at all S-ROIs, for younger bilinguals at FC, and LCP (with a trend at RCP), for older monolinguals at FC, and LCP, and for older bilinguals at FC.

Induced activity in the Simon task.

Theta 200-400. A main effect of Age Group indicated that younger adults had higher power than older adults. A main effect of Trial Type indicated that incongruent trials had higher power than congruent trials. There was a significant interaction between Age Group and Trial Type: older and younger adults did not differ on congruent trials, but on incongruent trials younger adults had higher power than older adults. Planned comparisons of Age Group indicated that younger monolinguals showed higher power than older monolinguals on both trial types at FC and RCP (and on incongruent trials at LCP), while younger bilinguals showed higher power than older bilinguals on both trial types at FC, (and on incongruent trials on RCP). Planned comparisons of Trial Type indicated that younger monolinguals had higher power on incongruent trials compared to congruent trials at FC and RCP. Both younger and older bilinguals had higher power on incongruent trials compared to congruent trials at FC. Older monolinguals did not show any difference between trial types.

Beta 400-600. A main effect of Age Group indicated that older adults had more beta suppression than younger adults. A main effect of Trial Type indicated that incongruent trials had more beta suppression than congruent trials. Planned comparisons of Age Group indicated that both older groups had stronger beta suppression than their younger counterparts on both types of trial, at all S-ROIs. Planned comparisons of Trial Type indicated that, for younger monolinguals, stronger beta suppression on incongruent trials compared to congruent trials occurred at FC, for older monolinguals it occurred at all S-ROIs, and for older bilinguals at FC. There was no difference between congruent and incongruent trials for younger bilinguals.

Induced activity in the Eriksen task.

Beta 400-600. A main effect of Age Group indicated that older adults showed more beta suppression than younger adults. There was a non-significant trend towards an interaction between Age Group and Trial Type: younger adults showed more beta suppression on incongruent trials compared to congruent trials, whereas the older adults showed no difference

between the two trial types. Planned comparisons of Age Group indicated that older monolinguals had more beta suppression than younger monolinguals on congruent trials at all S-ROIs, but did not differ on incongruent trials. Older bilinguals had significantly more beta suppression than younger bilinguals on congruent trials at FC with a trend that approached at RCP (p =.064), but did not differ on incongruent trials. Planned comparisons of Trial Type indicated that both younger monolinguals and younger bilinguals showed more beta suppression on incongruent trials compared to congruent trials at LCP and RCP. There were no significant differences between congruent and incongruent trials for either of the older adult groups.

Figure 5. Time-frequency representations of induced power at the frontocentral S-ROI on the Stroop task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Figure 6. Time-frequency representations of induced power at the fronto-central S-ROI on the Simon task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Figure 7. Time-frequency representations of induced power at the left centroparietal ROI on the Eriksen task for congruent trials, incongruent trials, and the difference (incongruent – congruent), for all participants.

Summary of analysis of induced activity. In summary, no significant pattern of Language Group effects was found in the induced activity across the three tasks. A pattern of Age Group effects was found; however it does not provide strong support for a language group processing difference (seen as purple squares in Figure 8, parts A and D). For the theta frequency band, younger monolinguals and younger bilinguals showed higher power than their older counterparts on both the Stroop and the Simon tasks, on both trial types. For the beta frequency band, no effects of Age Group were found in the Stroop task. On the Simon task, younger monolinguals and younger bilinguals showed less beta suppression than their older counterparts on both trial types. The Eriksen task showed some evidence of a language group processing difference, as older monolinguals showed more beta suppression than younger monolinguals on congruent trials, at all S-ROIs, whereas older bilinguals showed more beta suppression than younger bilinguals at FC only, though there was a non-significant trend for the right S-ROI as well..

A pattern of Trial Type effects were found (seen as green squares in Figure 8, parts C and F). For the theta frequency band, a trial type effect of higher power on incongruent than congruent trials is seen for all of the participants groups (at different S-ROIs), except for the older monolinguals who never show a trial type difference. For the beta frequency band the pattern of the effects of Trial Type were more varied across the three tasks. Both the Stroop and Simon tasks showed main effects of Trial Type, while the Eriksen did not. In the Stroop task all of the groups showed effects of Trial Type (at various S-ROIs), whereas in the Simon task the younger bilinguals showed no effects of Trial Type and in the Eriksen neither of the older groups showed an effect of Trial Type.

Figure 8. Data grid representing the planned comparisons from the four-way interaction for the theta band (Age Group (A), Language group (B), and Trial Type (C)) and beta band ((Age Group (D), Language group (E), and Trial Type (F)), for induced activity in the three tasks. Coloured squares indicate significant comparisons ($p < .05$), light coloured squares indicate values that approach significance.

5.6 Discussion

Research on the hypothesized bilingual advantage suggests that speaking more than one language contributes to better performance on non-linguistic executive functioning tasks; however, this finding has not been consistently reproduced. The goal of the current study was to use time-frequency analysis to look at oscillatory activity during cognitive control as a function of age and language experience. By using three tasks that differed in their locus of conflict, we were able to examine the dynamics of cognitive control in general and explore the nature of group differences across the tasks. The current results confirm that bilinguals may show different patterns of brain functioning than monolinguals, even when a bilingual advantage is not observed in end product measures like RT and accuracy. We found evidence for global functional differences between younger and older adults, as well as both global and conflict-specific differences between monolinguals and bilinguals, and between older monolinguals and older bilinguals in terms of how they differed from their younger language-specific counterparts. In contrast with previous ERP findings, our findings indicate that when conflict-specific language group differences are found, bilinguals showed greater conflict effects than monolinguals. Finally, our findings are in line with research indicating that conflict processing is best seen in induced, compared to evoked, activity, and also that the locus of conflict effect differs across cognitive control tasks. Each of the findings will be reviewed and interpreted in turn, as well as discussed in the context of relevant studies.

5.6.1 Behavioural Results

Not surprisingly, our results are consistent with the previously published analyses of the same datasets (see, Kousaie & Phillips, 2012b; 2017). Younger monolinguals and bilinguals performed similarly on the three tasks, with the exception of a global monolingual advantage on the Simon task (seen as a trend approaching significance in Kousaie & Phillips, 2012). For older adults we found evidence of a bilingual benefit on the incongruent trials of the Stroop task only. These results are in keeping with a number of other studies finding no bilingual advantage on cognitive control tasks when examining behavioural measures (e.g., Antón et al., 2016; Billig & Scholl, 2011; de Bruin et al., 2015; Gathercole et al., 2014; Kousaie et al., 2014; Kousaie & Phillips, 2012b).

In contrast to Kousaie and Phillips (2012b; 2016), we were able to combine the data from the younger and older adults to examine Age Group effects. Overall, we found that younger

adults were consistently faster and more accurate than older adults, with the exception of the Simon task where older adults were as accurate as younger adults. Importantly, we were also able to examine whether age differences in RT depended on the language group. In the RT data, the difference between younger and older adults was the same in each language group, for both the Stroop and the Eriksen tasks. For the Simon task, the effects of age group differed between the monolinguals and bilinguals. Specifically, the older monolinguals were slower than the younger monolinguals on both trial types, while the older bilinguals were slower than the younger bilinguals on incongruent trials, but were as fast on congruent trials. Although this at first suggests a bilingual advantage for the older bilinguals, this pattern actually appears to be driven by the superior performance of the younger monolinguals. This is consistent with previous research finding a monolingual advantage on congruent trials (Bialystok et al., 2008; Salvatierra & Rosselli, 2011; Schroeder & Marian, 2012).

Age differences in accuracy depended on the language group. For the older adults, the pattern was indicative of a bilingual advantage for the Stroop task. In the Stroop task, older monolinguals were significantly less accurate on incongruent trials than younger monolinguals, whereas older bilinguals were just as accurate as younger bilinguals. In the Eriksen task, older monolinguals were less accurate than younger monolinguals on both trial types in the Eriksen task, whereas older bilinguals were as accurate as younger bilinguals on congruent trials.

Overall, these behavioural results indicate that the current group of younger bilinguals did not show a bilingual advantage in any of the three tasks, while the older bilinguals showed a bilingual advantage in the Stroop task, in the form of faster RT on incongruent trials than older monolinguals, and accuracy performance that did not differ from their younger counterparts on incongruent trials (whereas accuracy was lower in older monolinguals compared to younger monolinguals on this task). This is in line with previous research suggesting that a language-group difference may be more easily observed in older adults, due to the expected age-related decline in cognitive abilities, than in younger adults who exhibit more efficient cognitive control (Bialystok et al., 2008; Salvatierra & Rosselli, 2011). Given that we found this bilingual advantage only for the Stroop task, it is important to note that the Stroop task was the only of the three cognitive control tasks that involved linguistic processing. Previous research has suggested that the bilingual advantage on the Stroop task may be driven by slower lexical access in bilinguals generating less conflict (Coderre:2014gf, but see Blumenfeld & Marian, 2014 for a

bilingual advantage on a non-linguistic task). Specifically, bilinguals may experience a delay in activation of the semantic information of the colour word, possibly due to reduced automaticity of lexico-semantic access in a less proficient language. If there is a delay in the activation of the semantic information of the colour word, one can expect a reduced conflict effect.

5.6.2 Electrophysiological Results

We used time-frequency decomposition to examine differences between younger and older monolinguals and bilinguals in the neural response to conflict. Time-frequency analysis allows for examination of the event-related brain dynamics not contained in the ERP average, which includes the ability to characterize changes in the full spectral content (i.e., in the various frequency bands) and changes induced by, but not phase-locked to, the stimuli. Because there are as of no studies using spectral decomposition to compare monolinguals to bilinguals on cognitive control tasks (for time-frequency analysis during a linguistic task see , Kielar, Meltzer, Moreno, Alain, & Bialystok, 2014), we employed an approach that was both data driven and guided by the previous literature. Information from time-frequency studies of cognitive control indicate that conflict processing is best measured in theta, and to a lesser degree, alpha frequency over frontocentral/midfrontal regions (Cohen & Donner, 2013; e.g., Ergen et al., 2014; Nigbur et al., 2011; 2012); however there is also evidence for conflict-related beta suppression, possibly representing motor processes, following the theta and alpha modulations (Q. Li et al., 2015; Lo, Pan, & Chen, 2015). The inclusion in the current research of a left and right centroparietal region was based on studies showing conflict-related power modulations in the alpha (Jiang, Zhang, & Van Gaal, 2015b) and theta (Pastötter, Dreisbach, & Bäuml, 2013; J. Zhao et al., 2015) frequency bands over centro-parietal regions. Finally, we analysed evoked and induced power separately based on previous research indicating that induced power is a better indicator of conflict processing (Cohen & Donner, 2013).

5.6.3 Age Group effects

We were interested in the main effect of age group as there is yet little research examining the effects of aging on event-related oscillations during executive functioning tasks. Our results demonstrated that younger participants showed higher theta and alpha power than older adults, and older adults showed more beta suppression than younger adults, on both trial types. These findings are in line with research showing decreased theta power (Schmiedt-Fehr & Basar-Eroglu, 2011) and increased beta suppression (Schmiedt-Fehr, Mathes, Kedilaya, Krauss, &

Basar-Eroglu, 2016) during Go/No-Go tasks for older adults compared to younger adults. These results are also in agreement with those of a video game cognitive training study (Anguera et al., 2013). Anguera and colleagues (2013) found that older adults showed lower mid-frontal theta power than younger adults, and further, that theta power increased for older adults with training and was correlated with improved performance. We suggest that our results are indicative of age-related altercations in neural recruitment, with under-recruitment of theta reflecting impaired conflict resolution and inhibitory processes, while the increased beta attenuation reflects over-recruitment related to response preparation.

5.6.4 Language Group effects

Given that monolinguals and bilinguals have consistently shown differences in brain functioning on a variety of executive function tasks (Ansaldo et al., 2015; Garbin et al., 2010; Gold, Kim, Johnson, Kryscio, & Smith, 2013b; Kousaie & Phillips, 2012b; 2017; Rodriguez-Pujadas et al., 2014), we predicted that we would find main effects of language group on the three tasks, despite the limited group differences in the behavioural data. We did not find overall differences between the monolinguals and bilinguals in oscillatory activity, in any of the three tasks. One explanation for this is that the language group differences vary by age group. In other words, the manner in which the two younger groups differ from each other is not the same as the manner in which the older groups differ from each other.

When we looked at younger and older adults separately, we found evidence for conflict-specific language-group processing differences. In the Eriksen task, younger bilinguals showed higher evoked theta power than younger monolinguals on incongruent trials but not on congruent trials. In fact, younger bilinguals were the only group to show higher power on incongruent than congruent trials in the Eriksen task, although this did not translate to a behavioural advantage over their monolingual counterparts. This finding is in contrast to the reviewed ERP studies, wherein conflict-specific language group differences generally showed that monolinguals showed a larger conflict effect than bilinguals (Coderre & van Heuven, 2014; Heidlmayr et al., 2015; Kousaie & Phillips, 2012b).

We also found a conflict-specific language group difference in the older adults. Older bilinguals showed higher evoked alpha power than older monolinguals on incongruent trials, but not congruent trials, in the left centroparietal region for the Stroop task and the left and right centroparietal regions for the Simon task. Additionally, our behavioural results correspond with

this finding in the Stroop task, with older bilinguals performing more quickly than older monolinguals on incongruent trials. Although our results are different from other ERP research (which finds smaller conflict effects for bilinguals compared to monolinguals Coderre & van Heuven, 2014; Heidlmayr et al., 2015), this is likely because our results were found in left and right centroparietal regions and not in the frontomedial region, which is where the other studies analysed. We did not find evidence for any conflict-specific language group differences in the induced oscillations.

5.6.4. Age effect within language groups

In order to explore whether monolinguals and bilinguals differ in terms of age-related neural changes, we examined how the older monolinguals and older bilinguals each differed from their younger counterparts. For the Stroop task, we did not find any differences in the age effect between the two language groups. For the Simon task, while older monolinguals showed lower alpha power than younger monolinguals on both trial types, the older bilinguals did not differ from the younger bilinguals. This is consistent with a global language-group processing difference, similar to the concept in behavioural data of a BEPA (Hilchey & Klein, 2011). For the Eriksen task, on incongruent trials, the older monolingual group showed lower alpha power than younger monolinguals in the left centroparietal region (with a trend for the frontocentral region), while the older bilinguals did not differ from the younger bilinguals. This is consistent with a conflict-specific language group difference, which is more similar to the BICA in behavioural data (see Kousaie & Phillips, 2012b). Taking these three tasks together we find that, given an overall tendency to see lower event-related power in older adults than younger adults, this pattern occurred more often in the monolinguals, and furthermore, in many of these cases, the older monolinguals differed from all three of the other groups, while those groups (younger monolinguals and bilinguals and older bilinguals) did not differ from each other.

5.6.5. Age-related compensatory mechanisms

Typically, when older adults perform similarly to younger adults on cognitive tasks but show a different pattern of brain functioning, it is assumed that the older adults made use of a compensatory network in order to counteract typical age-related declines in cognitive functioning. Two well-studied examples of age-related compensatory processes are the posterior-anterior shift in aging (PASA; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008) or the hemispheric asymmetry reduction in old adults (HAROLD; Cabeza, 2001; 2002), both of which

refer to age-related differences in the topographical patterns of neural activity. When older adults perform more poorly than younger adults it is not possible to state whether any differences in neural activity are indicative of inefficient processing or represent a pattern of compensatory processing that did not achieve its goal (for a discussion see Cabeza, 2001; Friedman, 2003). Given that the older monolinguals in this study perform more poorly than the younger monolinguals, we cannot say that their pattern of neural activity represents age-related compensatory processing - we are only able state that they show age-group differences in neural processing. As such, we are also unable to state that older bilinguals deviate from an age-related compensatory process used by older monolinguals - we can only say that older monolinguals and older bilinguals differ in terms of their aging-related neural activity. Further research into the effects of aging on neural processing during cognitive control tasks is necessary to help identify patterns of compensation that differentiate high from low performers.

5.6.6 The Conflict Effect across tasks

The results of our study contribute to the literature indicating that there is little convergent validity between these three commonly used cognitive control tasks. Although results from these tasks are often compared across studies, they differ with regard to the locus of the conflict. As previously outlined, while the Stroop and the Eriksen task contain conflict at the level of the stimulus (S-S conflict), the conflict in the Simon task is between the stimulus and the response (S-R conflict). Additionally, the Stroop differs from the Eriksen task in that it contains linguistic stimuli, and its conflicting elements are part of the same unit (i.e., it contains dimensional overlap). The conflicting information in the Eriksen task is contained in the flankers. Our results contribute to the literature by demonstrating that the electrophysiological manifestation of the conflict effect (a main effect of Trial Type) also varies across the tasks, and furthermore, within the tasks, varies by group. Additionally, our results are in line with the finding that conflict effects are likely to manifest in induced, rather than evoked activity (Cohen & Donner, 2013), as we found that conflict effects were mostly absent in the evoked activity, but were much more prominent in the induced activity.

In the evoked results, only the younger and older bilinguals showed a difference between congruent and incongruent trials. This occurred in the theta frequency band for the Stroop task, (where the older bilinguals showed a conflict effect at FC), in the alpha frequency band for the Simon task (where the older bilinguals showed a conflict effect at LCP and RCP), and in the

theta frequency band for the Eriksen task (where the younger bilinguals showed a conflict effect at FC).

ERP analysis of the same data also showed variability in the locus of the conflict effect (Kousaie & Phillips, 2012b; 2017). With younger adults, Kousaie and Phillips (2012) found a conflict effect for the Eriksen task when measuring the N2, but not for the Simon or Stroop tasks. This was similar to our finding of a conflict effect in evoked power in the theta frequency band during a similar time period, for younger bilinguals on the Eriksen task only. For the Stroop and Simon tasks, Kousaie and Phillips (2012) found the locus of the conflict manifested in the P3, with lower amplitude on incongruent compared to congruent trials. Although we did not measure during this time period, visual inspection of the time-frequency figures suggests that the activity measured in the theta and alpha TF-ROIs (from 100-300ms post-stimulus) is not distinct from any activity in the following 300-500ms time interval, and there appears to be higher power on congruent than incongruent trials for the Stroop and Simon task. With older adults, there was no conflict effect found on the Stroop task for the N2. For the Simon task, Kousaie and Phillips (2016) found a conflict effect for older bilinguals, but not monolinguals in N2 amplitude. This aligns with our finding of a conflict effect in the same direction, for older bilinguals only, in the alpha frequency band. However, on the Eriksen they found the opposite results, with a conflict effect for monolingual but not bilingual older adults in N2 amplitude. In the current analyses, there was no conflict effect for the Eriksen task for the older adults.

Contrary to our evoked results, all three tasks showed differences between congruent and incongruent trials when examining the induced activity, though the locus of the conflict effect varied somewhat. Broadly, we found that the Stroop and Simon tasks showed conflict effects in induced theta frequency band power, but that the timing of the effects differed (Stroop 400-600ms; Simon 200-400ms), additionally, older monolinguals did not show a conflict effect in either task. We also found that while the Stroop and Simon tasks showed a conflict effect in the beta frequency band, this main effect did not reach significance in the Eriksen task. In the Stroop and Simon tasks most of the groups showed the conflict effect in the frontocentral region (except for younger bilinguals, who did not show a conflict effect for the Simon task). In the Eriksen task a conflict effect was only seen for the younger adults, and only in the left and right centroparietal regions. Based on the differences between the tasks in terms of the locus of the conflict, we would have expected the manifestation of the conflict effect in the oscillatory activity to be more

similar for the Stroop and the Eriksen task. Instead we see that the Stroop and the Simon task appear to show similar patterns (a conflict effect in both theta and beta frequency bands), while the Eriksen task does not show a conflict effect. We note that although the Stroop and Simon task differ in terms of the locus of the conflict being within the stimulus and between the stimulus and the response, they are similar in that they contain dimensional overlap. In the Stroop task, the conflicting information from the written word is present in the same stimulus as the target information, and in the Simon task the conflicting information of the location is a facet of the target stimulus. This suggests that dimensional overlap may be a more important factor in eliciting conflict-related neural oscillations than whether the conflict is S-S or S-R. These results contribute to the literature indicating that these three tasks differ in terms of brain activity (X. Liu et al., 2004; Peterson et al., 2002; Wager et al., 2005).

Taken together, these findings are in line with previous neuroimaging studies that indicate that conflict processes may manifest differently depending on the task (Egner et al., 2007; Kousaie & Phillips, 2012b; e.g., 2017; Nee et al., 2007; Peterson et al., 2002; Wager et al., 2005). For example, the tasks show trial type differences in different neural networks (X. Liu et al., 2004), at different components (Kousaie & Phillips, 2012b), or in different time-frequency periods (Nigbur et al., 2011). Additionally, the fact that trial type differences are seen mostly in induced activity indicates that the mechanisms of conflict processing are not phase-locked and not tightly time-locked to the stimulus onset.

5.6.7 Summary

The current results make important contributions to the literature regarding the neural representation of cognitive control processing in younger and older monolinguals and bilinguals. Briefly, we found that the behavioural results reported here are consistent with the previously published analyses of this data, and show evidence for a bilingual advantage for older adults only, and only in the Stroop task. One of this study's strengths is that we were the first study to compare age group differences within monolingual and bilingual groups across these three cognitive control tasks. Our behavioural results did not provide support for a bilingual advantage in the form of attenuation of age-related decline. In other words, we did not find substantial evidence that the magnitude of the age group difference was larger for monolinguals than bilinguals.

Our data also contribute to the growing literature demonstrating that neural processing differences may be found even in the absence of language group differences in behavioural measures. Electrophysiological results revealed subtle differences in neural activity between younger and older monolinguals and bilinguals. There were conflict-specific language group differences for younger adults in evoked theta in the Eriksen task (at FC), and for older adults in evoked alpha in the Stroop (at LCP) and Simon tasks (at RCP), with larger conflict effects for bilinguals compared to monolinguals. Additionally, the results provide evidence for a pattern wherein the neural activity of older monolinguals differed from that of the other three groups, and showed less differentiation between congruent and incongruent trials.

Another one of this study's strengths is that in addition to being the first study to examine language group differences in cognitive control using time-frequency analysis, this is also the first to examine age group differences, and the first to compare oscillatory activity in the three different cognitive control tasks. We found that older adults show higher alpha and theta power and more beta suppression than younger adults, that induced activity showed a larger effect of Trial Type than evoked activity, and that the three cognitive control tasks differed in terms of the locus of the conflict effect with respect to neural oscillations. Therefore, not only do these results highlight the utility of electrophysiological methods in investigating language group processing differences, they also draw attention to the need for further efforts to investigate the neural mechanisms underlying cognitive control in general. Recent research highlights the utility in using time-frequency analysis to investigate attention and executive functioning in patients with mild cognitive impairment, with results showing differences between patients and healthy elderly controls in event-related oscillations (Caravaglios, Castro, Muscoso, Crivelli, & Balconi, 2016). Future research would benefit from examining whether language group differences in the oscillatory activity are seen in patients with MCI and AD, and whether bilingualism protects against changes associated with cognitive decline.

Chapter 6: General Discussion

As reviewed in Chapters 1 and 2 of this dissertation, there are currently two fairly separate research areas concerned with the cognitive effects of bilingualism. One of these is based within a cognitive reserve framework and has the goal of examining whether bilingualism delays the cognitive effects of dementia. This research area currently consists mainly of large database studies examining the age of diagnosis and age of onset of dementia in monolinguals compared to multilinguals. The second research area is concerned with exploring the extent and mechanisms of the bilingual advantage in executive functioning and has been an active area of research for approximately two decades. The bilingual advantage body of literature includes information from participants of all ages (from infants to late seniors), structural imaging methods measuring gray matter volume, white matter integrity, and white matter network connectivity, and functional neuroimaging techniques including fMRI, MEG, and EEG. Taken together, they provide evidence to suggest that bilingualism elicits neuroplastic changes related to executive functioning, and that these changes may act as neural reserve and/or neural compensation.

The overarching goal of this dissertation was to explore the impact of neural reserve and/or neural compensation related to bilingualism in older adults and patients with MCI and AD. Specifically, the two manuscripts presented here aimed to address whether being bilingual is related to structural brain differences in patients with MCI and AD and to explore the relationship between structural brain differences and cognitive outcomes (Manuscript 1) and whether being bilingual results in functional brain differences during the performance of cognitive control tasks in younger and older adults (Manuscript 2). Taken together, the results show that bilingualism appears to have an impact in a sublte way on brain functioning in younger and older adults, but a more robust or overt affect in older adults who have a diagnosed brian disease. I will begin with summaries of the results of the two studies, followed by a discussion of their theoretical and practical implications. Finally, the strengths and limitations of the dissertation and directions for future research will be explored.

6.1 Summary of presented studies

In the first manuscript I presented a study that examined the effect of bilingualism on brain structure in patients with MCI and AD. The study compared cortical thickness and tissue density in two families of brain regions (regions related to AD pathology and regions related to

bilingualism and cognitive control) between monolingual and multilingual MCI and AD patients who have been matched on a number of demographic and cognitive variables. Results showed that, despite being matched on episodic memory scores, multilingual AD patients had lower tissue density values in medial temporal lobe areas like the posterior parahippocampal gyrus (with similar directional trends for the rhinal cortices) compared to monolingual AD patients. MCI patients, also matched on episodic memory scores, did not show a language group difference in these areas. We interpreted this as evidence that multilingualism contributes to cognitive reserve in AD patients while, for MCI patients, we suggested that the disease may not have progressed enough to demonstrate any potential effects of cognitive reserve. Results also showed that multilingual MCI and AD patients had thicker cortex and greater tissue density than their monolingual counterparts in brain areas related to bilingualism and cognitive control. Multilingual patients showed correlations between episodic memory measures and brain regions related to cognitive control, while monolingual patients did not. Based on this, we hypothesized that the regions showing the effects of experience-induced neuroplasticity may support cognitive reserve by providing the structural mechanism for neural compensation. In other words, we suggested that despite AD-related atrophy in medial temporal areas, memory function was maintained in multilingual patients through reliance on an enhanced executive function network.

In the second manuscript, I presented a study that examined the effects of bilingualism on brain functioning. The study compared event-related oscillations during three cognitive control tasks in younger and older monolinguals and bilinguals. Results demonstrated that even in the absence of behavioural differences, monolinguals and bilinguals varied in the neurophysiological expression of cognitive control. For the Stroop task, the behavioural and EEG findings of a conflict-specific bilingual advantage were in accordance. Specifically, older bilinguals showed higher alpha power and had faster response than older monolinguals on incongruent trials but not congruent trials. We found conflict-specific language group differences in the EEG for the younger adults in the Eriksen task, and for the older adults in the Simon task, but did not see any language group differences in the behavioural data for either task. Specifically, younger bilinguals showed higher evoked theta power than younger monolinguals on incongruent but not congruent trials, and older bilinguals showed higher evoked theta and alpha power than older monolinguals on incongruent but not congruent trials. We interpreted these findings as evidence that bilinguals allocate attention and detect and resolve conflict differently from monolinguals.

Further, our results demonstrate that although the previously described language group differences were seen in evoked activity, the majority of the trial type differences were seen in non-phase locked activity.

6.2 Cognitive Reserve: Neural Reserve and Neural Compensation

The findings from the studies presented in this dissertation have implications for the supposition that bilingualism contributes to cognitive reserve. As discussed in Chapter 2 of the General Introduction, the cognitive reserve hypothesis posits that various lifelong experiences have a beneficial effect on the brain, allowing individuals to cope better with declines in cognition, such as those seen in aging and dementia (Stern, 2003; 2009). A person with high cognitive reserve (which may be due to higher levels of education, participation in cognitively stimulation activities, etc.) would be able to perform at the same cognitive level as someone with low cognitive reserve, despite having more brain atrophy (Barulli & Stern, 2013; Stern, 2009). It has been hypothesized that being bilingual may exercise the brain in a manner similar to having a higher level of education or participating in cognitively stimulating activities (Duncan & Phillips, 2016; Schweizer et al., 2012). The constant use of cognitive control mechanisms to manage competition between languages may strengthen executive functioning networks, providing neural reserve and/or neural compensation. Neural reserve refers to the strengthening of existing networks, and in the case of bilingualism would be seen as superior performance by bilinguals on tests of executive functioning, or as more efficient use of networks (i.e., less activation compared to monolinguals, while achieving similar or better performance). Neural compensation refers to the ability to recruit alternate or additional networks to compensate for those damaged by atrophy, and would be seen as recruitment of additional cognitive control or executive functioning networks to supplement aging-related atrophy in the frontal lobes or dementia-related atrophy of medial temporal memory areas. I will review how the findings from the two manuscripts contribute to our understanding of bilingualism and cognitive reserve.

6.3 Bilingualism and cognitive reserve in MCI and AD

Results from Manuscript 1 show that 1) multilingual AD patients do not differ from monolingual AD patients on episodic memory measures despite greater medial temporal lobe atrophy, 2) that both MCI and AD patients show greater cortical thickness in cognitive control regions, and finally, 3) that both MCI and AD patients show a correlation between cognitive control brain regions and memory scores. Taken together, these findings provide preliminary

evidence for neural compensation in multilinguals. One possible interpretation is that multilingual AD patients, who are farther along in the disease process, are able to maintain memory performance comparable to their monolingual peers by recruiting an enhanced cognitive control network. These findings are in line with the work of Schweizer and colleagues (2012), who found that bilingual AD patients showed greater atrophy in AD-relevant brain areas than monolinguals who were matched on age, education, and memory performance. Evidence for neural reserve in these two studies would have been seen as better executive function performance by the bilingual/multilingual patients compared to the monolingual patients. This was not seen in our study, although the executive functioning tests used (Victoria Stroop, Clock design, Orientation) were not particularly sensitive measures and it is possible that a bilingual advantage could have been seen in more sensitive computerized tasks. The study by Schweizer and colleagues is unable to address this question as their patients were specifically matched across language groups on tests of working memory and executive functioning.

Within the cognitive reserve literature, further evidence for a neural compensation explanation comes from two studies that failed to find a bilingual advantage on tests of executive functioning in MCI and/or AD patients (Bialystok, Poarch, Luo, & Craik, 2014b; Ossher et al., 2013). Bialystok and colleagues (2014) found that age of onset and age of diagnosis was delayed in bilingual compared to monolingual MCI and AD patients, but found no bilingual advantage in executive functioning scores from neuropsychological tests for either of the patient groups. Unfortunately, this study did not include scores from memory measures, so evidence for neural compensation comes indirectly from the finding that bilinguals had later age of onset and age of diagnosis than monolinguals. Ossher and colleagues (2013) found a later age of symptom onset and diagnosis for bilinguals with single-domain amnestic MCI (aMCI), but not multiple-domain aMCI. Their findings suggest that bilingual single-domain aMCI patients benefit from neural compensation – their enhanced executive functioning networks are able to compensate for their impaired memory abilities. Bilingual patients with multiple-domain aMCI may be experiencing greater amounts of frontal lobe pathology, impairing the network that would afford compensatory processing. Further research would benefit from comparing white matter connectivity in executive functioning networks between monolingual and bilingual patients with different MCI subtypes.

6.4 Bilingualism and cognitive reserve in healthy older adults

In contrast to the dearth of executive function findings in patients, bilingual advantage research, conducted mainly with healthy adults, consists primarily of studies comparing RT and accuracy on executive function tests between monolingual and bilinguals. Results from Manuscript 2 show that 1) younger and older bilinguals do not show consistent evidence of a bilingual advantage in behavioural data, 2) younger and older bilinguals show some processing differences in event-related oscillatory power compared to their monolingual counterparts, and 3) there is some evidence that older monolinguals show age-related effects where older bilinguals do not. A clear bilingual advantage in behavioural results for older bilinguals would be evidence towards the hypothesis that bilingualism contributes to neural reserve - a lifetime spent dealing with two languages strengthens the cognitive control system, so that older bilinguals can maintain higher levels of cognitive control ability despite age-related changes in the frontal lobe. The current results do not support this hypothesis.

Results of Manuscript 2 are consistent with fMRI studies showing language group differences in cognitive control processing, with no differences between monolinguals and bilinguals in behavioural data (Ansaldo et al., 2015; Gold, Kim, Johnson, Kryscio, & Smith, 2013b; Rodriguez-Pujadas et al., 2014). Two studies conducted with older adults found that older monolinguals show activation consistent with age-related compensation while older bilinguals did not, however neither showed significant evidence of a bilingual advantage in behavioural data (Ansaldo et al., 2015; Gold, Kim, Johnson, Kryscio, & Smith, 2013b). In one of the studies, older monolinguals recruited significantly more brain regions than younger monolinguals (consistent with age-related over-compensation) while older bilinguals did not differ from younger bilinguals (Gold, Kim, Johnson, Kryscio, & Smith, 2013b). In the second study, older monolinguals showed a pattern congruent with age-related compensation known as the posterior-anterior shift in aging (PASA), while older bilinguals showed activation in the left IPL, an area implicated in bilingual language processing and cognitive control (Ansaldo et al., 2015).

Results from ERP studies show similar results, with different patterns of neural activity for bilinguals and monolinguals but no evidence of a bilingual benefit in behavioural data. To date, no study has compared whether older bilinguals show similar age-related patterns of electrophysiological activity compared to older monolinguals. Indeed, very little research has been done generally to define age-related patterns of compensation in event-related EEG. Studies

have found that older adults show increased latency of ERP components related to cognitive control when compared to younger adults (I. J. Bennett, Golob, & Starr, 2004; Falkenstein, Hoormann, & Hohnsbein, 2002); however, findings regarding age-related changes in ERP amplitude are mixed (van Dinteren, Arns, & Jongsma, 2014; West, 2004; West & Moore, 2005). There is evidence to suggest that older adults show an ERP counterpart to the PASA-effect seen in fMRI studies, with increased amplitude seen in the frontal N2 component and decreased amplitude seen in the parietally distributed P3 components, and relatedly, that older adults show decreased midline frontal theta power compared to younger adults (Anguera et al., 2013). In sum, clear evidence for a bilingual advantage in non-linguistic cognitive control tasks is sparse. Commentators have suggested that the bilingual advantage found in previous studies is either extremely subtle and arises only under a set of circumstances that has not yet been defined, or does not exist and positive findings are the result of, among other possibilities, small sample sizes, a publishing bias towards positive results, or the result variables like immigration status (Duñabeitia & Carreiras, 2015; Hilchey & Klein, 2011; Paap et al., 2015).

I suggest that the results reviewed in Chapters 2 and 3, and those found in Manuscripts 1 and 2 provide evidence for bilingualism's contribution to cognitive reserve but demonstrate that a bilingual advantage is most consistently seen in the form of neural compensation, while evidence for neural reserve is less clear.

6.5 Executive functioning and memory abilities

I have reviewed evidence that bilingualism appears to be related to neuroplastic changes in brain structure (Abutalebi et al., 2014 manuscript 1; Grogan et al., 2012; e.g., Mechelli, Crinion, Noppeney, & O'Doherty, 2004; Ressel et al., 2012), and brain functioning (Ansaldo et al., 2015; Kousaie & Phillips, 2012b; e.g., 2017; Luk et al., 2010 manuscript 2) but evidence for a bilingual advantage in executive functioning is mixed, with some studies finding no bilingual advantage, even in older adults (manuscript 2; Gathercole et al., 2014; Kirk et al., 2014; Kousaie & Phillips, 2012b; 2017; Paap & Greenberg, 2013). At this time, data do not indicate that the bilingual advantage is manifested as enhanced executive functioning itself (i.e., as neural reserve), although this area certainly merits additional research. For example, this has not yet been directly tested in patients - future research would benefit from using computerized executive functioning tasks measuring RT and accuracy to assess whether a bilingual advantage exists for MCI and AD patients. To date there has been one study examining bilingualism's contribution to cognitive

reserve in patients with executive functioning deficits. Hindle and colleagues (Hindle et al., 2015) found no differences in performance of monolingual and bilingual patients with Parkinson's disease on a number of executive functioning tests. Similar to the findings in multiple-domain aMCI patients, this could indicate that when the executive function network itself is impaired, any benefit of bilingualism is eradicated.

Taken together, the results of these studies, and those from Manuscript 1, indicate that the benefits of bilingualism in MCI and dementia are detectable as the enhanced ability to harness executive functioning abilities to compensate for weaknesses in other cognitive areas (in this case, memory processing). Currently, we do not have information on whether brain differences related to bilingualism compensate for memory decline in healthy older adults. There are only three studies examining memory abilities in monolinguals and bilinguals, one showing superior performance for monolinguals (Fernandes, Craik, Bialystok, & Kreuger, 2007), one for bilinguals (Schroeder & Marian, 2012) and one with mixed results depending on modality of the memory test (Wodniecka et al., 2010). Support for a neural compensation hypothesis does come from the well-recognized idea that executive functioning abilities may mediate aspects of memory performance in older adults (Angel et al., 2016; e.g., Angel, Fay, Bouazzaoui, & Isingrini, 2011; Troyer et al., 2007). Therefore, if being bilingual exercises executive function mechanisms, perhaps the benefit is not strong enough to give an advantage in cognitive control, but language group differences might appear in how older adults are able to compensate for declining memory abilities.

6.6 ***Relationship between structure, function, and behaviour***

One of the major issues within both the cognitive reserve and the bilingual advantage literatures is the need for more studies using some combination of structural, functional, and behavioural measures. Combining behavioural and brain measures is necessary for avoiding a number of interpretation errors, one of which is the valence-ambiguity problem. The valence-ambiguity problem describes the difficulties in interpreting whether functional/structural brain differences can considered beneficial/advantageous in the absence of behavioural differences (Paap et al., 2015).

In terms of the relationship between function and behaviour, to date, only a few studies examine the relationship between brain functioning and behaviour in younger and older monolinguals and bilinguals. Similar to our findings in Manuscript 2, the majority of these

studies show a bilingual processing difference, but no behavioural bilingual advantage (Ansaldo et al., 2015; Coderre & van Heuven, 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013b; Heidlmayr et al., 2015; Kousaie & Phillips, 2012b; 2017; Mohades et al., 2014). Some have argued that increased brain activation in response to conflict (i.e., higher activation for incongruent compared to congruent trials) reflects recruitment of brain regions to support cognitive control processes (Mohades et al., 2014), whereas others have argued that decreased brain activity may reflect more efficient processing (Ansaldo et al., 2015).

In terms of the relationship between structure and behaviour, a number of studies indicate structural brain differences between younger and older monolinguals and bilinguals (although there does not yet appear to be a consensus in terms of brain regions), however, very few of the studies include behavioural tasks. Some researchers have interpreted an increase in white matter connectivity as a bilingual advantage (Luk et al., 2011a; Pliatsikas, Moschopoulou, & Saddy, 2015), while others have interpreted a decrease in values to suggest a bilingual advantage (Cummine & Boliek, 2012; Gold, Johnson, & Powell, 2013a). Without behavioural data, it is not possible to make a connection between increased brain tissue and a bilingual advantage. As pointed out by Garcia-Penton (2016), researchers run the risk of committing a logical fallacy – using structural differences to argue for a bilingual advantage, while also using the bilingual advantage theory to explain language-group differences in structure.

6.7 Limitations

The research included in this dissertation is not without its limitations. Limitations common to both of the studies included factors surrounding data acquisition/participant recruitment. In Manuscript 1, data were acquired from the database of the Jewish Hospital Memory Clinic, and language background information was gathered from the interviews conducted as part of the patients' neuropsychological assessments. As reviewed in Chapter 2 and a number of published commentaries (Bak, 2016; Calvo et al., 2016; Duncan & Phillips, 2016), due to bilingualism's multifaceted nature, objective measures of bilingualism that include information on proficiency, fluency, age of acquisition, and amount of switching between languages would be beneficial to our understanding of what aspects of bilingualism may contribute to cognitive reserve. Access to MRI data from a group of healthy older adults would have also provided us with additional information to help clarify the relationship between cognitive scores and the trajectory of brain atrophy between the two language groups. In

Manuscript 2, as can be seen in our sample sizes, it was difficult to obtain a large number of older adults who met our stringent criteria for monolingualism and bilingualism. Although we consider this a strength of this study, future research could benefit from comparing a diverse range of monolinguals and bilinguals/multilinguals, as it is possible that only certain bilingual/multilingual groups show a bilingual advantage in executive functioning.

As much as we have extolled the need for combining structural, functional, and behavioural measures in one task, we were obviously unable to do so for this particular dissertation. Each of the studies would have benefitted from information from the missing domain. In Manuscript 1, although we analysed information from cognitive tests conducted as part of the neuropsychological assessment, behavioural data from more sensitive cognitive control tasks, as well as functional neuroimaging would have given us a more clear picture of whether the multilingual patients experienced any benefit (or any bilingual processing difference) that correlated with the increased gray matter seen in cognitive control and bilingualism-related brain areas. Similarly, in Manuscript 2, access to structural scans from the younger and older monolinguals and bilinguals would have allowed us to bridge the gap between the two manuscripts, and examine whether the gray matter differences seen in Manuscript 1 were presented in healthy adults.

6.8 Future Directions

The main avenue through which future research would benefit is by working to combine methodology used in both of the bodies of literature reviewed in this dissertation. Prospective longitudinal studies, ideally large-scale and multi-national would be able to address a number of the unanswered questions. As reviewed in an upcoming chapter (Duncan, Chauvin & Phillips, in press), the challenge for bilingualism researchers is to ensure that detailed and relevant measures of language history be included in current and ongoing data collection protocols. Studies from the cognitive reserve perspective would benefit from collecting functional and behavioural data from executive functioning tasks, while studies from the bilingual advantage perspective would benefit from including structural information as well as detailed information on memory abilities in aging. Furthermore, given the relationship between executive functioning and the ability to function independently, and the relationship between independent functioning and poor outcomes (Cahn-Weiner et al., 2000; J. K. Johnson, Lui, & Yaffe, 2007), the study of a potential bilingual benefit in activities of daily living would be of both theoretical and practical benefit.

6.9 Conclusion

In conclusion, our data contribute to the growing literature suggesting that speaking more than one language may result in subtle changes in the function and structure of the brain. Manuscript 1 demonstrated that multilingual MCI and AD patients show structural brain differences compared to monolinguals matched on cognitive functioning, age, and education. We demonstrated that multilinguals showed a correlation between memory functioning and gray matter in areas related to bilingualism. Manuscript 2 showed that there were differences in brain functioning between younger and older monolingual and bilingual adults when performing cognitive control tasks, but that these differences did not result in a bilingual advantage in behavioural data. The results here support the hypothesis that speaking more than one language results in neural compensation, wherein bilinguals are able to use alternate networks to support compromised memory processing. Findings from the current manuscripts have implications for research outside the area of bilingualism, as they contribute to our general understanding of cognitive aging, compensatory processing, neuroplasticity, and cognitive reserve.

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Appendix A

Supplementary Materials Manuscript 1

A.1. World coordinates and Brodmann area numbers for: current study Family 1 ROIs and ROIs from supporting researching.

Anatomical location	**Hemisphere**	**Coordinates**	**BA**
A) Inferior frontal gyrus			
Current study	L	-49, 27, 20	45
Current study	R	55, 30, 0	45
(D. Klein et al., 2014)	L	-25, 25, 20	- (47)
(D. Klein et al., 2014)	R	30, 20, -9	- (13)
B) Anterior temporal gyrus			
Current study	L	-51, -10, -40	20
Current study	R	55, 5, -31	21
(Abutalebi et al., 2014)	L	-45, -4, -36	- (21/20)
(Abutalebi et al., 2014)	R	-	-
C) Medial superior frontal gyrus (ACC)			
Current study	L	-6, 31, 41	8
(Abutalebi, Guidi, Borsa, Canini, Rosa, Parris, et al., 2015b)	L	-	-
(Abutalebi, Guidi, Borsa, Canini, Rosa, Parris, et al., 2015b)	R	5, 38, -8	- (24)
D) Inferior parietal lobule			
Current study	L	-39, -69, 47	39
(Mechelli et al., 2004)	L	-45, -59, 48	- (40/39)
(Mechelli et al., 2004)	R	56, -53, 42	- (40/39)
(Abutalebi, Canini, Rosa, Green, & Weekes, 2015a)	L	-48, -59, 47	- (40/39)
(Abutalebi, Canini, Rosa, Green, & Weekes, 2015a)	R	56, -53, 42	- (40/39)
E) Supramarginal gyrus			
Current study	L	-59, -26, 35	40
Current study	R	62, -37, 40	40
(Grogan et al., 2012)	L	-50, -50, 46	- (40/39)

(Grogan et al., 2012)	R	44, -54, 52	- (40/39)
F) Cerebellum			
Current study	L	-39, -59, -29	*n/a*
Current study	R	41, -55, -31	*n/a*
Current study	R	7, -49, -49	*n/a*
(Pliatsikas et al., 2014)	L	-22, -92, -30	*n/a*
(Pliatsikas et al., 2014)	R	26, -86, -46	*n/a*
(Pliatsikas et al., 2014)	R	18, -44, -20	*n/a*
G) Ventromedial prefrontal cortex			
Current Study	R	3, 44, -15	11/32
(Abutalebi et al., 2014)	L	-	-
(Abutalebi et al., 2014)	R	-	-
H) Putamen			
Current study	*n/a*	*n/a*	*n/a*
(Abutalebi et al., 2013)	L	-	-
I) Heschl's gyrus			
Current study	*n/a*	*n/a*	*n/a*
(Ressel et al., 2012)	L	-52, -13, 5	- (22/41)
(Ressel et al., 2012)	R	-	-

Notes: BA = Brodmann's area; L = left; R = right; - = information not provided in study; () = BA provided by current authors. BA determined using Mango version 3.17 (http://rii.uthscsa.edu/mango/) and mni2tal (http://sprout022.sprout.yale.edu/mni2tal/mni2tal.html).

Table A.2. Group means and standard errors for cortical thickness and tissue density values.

			MCI				AD			
			Mono (n=34)		Multi (n=34)		Mono (n=13)		Multi (n=13)	
			M	*SE*	M	*SE*	M	*SE*	M	*SE*
ROI	Family	Coordinates	Gray Matter Density Values							
L Hippo	2	-30, -20, -19	0.71	0.01	0.75	0.01	0.64	0.03	0.69	0.02
R Hippo	2	32, -20, -20	0.71	0.01	0.75	0.01	0.62	0.03	0.68	0.02
L Rhin sulcus	2	-28, -19, -25	0.59	*0.02*	0.64	*0.02*	0.66	*0.02*	0.60	*0.03*
R Rhin sulcus	2	30, -12, -30	0.58	*0.02*	0.61	*0.02*	0.60	*0.02*	0.54	*0.02*
L pPHC	2	-25, -31, -11	0.56	*0.01*	0.59	*0.01*	0.57	*0.03*	0.51	*0.02*
R pPHC	2	26, -33, -10	0.59	*0.01*	0.63	*0.01*	0.60	*0.02*	0.53	*0.01*
L Cer	1	-39, -58, -30	0.69	0.02	0.74	0.01	0.65	0.02	0.70	0.03
R Cer	1	41, -55, 31	0.66	0.02	0.70	0.01	0.58	0.02	0.67	0.02
R cerTon	1	7, -49, -49	0.46	0.01	0.54	0.02	0.49	0.02	0.55	0.02
Putamen*	1	-								
Heschl's gyrus*	1	-								

			MCI				AD			
			Mono (n=34)		Multi (n=34)		Mono (n=13)		Multi (n=13)	
			M	*SE*	M	*SE*	M	*SE*	M	*SE*
ROI	Family	Coordinates	Cortical Thickness in mm							
L IFG	1	-49, 27, 20	2.69	*0.04*	2.83	*0.04*	2.60	*0.08*	2.65	*0.08*
R IFG	1	55, 30, 0	3.05	*0.05*	3.22	*0.05*	2.97	*0.06*	3.21	*0.10*
L mSFG	1	-6, 31, 41	3.46	*0.05*	3.60	*0.05*	3.39	*0.07*	3.52	*0.07*

R vmPFC	1	3, 44, -15	3.08	*0.05*	3.27	*0.04*	2.96	*0.06*	3.10	*0.08*
L aTG	1	-51, -10, -40	3.13	*0.07*	3.36	*0.06*	2.83	*0.10*	3.07	*0.14*
R aTG	1	55, 5, -31	3.18	*0.07*	3.36	*0.07*	2.83	*0.13*	3.17	*0.10*
L IPL	1	-39, -69, 47	2.71	*0.05*	2.89	*0.05*	2.61	*0.07*	2.69	*0.08*
L SMG	1	-59, -26, 35	2.89	*0.04*	3.04	*0.05*	2.96	*0.05*	2.83	*0.06*
R SMG	1	62, -37, 40	2.97	*0.06*	3.10	*0.05*	3.04	*0.14*	2.84	*0.08*
L VAC	ph	-10, -98, 15	2.36	*0.04*	2.59	*0.05*	2.46	*0.11*	2.29	*0.06*

* not included as no value exceeded threshold of t>2.00 in the global regression analyses
Notes: aTG = anterior temporal gyrus; Cer = cerebellum; cerTon = cerebellar tonsil; Hippo = hippocampus; IFG = inferior frontal gyrus; IPL = inferior parietal lobule; L = Left; mSFG = medial superior frontal gyrus; pPHC = posterior parahippocampal cortex; Rhin = rhinal; R = Right; SMG = supramarginal gyrus; vmPFC = ventromedial prefrontal cortex

Appendix B

Supplementary Materials Manuscript 2

Sample Stimuli

Simon task: "Please respond with a left button press if the stimulus is blue, and a right button press if the stimulus is red"

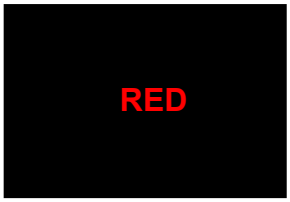
Neutral

Congruent

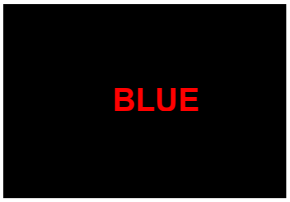
Incongruent

Stroop task: "Please name the colour of the print, do not read the word" or "please indicate the colour of the print using the corresponding button"

Neutral

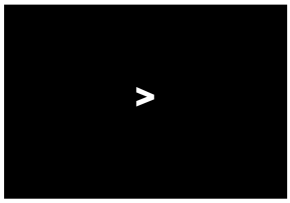


Congruent

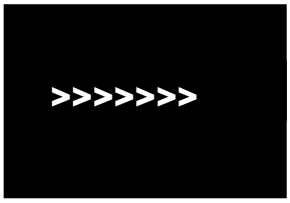


Incongruent

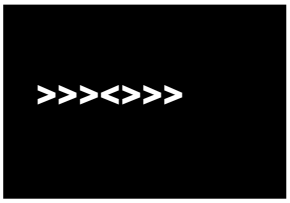
Eriksen flanker task: "Please indicate the direction of the central arrowhead. Use the left button if the arrowhead is pointing to the left and the right button if the arrow is pointing to the right"



Neutral



Congruent



Incongruent

Table B.1.

Demographic Information for Participant Groups, for the Stroop, Simon, and Eriksen tasks.

	YM	YB		OM	OB	
Stroop	(n = 25)	(n = 26)		(n = 14)	(n = 14)	
	M *(SD)*	M *(SD)*	*p*	M *(SD)*	M *(SD)*	*p*
Age	23.8 *(4.7)*	24.5 *(3.4)*	*.53*	72.5*(5.8)*	69.7 *(4.6)*	*.17*
Years Education	15.4 *(1.5)*	15.6 *(1.1)*	*.52*	15.0 *(3.6)*	15.4 *(3.8)*	*.80*
MoCA	28.2 *(1.3)*	28.4 *(1.3)*	*.72*	27.5 *(1.6)*	27.6 *(1.8)*	*.83*
L1 self-reported	5.0 *(0.0)*	4.9 *(0.2)*	*.20*	5.0 *(0.0)*	4.9 *(0.3)*	*.12*
L2 self-reported	n/a	4.6 *(0.4)*	*n/a*	1.4 *(0.7)*	4.3 *(0.5)*	*<.01*
L1 CV	n/a	.24 *(.08)*	*n/a*	.25 *(.07)*	.23 *(.08)*	*.48*
L2 CV	n/a	.25 *(.09)*	*n/a*	.31 *(.09)*	.24 *(.07)*	*.05*
	YM	YB		OM	OB	
Simon	(n = 24)	(n = 26)		(n = 17)	(n = 18)	
	M *(SD)*	M *(SD)*	*p*	M *(SD)*	M *(SD)*	*p*
Age	23.8 *(4.8)*	24.5 *(3.4)*	*.57*	71.9 *(6.9)*	68.9 *(5.5)*	*.15*
Years Education	15.3 *(1.5)*	15.6 *(1.1)*	*.48*	15.1 *(3.6)*	15.8 *(3.2)*	*.54*
MoCA	28.3 *(1.3)*	28.4 *(1.3)*	*.83*	27.6 (1.5*)*	27.4 *(1.8)*	*.80*
L1 self-reported	5.0 *(0.0)*	4.9 *(0.2)*	*.20*	5.0 *(0.0)*	4.9 *(0.2)*	*.19*
L2 self-reported	n/a	4.6 *(0.4)*	*n/a*	1.5 *(0.7)*	4.4 *(0.5)*	*<.01*
L1 CV	n/a	.24 *(.08)*	*n/a*	.27 *(.08)*	.24 (.09*)*	*.36*
L2 CV	n/a	.25 *(.09)*	*n/a*	.30 *(.09)*	.25 *(.07)*	*.07*
Eriksen	YM	YB		OM	OB	
	(n = 24)	(n = 26)		(n = 16)	(n = 18)	
	M *(SD)*	M *(SD)*	*p*	M *(SD)*	M *(SD)*	*p*
Age	23.8 *(4.8)*	24.5 *(3.4)*		71.3 *(6.4)*	68.7 *(5.5)*	*.23*
Years Education	15.3 *(1.5)*	15.6 *(1.1)*		15.4 *(3.5)*	15.3 *(3.4)*	*.97*
MoCA	28.3 *(1.3)*	28.4 *(1.3)*		27.6 *(1.5)*	27.4 *(2.0)*	*.78*
L1 self-reported	5.0 *(0.0)*	4.9 *(0.2)*		5.0 *(0.0)*	4.9 *(0.3)*	*.09*
L2 self-reported	n/a	4.6 (0.4)		1.5 (0.7)	4.3 (0.5)	*<.01*
L1 CV	n/a	.24 *(.08)*		.26 (.09)	.24 *(.09)*	*.41*
L2 CV	n/a	.25 *(.09)*		.30 (.09)	.25 *(.06)*	*.12*

Table B.2

ANOVA Results: Evoked Power during the Stroop Task

	F	df	*p*	dir.
Theta 100-300				
Age Group	14.414	1, 75	*<.001*	Y>O
Language Group	0.237	1, 75	*.628*	
Age Group x Language Group	0.307	1, 75	*.581*	
Trial Type	6.721	1, 75	*.011*	C>I
Trial Type x Language Group	0.319	1, 75	*.574*	
Trial Type x Age Group	0.282	1, 75	*.597*	
Age Group x Language Group x Trial Type	0.056	1, 75	*.814*	
Age Group x Language Group x Trial Type x S-ROI*	2.297	1.5, 150	*.118*	
Alpha 100-300				
Age Group	37.742	1, 75	*<.001*	Y>O
Language Group	0.855	1, 75	*.358*	
Age Group x Language Group	1.194	1, 75	*.278*	
Trial Type	1.291	1, 75	*.259*	
Trial Type x Language Group	0.144	1, 75	*.706*	
Trial Type x Age Group	0.015	1, 75	*.903*	
Age Group x Language Group x Trial Type	0.899	1, 75	*.346*	
Age Group x Language Group x Trial Type x S-ROI*	0.240	1.7, 150	*.754*	

Table B.3.

ANOVA Results: Evoked Power during the Simon Task

	F	df	*p*	dir.
Theta 100-300				
Age Group	16.537	1, 81	*<.001*	Y>O
Language Group	0.133	1, 81	*.717*	
Age Group x Language Group	1.010	1, 81	*.318*	
Trial Type	1.863	1, 81	*.176*	
Trial Type x Language Group	<0.1	1, 81	*.983*	
Trial Type x Age Group	1.719	1,81	*.193*	
Age Group x Language Group x Trial Type	0.532	1,81	*.468*	
Age Group x Language Group x Trial Type x S-ROI*	0.649	1.6, 162	*.494*	
Alpha 0-200				
Age Group	4.574	1,81	*.035*	Y>O
Language Group	1.832	1,81	*.180*	
Age Group x Language Group	2.661	1,81	*.107*	
Trial Type	7.447	1,81	*.008*	I>C
Trial Type x Language Group	1.792	1,81	*.184*	
Trial Type x Age Group	1.086	1,81	*.300*	
Age Group x Language Group x Trial Type	2.706	1,81	*.104*	
Age Group x Language Group x Trial Type x S-ROI*	1.506	1.7, 162	*.227*	

Table B.4.

ANOVA Results: Evoked Power during the Eriksen Task

	F	df	*p*	dir.
Theta 100-300				
Age Group	4.194	1,80	*.044*	Y>O
Language Group	1.424	1,80	*.236*	
Age Group x Language Group	1.574	1,80	*.213*	
Trial Type	<0.1	1,80	*.988*	
Trial Type x Language Group	2.870	1,80	*.094*	
Trial Type x Age Group	0.118	1,80	*.732*	
Age Group x Language Group x Trial Type	0.387	1,80	*.536*	
Age Group x Language Group x Trial Type x S-ROI*	3.964	1.6, 160	*.030*	
Alpha 0-200				
Age Group	3.204	1,80	*.077*	
Language Group	2.857	1,80	*.095*	
Age Group x Language Group	0.393	1,80	*.533*	
Trial Type	.302	1,80	*.584*	
Language Group X Trial Type	1.108	1,80	*.316*	
Age Group x Trial Type	1.716	1,80	*.194*	
Age Group x Language Group x Trial Type	0.013	1,80	*.909*	
Age Group x Language Group x Trial Type x S-ROI*	1.413	1.5, 160	*.246*	

Table B.5.

ANOVA Results: Induced Power during the Stroop Task

	F	df	*p*	dir.
Theta 400-600				
Age Group	14.918	1,75	*<.001*	Y>O
Language Group	0.486	1,75	*.488*	
Age Group x Language Group	0.016	1,75	*.900*	
Trial Type	16.017	1,75	*<.001*	I>C
Trial Type x Language Group	0.014	1,75	*.906*	
Trial Type x Age Group	<.01	1,75	*1.0*	
Age Group x Language Group x Trial Type	1.100	1,75	*.298*	
Age Group x Language Group x Trial Type x S-ROI*	0.105	1.6,150	*.855*	
Beta 400-800				
Age Group	1.154	1,75	*.286*	
Language Group	0.069	1,75	*.793*	
Age Group x Language Group	0.048	1,75	*.827*	
Trial Type	29.093	1,75	*<.001*	C>I
Language Group X Trial Type	0.146	1,75	*.704*	
Age Group x Trial Type	1.660	1,75	*.202*	
Age Group x Language Group x Trial Type	0.134	1,75	*.715*	
Age Group x Language Group x Trial Type x S-ROI*	0.933	1.6, 150	*.378*	

Table B.6.

ANOVA Results: Induced Power during the Simon Task

	F	df	*p*	dir.
Theta 200-400				
Age Group	14.272	1, 81	<.001	Y>O
Language Group	0.012	1, 81	.911	
Age Group x Language Group	0.600	1, 81	.441	
Trial Type	19.786	1, 81	<.001	I>C
Trial Type x Language Group	0.049	1, 81	.825	
Trial Type x Age Group	7.713	1,81	.007	C: Y=O I: Y>O
Age Group x Language Group x Trial Type	0.621	1,81	.433	
Age Group x Language Group x Trial Type x S-ROI*	0.319	1.4,162	.646	
Beta 400-600				
Age Group	19.411	1,81	<.001	O>Y
Language Group	0.001	1,81	.970	
Age Group x Language Group	0.070	1,81	.792	
Trial Type	13.645	1,81	<.001	C>I
Trial Type x Language Group	2.936	1,81	.090	
Trial Type x Age Group	0.848	1,81	.360	
Age Group x Language Group x Trial Type	0.044	1,81	.835	
Age Group x Language Group x Trial Type x S-ROI*	0.515	1.5, 162	.547	

Table B.7.

ANOVA Results: Induced Power during the Eriksen Task

	F	df	*p*	dir.
Beta 400-600				
Age Group	6.832	1,80	*.011*	O>Y
Language Group	1.739	1,80	*.191*	
Age Group x Language Group	1.132	1,80	*.291*	
Trial Type	3.026	1,80	*.086*	
Trial Type x Language Group	0.016	1,80	*.899*	
Trial Type x Age Group	3.375	1,80	*.070*	
Age Group x Language Group x Trial Type	0.004	1,80	*.952*	
Age Group x Language Group x Trial Type x S-ROI*	0.710	1.6, 160	*.463*	