University of Reading

CHANGING OUR BRAINS AND MINDS: EXPLORING THE EFFECTS OF INDIVIDUAL DIFFERENCES IN BILINGUAL LANGUAGE EXPERIENCE ON BRAIN STRUCTURE, FUNCTION, AND COGNITION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

School of Psychology and Clinical Language Sciences

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DEDICATION

To my parents- you have been the major source of not only guidance and support, but also inspiration, from the very beginning of childhood. I owe much of where I am today to you.

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Vincent F. DeLuca

31st of July 2018, Reading, United Kingdom

DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Vincent F. DeLuca

The work in Chapters 2-5 is either published or submitted for publication. These are as follows:

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ABSTRACT

Current research suggests that bilingualism affects both the structure of the brain and several cognitive processes. However, few studies have specifically examined effects of individual differences in bilingual language use on domain-general control processes and their neural correlates. This thesis project assesses the hypothesis that specific language use factors within the bilingual experience will alter neural activity and plasticity in regions implicated in language/executive control. Three studies are run. The first study is longitudinal, examining effects of long-term linguistic immersion on neural plasticity in highly proficient non-native (L2) speakers of English. Data from this study shows adaptations in brain structure related to increased efficiency of language processing and control and modulated by the length of L2 use prior to the study. The second and third studies are cross-sectional, examining effects of specific language use factors on 1) neural structure and intrinsic functional connectivity and 2) performance and neural activation patterns on executive function tasks. Factors related to duration of L2 use correlate to neurocognitive adaptations suggesting increased efficiency in language control. Factors related to extent of L2 use correlate to neurocognitive adaptations suggesting increased language control demands. Considered together, the data suggest that the brain constantly strives to be maximally effective and efficient in language processing control, which in turn affects domain-general cognitive processes. Crucially, the data highlight the necessity of considering specific, individual language experiences in assessing neurocognitive effects of bilingualism.

CHAPTER 1: INTRODUCTION

Over the past two decades, there has been a substantial increase in research covering the effects of bilingualism on the mind/brain. Bilingual language use has been found to have several implications for both brain structure and function (P. Li, Legault, & Litcofsky, 2014; Pliatsikas & Luk, 2016), but also several domain-general cognitive processes, specifically the executive functions (Bialystok, 2017; Luk, Bialystok, Craik, & Luk, 2012). However, the specific effects of bilingualism on these processes has come to the forefront of debate in recent years (Bialystok, 2016; R. M. Klein, 2014; Paap, Johnson, & Sawi, 2015a; Titone & Baum, 2014), in no small part due to inconsistencies in results found across studies both in terms of cognitive (Valian, 2015a) and neurological effects (García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2016b). While several calls have been made to address these discrepancies, one often overlooked variable is that of bilingualism itself. Bilingualism is often operationalized as a categorical or binary variable (that is, one ‘is’ or ‘is not’ bilingual) and is compared to a matched monolingual baseline (Luk & Bialystok, 2013). Bilingualism is a complex and dynamic process with a range of factors which have the potential to drive and differentially affect neurocognitive adaptations. However, very few studies to date have comprehensively examined individual differences in language experience and their respective effects on brain structure, function, and cognition, or how these are modulated with changes to language use. The goal of this thesis, then, is to move practice in the field away from traditional categorical (e.g. ‘bilingual’ vs ‘monolingual’) designs and instead towards individual differences approach in assessing the neurocognitive effects of bilingualism.

1.1 Cognitive and neurophysiological effects of bilingualism

The mechanisms behind the relationship between bilingualism and neurocognitive change are thought to be a result of the way the brain stores and uses the languages at one's disposal. It is argued that the languages one uses are constantly, jointly active in the mind/brain, which creates a state of competition for selection in language processing and production (Bialystok, Craik, Green, & Gollan, 2009; Kroll, Dussias, Bice, & Perrotti, 2015). Proposals such as the Inhibitory Control model (Green & Eckhardt, 1998), and the Bilingual Interactive Activation model (van Heuven, Dijkstra, & Grainger, 1998) state that all but one of the two (or more) languages must be inhibited for the speaker to engage in a conversational situation. More recently, the notion of inhibition has been revised to a view of constant activation of both languages, which creates conflict that must be resolved for successful language processing and production to occur (Abutalebi & Green, 2007; Kroll, Dussias, Bogulski, & Kroff, 2012; Luk et al., 2012). Resolving this competition confers increased demands on the neurocognitive systems involved in language processing, production, and control. The brain is thought to adapt at both the functional and structural level to more effectively handle the increased demands of bilingual language control (see for review Li et al., 2014; Pliatsikas, 2019). These adaptations have implications for a host of linguistic and non-linguistic cognitive processes including lexical retrieval, vocabulary size, domain-general cognitive processes (Bialystok, 2009). A subset of these- the executive functions- have garnered a large amount of research attention (for review see Bialystok, 2009; Bialystok, Craik, Green, & Gollan, 2009), and will be one of the primary foci of this thesis.

For the remainder of this introduction I review existing evidence covering the neurocognitive effects of bilingualism and address the inconsistencies in the literature. I will then offer how this thesis will use bilingualism as a continuum of experiences which drive neurocognitive adaptions to help shed light on the current debates and understanding in the field.

1.1.1 Executive Functions

Executive functions are an overarching term for several cognitive processes which are applicable to given contexts but generally refer to the ability of the brain to regulate and control information processing and direct behavior towards an intended goal (Braver, 2012; Diamond, 2013; Haas & Keel, 2001; Miyake & Friedman, 2012; Niendam, Laird, Ray, Dean, & Carter, 2013). Miyake and colleagues propose three main subsets of executive functions: 1) ‘shifting’, or switching between mental sets and tasks, 2) ‘updating’, or maintaining and updating working memory representations, and 3) ‘inhibition’, that is controlling dominant or prepotent responses (Miyake et al., 2000; Miyake & Friedman, 2012). The Dual Mechanisms of Control (DMC) Framework (Braver, 2012) argues that executive functions can be broken down into two general types- proactive and reactive control. Proactive control refers to maintenance of goal-relevant information during a cognitively demanding event, to maintain optimal bias to the goal/positive outcome. By contrast, reactive control refers to quickly re-directed attention when an event interferes with a goal. The use of either type of control is dictated by several factors including environmental demands and internal differences.

A number of tests have been designed to measure one’s capacity for executive function (Soveri et al., 2018). These tests are designed to elicit specific responses from participants regarding stimuli presented to them. Typically, reaction time (the time from stimulus presentation to response) and accuracy (whether the target answer is given or not) are recorded. In addition to the target stimulus, other information, spatial, descriptive, or otherwise, is also presented. Information that facilitates a correct response, known as a congruent stimulus, indicates a decreased cognitive load which is also referred to as facilitation (see e.g. Luk, Anderson, Craik, Grady, & Bialystok, 2010). Where potentially conflicting information is present (incongruency), the cognitive load is increased compared to congruent or baseline stimuli, which is referred to as a ‘cost’. In executive function tasks, this manifests as either higher reaction time to a target (incongruent) stimulus over a baseline (congruent or neutral) stimulus, or lower accuracy rates for the incongruent stimulus. Several tasks are commonly used in the field at present. The Flanker Task (Eriksen & Eriksen, 1974) is one such task. Participants are presented with a target arrow and must indicate its direction (left or right). Additional arrows are presented on either side of the target arrow, and either align in the same direction (congruent) or point in the opposite direction (incongruent). A neutral condition using a non-associative shape (e.g. diamonds) is also presented, along with a control condition in which the target arrow is presented alone. This task is thought to primarily test interference suppression (ignoring of irrelevant information) and facilitation (use of helpful information) effects, although some manipulations of the task have also allowed to test the capacity to inhibit prepotent responses (response inhibition) with additions of other cues (see e.g. Luk et al., 2010). The Attentional Network Task (ANT) (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005) is a variant on the flanker task, but also includes cues for both time and location of the target stimuli to tap into the ability of participants to respond to these in addition to conflict monitoring and interference suppression. The Simon Task is another widely used test. It uses color and screen position of an object to facilitate or interfere with decision making (Simon & Wolf, 1963). The color of a presented object will cue pressing ‘left’ or ‘right’ (e.g. a green button for left and a blue button for right). The object will appear on either the left or right side of the screen giving rise to either facilitative (same side of the screen as color’s target direction) or interfering (different side of the screen to the target direction of the color). This task is thought to assess both working memory and interference suppression. Another test is the AX- Continuous Performance Task (AX-CPT) (Green & Eckhardt, 1998). This is a letter sequence paradigm in which a given cue letter (A or B) is presented followed later in a sequence by a target letter which is either congruent (X or Y, respectively) or incongruent (any other letter) to the cue letter. This task is thought to tap into both response inhibition and aspects of working memory.

1.1.2 Cognitive Effects of bilingual language use- significant, mixed, and null effects

A large body of literature has shown positive effects of bilingualism on domain-general cognitive processes (for review see Bialystok, 2017). Indeed, behavioral evidence from several studies supports the notion that speaking an additional language has positive impacts on aspects of executive control throughout the lifespan. Evidence for these effects has historically come from studies comparing a group, or groups, of bilingual participants to a monolingual control group. Any cognitive differences found between the groups in terms of task performance is thought to then stem from speaking additional language(s). Studies which find significant differences between bi- and monolinguals typically test either children (Bialystok & Viswanathan, 2009; Carlson & Meltzoff, 2008; Grundy & Keyvani Chahi, 2017; Martin-Rhee & Bialystok, 2008; Poarch & van Hell, 2012; Tse &

Altarriba, 2014) or older adults (Bak, Nissan, Allerhand, & Deary, 2014; Bialystok, Craik, Klein, & Viswanathan, 2004), although some report significant differences between bi- and monolinguals in testing young adults as well (Costa, Hernández, & Sebastián-Gallés, 2008; Kerrigan, Thomas, Bright, & Filippi, 2016; Vega-Mendoza, West, Sorace, & Bak, 2015; Zhou & Krott, 2018). Two illustrative examples of such studies are discussed in detail here.

A study by Prior & Macwhinney (2010) examined effects of bilingualism on global switching processes. Ninety-two participants participated in the experiment (45 monolingual, 47 bilingual). All were university undergraduate students and were matched for vocabulary and spatial reasoning. Bilingual participants were either simultaneous or sequential L2 English (AoA before 6). All completed a task switching paradigm, in which they had to indicate either the color or shape of an object presented to them, the mixed block design required either to be chosen. They indicated shape with the left hand and color with the right. Bilinguals were found to have lower switching costs than monolinguals, with respect to reaction time (both groups performed at ceiling for accuracy >95%). The authors interpret the difference in reaction time as an increase in efficiency with task switching as an effect of bilingual language use. Other studies find differences in conflict monitoring. An example of this is the study by Costa, Hernández, & Sebastián-Gallés (2008) which used the ANT to examine differences in several cognitive control processes as an effect of bilingualism. Bilingual (n=100) and monolingual (n=100) participants were tested. The large sample size was selected to help keep the population robust against typical confounding factors such as intelligence, task motivation, and others. All participants were undergraduate university students from various regions of Spain (average age 22). The bilingual participants were Catalan dominant, and were early L2 Spanish speakers, and had varying amounts of daily exposure to each language. The monolingual participants were not functionally fluent in any second language, but all likely had some level of exposure to other languages. Bilinguals had faster RTs than monolinguals across all trial types, exhibited lower interference cost in incongruent trials and lower switching costs and took more advantage of the alerting cue. The authors conclude that the bilingual experience has a positive effect on domain general cognitive function.

However, such findings are not consistent across studies. Others only find significant modulations of effects by bilingual language use in only in specific aspects or subsections of given tasks (Calabria, Branzi, Marne, Hernández, & Costa, 2013; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Hernández, Martin, Barceló, & Costa, 2013; Morales, Gómez-Ariza, & Bajo, 2013; Prior & Gollan, 2013). Two key examples of such studies are discussed in further detail.

One example of mixed findings is that of a follow-up study by Costa and colleagues (Costa et al., 2009), who examined the effect of bilingualism on executive functions in young adults using the (ANT). Crucially, they manipulated the ratio of congruent and incongruent trials. Experiment 1 had either 8% or 92% congruent trials (low monitoring), whereas Experiment 2 had either 25% or 50% congruent trials (high monitoring). Bilinguals and monolinguals were only found to differ on the high-monitoring task, with bilinguals outperforming monolinguals in RT across trials. No difference was found between groups on the low monitoring task. Another study (Hernández et al., 2013) explored the effect of bilingualism on various task switching mechanisms, via three experiments on Spanish monolinguals and highly proficient, balanced Spanish-Catalan bilinguals. Experiment 1 was a matching task. A series of cards was presented to the participants and they were asked to classify them by either color or shapes as quickly as possible. Classification would either remain constant or switch. Bilinguals outperformed the monolinguals on the switch cost only in this experiment. Experiment 2 was a matching task between a cue and picture, the combination of which was designed to elicit a specific button press. This time, switching costs were present for all types of trials. Bilinguals were overall faster than monolinguals, however the magnitude of the switch cost was equivalent in both groups. Experiment 3 was a replication of a task-switching paradigm from Prior & Macwhinney, (2010). Bilinguals and monolinguals showed similar processing costs (mixing and switching).

A number of other studies do not find the predicted effects of bilingualism (Antón et al., 2014; Antón, Fernández García, Carreiras, & Duñabeitia, 2016; Duñabeitia et al., 2014; Gathercole et al., 2014; Kirk, Fiala, Scott-Brown, & Kempe, 2014; Morton & Harper, 2007; Paap et al., 2017; Paap, Johnson, & Sawi, 2014; Ramos, Fernández García, Antón, Casaponsa, & Duñabeitia, 2017). Two poignant examples are discussed in detail.

A study by Paap and Greenberg was one of the earliest to directly challenge the notion of an effect of bilingualism on executive functions at all (Paap & Greenberg, 2013). The authors present results from three different experiments, all of which were assessing the impact of bilingualism on executive control on young adults. Questionnaires and rating scales were used to threshold classification of bilingual or monolingual. Participants were also matched for intelligence. All three experiments employed the Simon Task and a color-shape switching protocol. The third experiment also employed the Flanker task. The congruency effects for the Simon task were not significantly different between bilinguals and monolinguals in any of the experiments. The results were not seen to be affected after controlling for parents' education levels, SES, and proficiency in respective languages. Regarding the Flanker task, the results found here were broadly similar, in that no distinct differences were seen between groups. The authors discuss various reasons behind this set of results, but generally conclude that the bilingual experience does not affect executive functions to the capacity it is so claimed.

Duñabeitia et al. (2014) called into question the bilingual advantage in children. 504 children from various elementary and high schools in the local area were tested (252 monolingual and 252 bilingual). The bilingual children were all Spanish-Basque, with a mean AoA of 2.77yrs for Basque. They were all Spanish-dominant and were educated in a bilingual setting. All testing took place in the Basque country. The monolingual children were all native Spanish speakers. All children were tested in similar surroundings with the same equipment. Two different tasks were run: a standard Stroop task (color of letters and semantic color are the same or different) and a numerical Stroop task (in which numbers which differed in physical size and magnitude respectively, and the participants had to pick the number of larger magnitude), to ensure that lexical access (known to be slower for bilinguals (see Bialystok, 2009)) would not necessarily conflate with interference suppression processes. For both tasks, no differences were found between groups for task performance. Furthermore, regressions of bilingual performance with Likert-scale measures of proficiency (etc.), showed no significant trends. The authors are cautious not to make many implications given their results but do say this reinforces a notion that the bilingual advantage is not so clear cut as to what cognitive differences stem from speaking an additional language.

1.1.3 The ‘bilingual advantage’ debate and conflating issues

As is becoming clear, inconsistency of behavioral effects related to bilingualism exists between studies. This inconsistency comes in two forms: 1) how an effect manifests within a task (e.g. accuracy (Morales et al., 2013), reaction time for a specific contrast (Hernández et al., 2013) or across all conditions on a given task (Hilchey & Klein, 2011)) and 2) whether an effect manifests at all (Antón et al., 2014; Paap, Johnson, et al., 2014).

The lack of replication of a consistent bilingual effect across studies has invited several discussions as to why this may be the case. Some use this inconsistency to actively argue against the notion of any bilingual advantage (Goldsmith & Morton, 2017; R. M. Klein, 2014; Paap et al., 2015a; Paap, Johnson, & Sawi, 2015b; Paap, Johnson, et al., 2014). Some have put forth the argument that, as significant results tend to be published more often than null results, the effect of bilingualism found in the field is a result of publication bias (de Bruin, Treccani, & Della Sala, 2015). Paap and colleagues argue any positive effect of bilingualism on executive function task performance is likely a by-product of poorly controlled experimental factors, statistical measures used, and insufficient sample sizes. They further claim that if the bilingual experience does confer effects within executive functions, it does so in isolated instances and is likely mitigated by other factors (Paap et al., 2015a). Furthermore, they consider further research in this area to be unnecessary given that differences found are a result of experimental variability (Paap et al., 2015b).

The above arguments have drawn heavy criticism from others on two fronts. First, it is rightfully noted that in any instance of study failure to find an effect or differences between groups means only that; crucially, it does not necessarily mean that the underlying (neurocognitive) effect does not exist (Bialystok, 2016). Second, failure to replicate an effect does not automatically disqualify the findings of those who do find it but should warrant further discussion or research on what is causing the disparity (see e.g. Valian, 2015b).

Other calls have been made to further examine what other underlying mechanisms may be driving this effect, and any variability in their effects. One line of inquiry is about the tests employed. It is argued that the test-retest reliability of a number of the standard executive function tasks employed in the field is not optimal (e.g. Soveri et al., 2018). Furthermore, it is noted that many of the tasks are ‘impure’, in that they may tap into several cognitive processes at once, which further obscures what cognitive processes bilingual language use is affecting (Valian, 2015a). Other arguments caution that methods used for statistical analysis (e.g. removal of values beyond 2 standard deviations from group mean RTs can artificially remove effects of bilingualism, given how differences in task performance distribute across bilinguals and monolinguals (Zhou & Krott, 2015, 2018). Others still have made arguments for reverse causality in the effects of bilingualism; that is, higher executive control capacity allows for a more effective/efficient acquisition and use of an additional language (Cox et al., 2016).

What can be taken from the inconsistency in the literature is that the effect of bilingualism on cognitive function is clearly nuanced and as such should be examined with more fine-grained measures. Performance within tests of executive function offer only one aspect of several possible neurocognitive adaptations. Two directions in research can aid in the understanding of the nature of the effect of bilingual language use. The first is research on the neural adaptations to bilingual language control; specifically, how these neurocognitive adaptations manifest and what implications these adaptations have for domain-general cognitive processes (Buchweitz & Prat, 2013; Marie & Golestani, 2017). Second, several have argued that bilingualism should be re-examined as a continuum on which a variety of experience-based factors place individuals (e.g. Bak, 2016; Luk & Bialystok, 2013; Yang, Hartanto, & Yang, 2016), although only a handful of studies have taken this route in research. Both directions are discussed in the following sections.

1.2 Neurophysiological effects of bilingualism

As we have discussed in the previous section, cognitive differences within the behavioral literature are mainly based on reaction time and accuracy. While potentially useful, they only demonstrate one potential outcome of the neurocognitive impacts of bilingual language use. Neuroimaging methods have been used increasingly in the past decade to better understand the pattern of effects of bilingualism on both neurocognitive processes and neuroanatomy (see for review Calabria, Costa, Green, & Abutalebi, 2018; P. Li et al., 2014; Pliatsikas, 2019; Pliatsikas & Luk, 2016).

1.2.1 Background- the neuroanatomy of language processing and control

A number of brain regions and pathways implicated in language processing and control functions are known to be affected by bilingual language use (Abutalebi & Green, 2016; Pliatsikas, 2019). Specifically, adaptations are seen in the functional recruitment and/or morphology of these regions to more effectively accommodate the changing neurocognitive demands of bilingual language use. However, before discussing the significance of neuroanatomical adaptations to bilingualism, it is useful to first delineate the general architecture of the brain.

The brain is composed of neurons, which are comprised of two main sections: 1) the body (axon terminals and dendrites) in which electrical signals are both collected and produced, and 2) the axon, in which information is conveyed between bodies/soma (Fig 1).

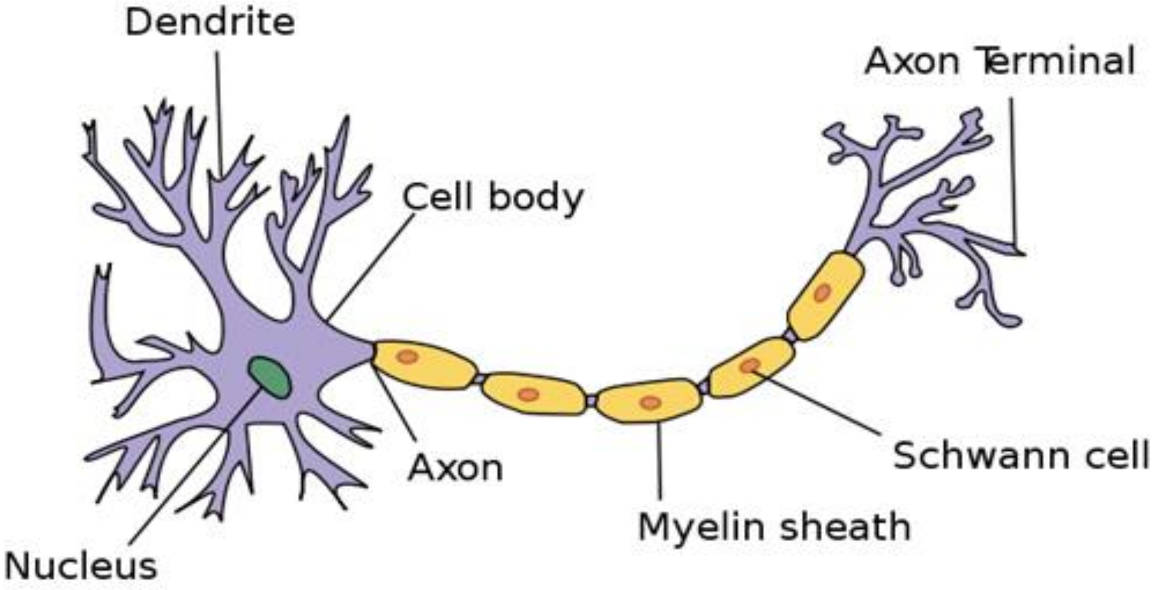


Figure 1-1 The component parts of the neuron. Figure adapted under creative commons CC BY 3.0 (http://creativecommons.org/licenses/by/3.0)], via Wikimedia Commons)

The neuron bodies form the ‘grey matter’ of the brain in which specific computations take place. Neuronal bodies can be grouped together to ‘regions’ of the brain, which are associated with different computational processes. The axon is covered in a lipid layer called myelin, which functions as insulation to increase efficiency of information transfer. Bundles of axons form tracts which transfer information between both neighboring and remote regions of the brain. Due to the pale color of myelin, these axon bundles are termed the ‘white matter’ of the brain. Brain regions and pathways operate in conjunction with one another as ‘networks’ to perform various complex cognitive tasks. Among such networks are those used in language processing and control (see e.g. Friederici & Gierhan, 2013; Green & Abutalebi, 2013). Several neural regions are known to be involved in language processing and control networks (Fig. 2). Their respective contributions to language processing and control processes are discussed.

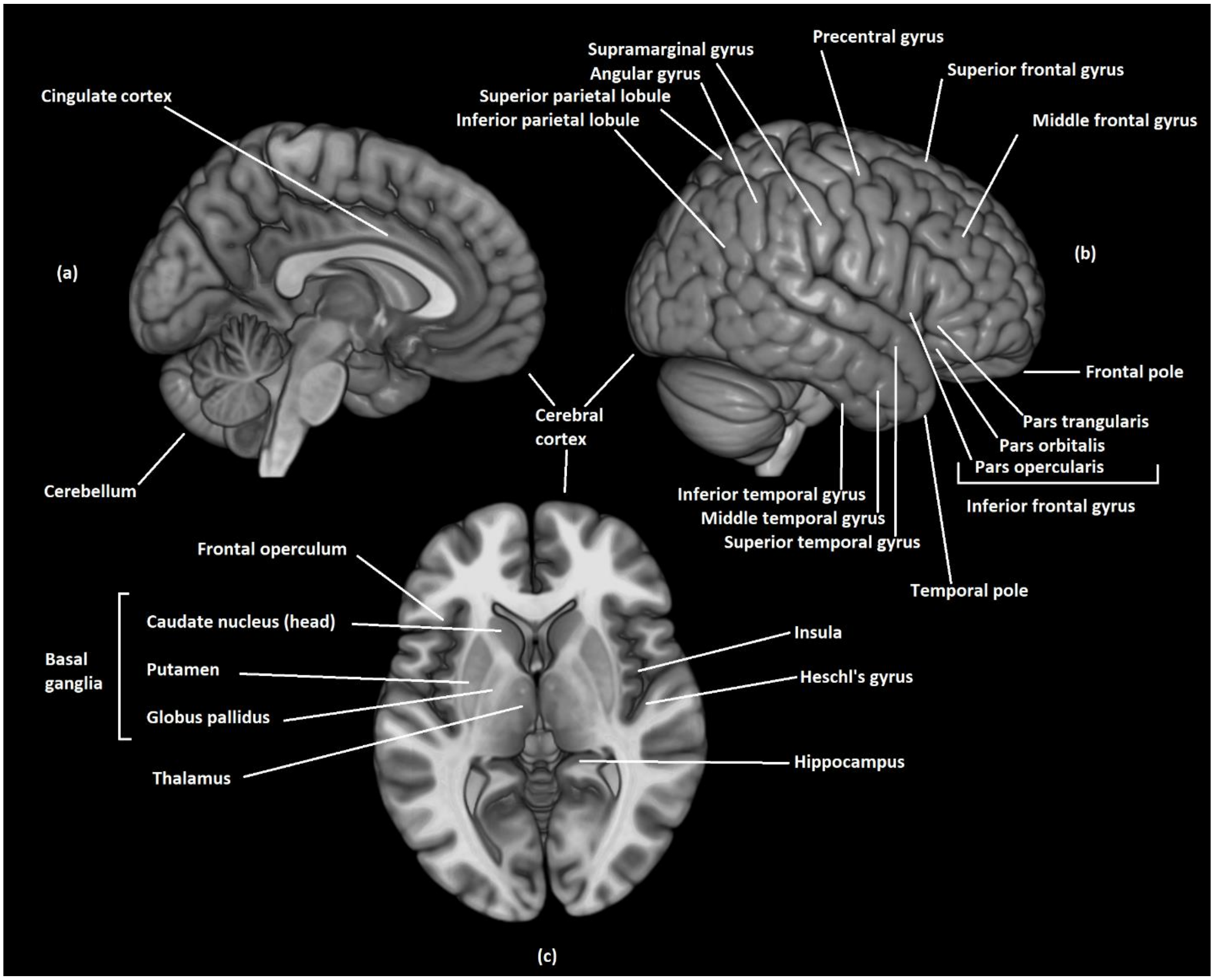


Figure 1-2 Grey matter (GM) regions of the brain involved in language processing and control. Adapted from "Multilingualism and Brain Plasticity" By C. Pliatsikas, 2019. In J. Schweiter (ed) The Handbook of the Neuroscience of Multilingualism. Wiley Blackwell.

One of the most highly implicated regions among these is the left inferior frontal gyrus (IFG). The left IFG has been implicated in a wide variety of functions in both language processing and production, including semantic (D. Klein, Milner, Zatorre, Meyer, & Evans, 1995), syntactic (Kotz, 2009; Petersson, Folia, & Hagoort, 2012) and phonological processing and production (Wong, Yin, & O'Brien, 2016). The left IFG is also used in language control processes, specifically suppression of interfering information and response control, particularly in cognitively demanding situations (Abutalebi & Green, 2016). Its right hemisphere analogous structure, the right IFG, is also implicated in language control processes, specifically inhibitory control and response inhibition (Aron, Robbins, & Poldrack, 2014). The anterior cingulate cortex (ACC) is another routinely implicated region in the language control network. It functions primarily in conflict monitoring processes, both in language control and domain-general control (Abutalebi et al., 2012). The pre-supplementary motor area (pre-SMA) works in tandem with the ACC in conflict monitoring processes in language control situations, and has been primarily implicated in conflict resolution in both linguistic and domain-general control processes (Luk, Green, Abutalebi, & Grady, 2011).

Several temporal and parietal regions also contribute to language and cognitive control processes. The inferior parietal lobule (IPL) which is comprised of the angular gyrus (AG) and supramarginal gyrus (SMG) is typically implicated in language and response selection and short term memory processing (Abutalebi & Green, 2016). The superior temporal gyrus (STG) has been implicated in mainly in language processing, specifically in acoustic/phonetic analysis of speech (Hickok & Poeppel, 2007). The middle temporal gyrus (MTG) has been implicated in syntactic and lexico-semantic processing (Rodriguez-Fornells, Cunillera, Mestres-Misse, & de Diego-Balaguer, 2009). The right hippocampus and bilateral anterior temporal lobe (ATL) are involved in vocabulary acquisition processes, specifically contributions of short-term memory encoding (Mårtensson et al., 2012; Stein et al., 2012).

Finally, several subcortical and posterior grey matter regions act as hubs of both the language processing and control networks, and are often implicated in greater automation and efficiency of language control (further discussed in the following section) (Abutalebi & Green, 2016; Grundy, Anderson, & Bialystok, 2017b; Stocco, Yamasaki, Natalenko, & Prat, 2014). The cerebellum, which has extensive connections to regions throughout the brain, is thought to be involved in several processes related to language (Booth, Wood, Lu, Houk, & Bitan, 2007), including facilitating language production and automating language processing and production (Pliatsikas, Johnstone, & Marinis, 2014a, 2014b). It also is implicated in language- and domain general cognitive control processes (Tyson, Lantrip, & Roth, 2014). The basal ganglia, specifically the caudate nucleus and putamen, are key structures in language processing and control. The caudate nucleus has extensive connections to both the IFG and cerebellum and is a hub in the language control network. It is frequently implicated in language selection and interference suppression processes in language control (Green & Abutalebi, 2013). The putamen has typically been implicated in phonological processing and control, specifically articulatory processes (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013) and phonological monitoring (Hervais-Adelman, Moser-Mercer, Michel, & Golestani, 2015). The thalamus is another key structure, which links the basal ganglia to the cerebellum and to the IFG. It plays a role in language production and control, typically lexical selection (Llano, 2013).

White matter tracts also play a key role in language control and processing by connecting regions to form networks by which specific cognitive tasks can be performed (e.g. Friederici, 2009; Wong, Yin, & O’Brien, 2016). Given their sheer number, it is beyond the scope of this thesis to discuss all the white matter (WM) tracts involved in language. However, several key tracts have been implicated in this across studies, and are known to form essential parts of the language control and processing/production networks (Friederici & Gierhan, 2013).

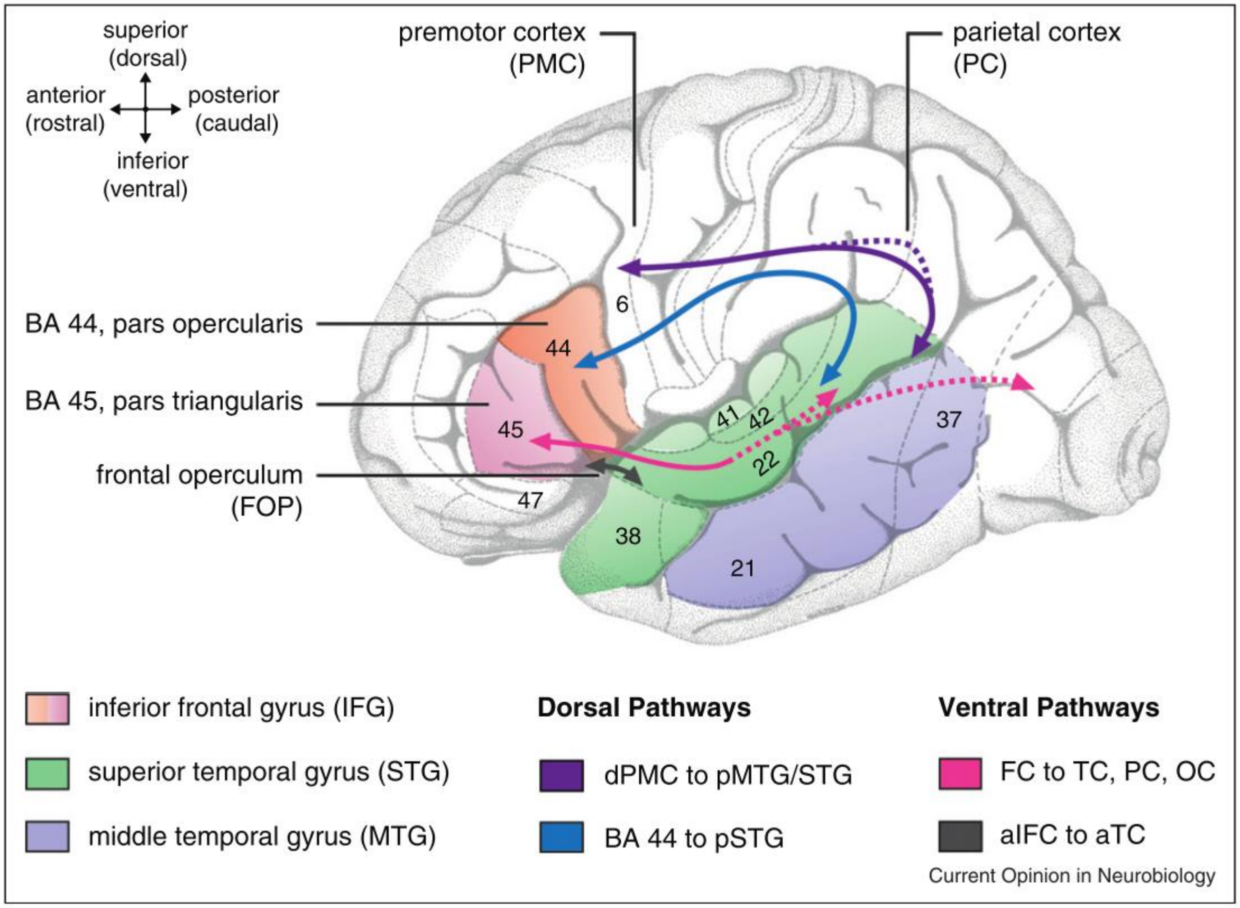


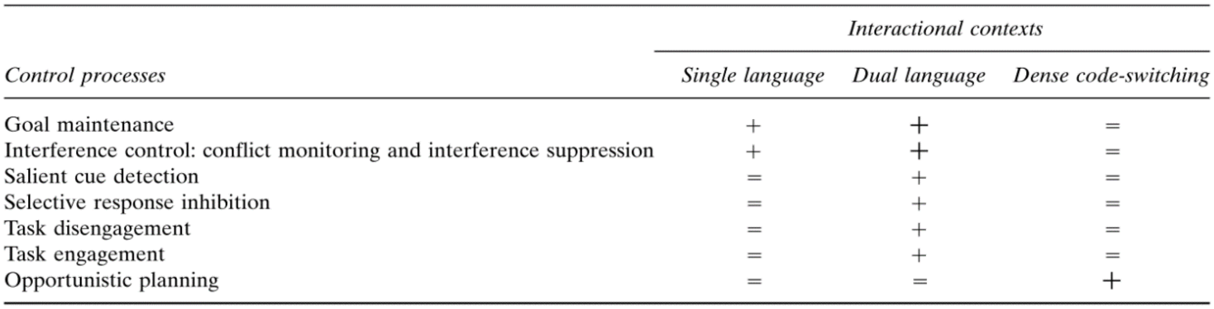
Figure 1-3 Example of several white matter tracts involved in language processing, including the IFOF (pink), SLF (purple), and UF (blue). Adapted from “The language network” by A. Friederici and S. Gierhan. Current Opinion in Neurobiology (23), p. 251. Copyright 2013 Elsevier Ltd.

One of the more commonly implicated in language processing/control is the inferior fronto-occipital fasciculus (IFOF), which connects frontal and occipital regions for both hemispheres, and has been implicated in a host of language processing functions and higher-order cognitive functions (Sarubbo, De Benedictis, Maldonado, Basso, & Duffau, 2013). The superior longitudinal fasciculus (SLF) connects the IFG to temporal/parietal areas including the STG and IPL, and has been implicated in a variety of language processing functions (Hickok & Poeppel, 2007). The uncinate fasciculus (UF) connects the IFG to anterior portions of the temporal cortex, and is often recruited for syntactic processing (Friederici & Gierhan, 2013). The anterior thalamic radiation (ATR) connects the thalamus to prefrontal regions and has previously been implicated in language processing, primarily lexico-semantic processing and production (Han et al., 2013). Finally, the corpus callosum (CC) connects both hemispheres and has been implicated in both language- and domain-general cognitive control processes, specifically interhemispheric communication in executive functioning and lateralization of brain functions (Luk, Bialystok, Craik, & Grady, 2011; Pliatsikas, Moschopoulou, & Saddy, 2015; Schlegel, Rudelson, & Tse, 2012).

1.2.2 Current models of neurological adaptation to bilingual language use

Given the number of regions and tracts which are known to be used for language control and processing, several models have been proposed which make specific predictions about what neuroanatomical adaptations are incurred by various aspects of bilingual language use, and their cognitive correlates. Three of these models are particularly relevant and are discussed here.

The Adaptive Control Hypothesis (Abutalebi & Green, 2016; Green & Abutalebi, 2013) is one of the most prominent of such proposals, and states that cognitive control is dictated by changing communicative demands. The hypothesis proposes that several cognitive control processes are used in bilingual language control during conversation; these include goal maintenance, response inhibition, conflict monitoring, interference suppression, salient cue detection, task engagement and disengagement, and opportunistic planning. Crucially these processes are variably enhanced and applied in combination depending on the conversational context in which on is engaged to most effectively facilitate communication. In this model, communicative contexts fall under three general categories- 1) single language context (in which only one language is used) 2) dual language context (both languages are available, but usually with different interlocutors), and 3) dense code-switching context (both languages are constantly available and are switched between frequently, within utterances) (Fig 4). For example, dense code-switching would not require enhanced response inhibition or conflict monitoring, given the constant availability of both languages with all speakers, however opportunistic planning would enhance as the speaker would make sue of whatever of each language comes to had



	Interactional contexts		
Control processes	*Single language*	*Dual language*	*Dense code-switching*
Goal maintenance	+	**+**	=
Interference control: conflict monitoring and interference suppression	+	**+**	=
Salient cue detection	=	+	=
Selective response inhibition	=	+	=
Task disengagement	=	+	=
Task engagement	=	+	=
Opportunistic planning	=	=	**+**

Figure 1-4: the eight cognitive control processes and their enhancement based upon conversational/interactional context. + indicates enhancement (more if bolded) and = indicates that no change in application occurs. Adapted from "Language control in bilinguals: The adaptive control hypothesis" By D.W. Green and J. Abutalebi, 2013. Journal of Cognitive Psychology (25), p. 519. Copyright 2018 by Informa UK Ltd.

to facilitate their utterance in conversation. Further to this, each control process is served by a network of regions which are recruited with varying degrees of intensity, depending on what process is used; these include the inferior frontal cortex (IFC), prefrontal cortex (PFC), pre-supplementary motor area (pre-SMA), anterior cingulate cortex (ACC), cerebellum, insula, basal ganglia, and thalamus. Prolonged or increased engagement with specific communicative contexts then reinforces both the cognitive processes required by them, but also their neural substrates (Fig. 5). Taking again the example of dense code-switching, the enhanced process of opportunistic planning would more intensively involve the cerebellum and left IFC (Fig 5). These reinforcements from use would then be measurable as increased performance on tasks that tap into these cognitive processes and increased neural plasticity and connectivity in those regions with increased control demands.

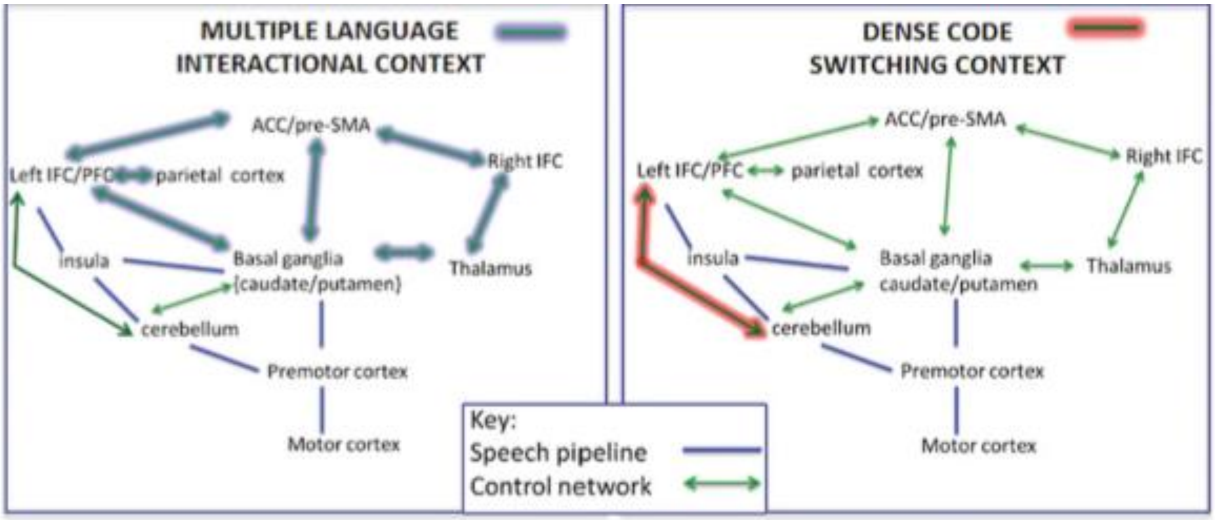


Figure 1-5: Model of the adaptive control hypothesis showing the proposed language production and control network, and how this is modulated under different conversational contexts. Reprinted from "Neuroimaging of language control in bilinguals: neural adaptation and reserve" by J. Abutalebi and D.W. Green, 2016. Bilingualism: Language and Cognition, 19(4), p. 3. Copyright 2016 by Cambridge University Press.

The Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) framework (Grundy et al., 2017b) considers effects of bilingual/non-native language use from a more longitudinal perspective. It states that initial stages of contact with an additional language incur reliance on frontal areas, due to increased demands on working memory and several language/executive control processes which are served by these regions. As L2 exposure and use/proficiency increase, reliance shifts commensurately from frontal regions involved in more intensive cognitive control processes (e.g. ACC and PFC) to subcortical and posterior regions (e.g. basal ganglia, thalamus, occipital lobes) (Fig. 6) which are known to be involved in more efficient and automated cognitive processing.

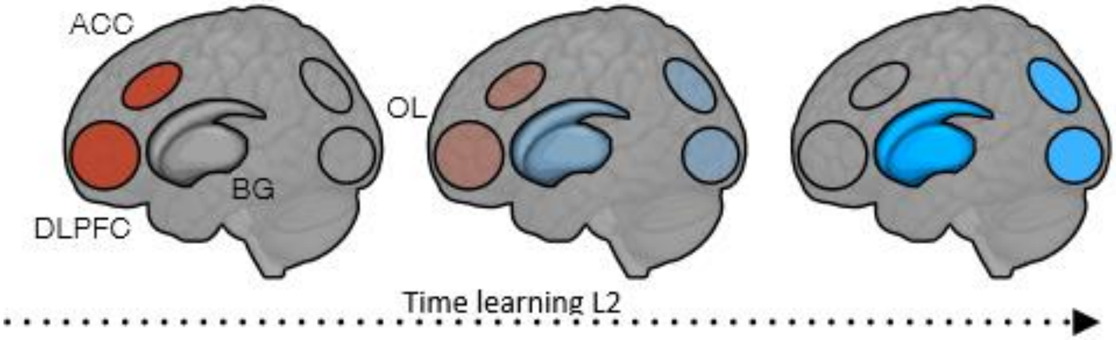


Figure 1-6: Predictions of the BAPSS framework- reliance shifts from frontal to posterior regions (image adapted from "Neural correlates of cognitive processing in monolinguals and bilinguals" by J. Grundy, J.A.E Anderson, and E. Bialystok. 2017. Annals of the New York Academy of Sciences, 1396(1), p. 188. Copyright 2018, the New York Academy of Sciences)

Finally, the Conditional routing model (Stocco, Lebiere, & Anderson, 2010; Stocco et al., 2014) provides a neurobiological framework describing the links between bilingual language acquisition and use, commensurate functional neural adaptations, and how these link to differences in executive function. This model is based on the notion of the gating of neural signals through the basal ganglia to prefrontal and other cortical regions under specific, prerequisite conditions. The acquisition and use of an additional language stresses and ‘trains’ this system in which the onus of rule selection is transferred to the basal ganglia (Fig. 7). Additionally, the basal ganglia (specifically caudate and putamen) override other cortico-cortical connections in the application of these rules. This situation gives increased efficiency in rule acquisition, selection, and application, all of which are implicated in executive function processes, particularly many of the tasks that tap into these.

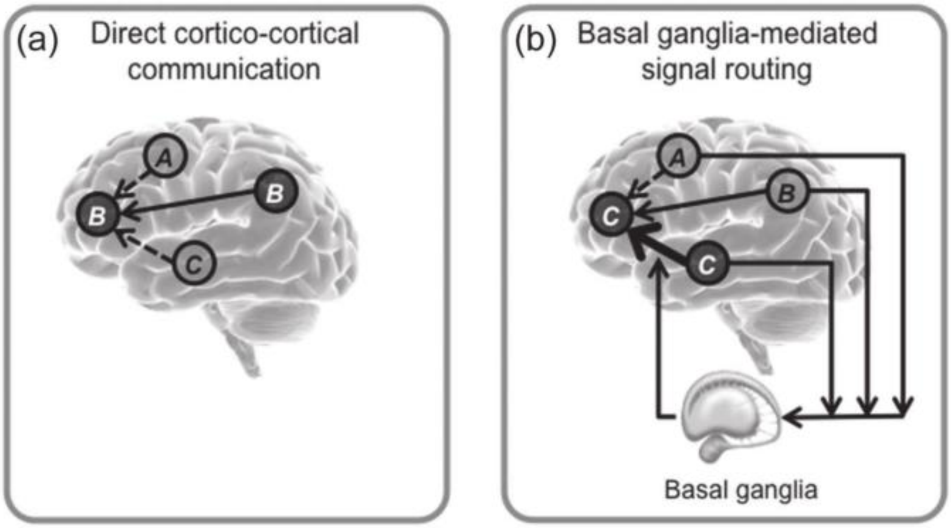


Figure 1-7: The conditional routing model, and predictions regarding changing information signal routing with acquisition of an additional language. Reprinted from "Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function” by A. Stocco, B Yamasaki, R. Natalenko, and C.S. Prat. 2014. International Journal of Bilingualism, 18(1), p. 13. Copyright 2018 by Sage Publications.

Some are skeptical about the validity of conducting research using neuroimaging methods, given mixed results of behavioral studies (Paap, Sawi, Dalibar, Darrow, & Johnson, 2014). However, that argument is backward. It assumes both that for a behavioral difference must be present for differences in neural activation to be meaningful and that differences in neural processing must have behavioral correlates (e.g. button pressing). If anything, neuroimaging methods are able to demonstrate effects of finer granularity, and as such the attention to any differences in neurocognitive processes should start in this modality and how this might affect behavioral performance (see for discussion Bialystok, 2016). Indeed, neuroimaging methods have, in many cases, contributed to a better understanding of the effects of bilingual language use than behavioral evidence alone (Ansaldo, Ghazi-Saidi, & Adrover-Roig, 2015; Luk et al., 2010; Morales et al., 2013; among others). Such contributions are discussed in the following section.

1.2.3 Electrophysiological evidence

Several studies have used electroencephalography (EEG) and/or magnetoencephalography (MEG) to determine differences in cognitive processing between bilinguals and monolinguals (Bialystok et al., 2005; Coderre, Heuven, Van Heuven, Heuven, & Van Heuven, 2014; Grundy, Anderson, & Bialystok, 2017a; Morales, Yudes, Gómez-Ariza, & Bajo, 2015; Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014; Timmer, Grundy, & Bialystok, 2017). Neuroimaging methods can provide insights into underlying processing differences between bilinguals and monolinguals when no differences can be in behavioral data alone. While the modalities of EEG and MEG are outside the methodological scope of this thesis, evidence from them provide insights into a divide between the effects of bilingual language use on performance on executive function tasks (here, a proxy for cognitive processes) and neurological processes that potentially underlie them. Two key examples of this are discussed here.

A study by Bialystok and colleagues examined neural recruitment patterns for monolingual and bilingual adults while completing a Simon task, using MEG (Bialystok et al., 2005). Three groups were examined: Cantonese-English bilinguals, French-English bilinguals, and a monolingual (English) control group. With respect to reaction times, the Cantonese-English bilinguals were consistently faster than the other two groups, who were not found to differ in terms of task performance (RT or accuracy). However, the bilingual and monolingual groups were found to recruit distinct neural networks in handling the cognitive load of the task. Both bilingual groups were found to show higher activation in the right temporal and left cingulate areas for faster responses, and activation in the occipital and parietal regions for slower responses. The cingulate regions are known to be involved in conflict monitoring, while parietal regions, particularly the inferior parietal lobule (IPL) are known to be involved in selection processes (Abutalebi & Green, 2016). Monolinguals showed increased activation in middle frontal regions in correlation with faster responses, which is often implicated in interference suppression processes. The authors conclude that bilingual language use provides a more tuned neural network to handling conflict resolution in domain-general cognition, which crucially is not always shown in task performance.

Using EEG/ERP, Morales, Yudes, Gómez-Ariza, & Bajo, (2015) examined activation pattern differences between simultaneous bilinguals and monolingual young adults while performing an AX-CPT task. Behaviorally, the two groups did not differ with respect to RT, but the bilingual participants committed fewer errors across all conditions, particularly in incongruent conditions. Bilinguals exhibited amplitudes in the N200 window across all the incongruent and control conditions, similarly the P300 waveforms were larger for bilinguals in that time window across the incongruent conditions. The N200 component is known to index conflict monitoring processes (Rodriguez-Fornells et al., 2006), and the P300 is known to index inhibition of prepotent responses. Finally, monolinguals showed larger error-related negativity waveforms for incorrect trials than bilinguals. The authors conclude that bilingual language use has positive implications for several executive control processes.

1.2.4 Magnetic resonance imaging (MRI)

In recent years, magnetic resonance imaging (MRI) has also been used to identify neurological underpinnings of adaptations to using an additional language (García-Pentón et al., 2016b; P. Li et al., 2014), and how this reflects in the way the brain is recruited for linguistic and non-linguistic cognitive tasks (Pliatsikas & Luk, 2016). Here I discuss results from two general protocols relevant to brain plasticity and processing: 1) structural scans detailing aspects of specific regions/structures and pathways within the brain, and 2) functional scans (fMRI) which can be used to measure both neural activation and functional connectivity in relation to stimuli and at rest.

Given its high degree of spatial resolution, fMRI can also give key information about the effects of bilingualism on domain-general cognitive control and processing. Specifically, it contributes to our understanding about how multiple languages are represented and controlled in the brain (e.g. Abutalebi, 2008; Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005) and what effects this might have on domain-general cognitive processes (e.g. Grundy, Anderson, & Bialystok, 2017b).

Evidence from functional MRI

Functional differences are measured in terms of connectivity between various regions (e.g. Beckmann & Smith, 2005) at rest or during tasks, or functional activation of specific regions during a task/stimulus presentation (e.g. Smith et al., 2004). Functional connectivity can also be measured through predefined networks, groups of regions known to be recruited together for specific sets of cognitive functions (see e.g. Smith et al., 2009).

Within the neuroimaging literature, there is a sizeable body of research examining language the neural correlates of language processing and control as a function of either acquiring and/or using an additional language (Abutalebi, 2008; Abutalebi et al., 2008; De Grauwe, Lemhöfer, Willems, & Schriefers, 2014; Friederici & Gierhan, 2013; Garbin et al., 2011; Grant, Fang, & Li, 2015; Lei, Akama, & Murphy, 2014; Parker Jones et al., 2012; Pliatsikas et al., 2014a; Reverberi et al., 2018; Seo, Stocco, & Prat, 2018; Stocco et al., 2014). Previous research has shown overlap between the regions and networks recruited during the processing and production of the two languages one uses (Frenck-Mestre et al., 2005), which gives neurophysiological evidence in support of the account of two active and competing representations formed by ones respective languages (Kroll et al., 2012). Given the overlap, and limited resources to handle these, the system must then adapt to more efficiently handle the control of the two languages (Green & Abutalebi, 2013; Pliatsikas, 2019). Crucially, language control has been found to make use of highly similar networks used for domain-general executive control, and modulate activity within these with consistent bilingual language use (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013; Buchweitz & Prat, 2013; Grant et al., 2015).

Evidence for domain-general neurocognitive effects of bilingualism supports the argument of some relationship between language control and executive control more generally. A number of studies have employed fMRI methodology in combination with tests of executive function and report different patterns of activation depending upon both the linguistic experience of the participant group and the experimental paradigm used by that study. Modulations of neural recruitment (as a function of bilingual language use) have been found in both children (Mohades et al., 2014), young adults (Abutalebi et al., 2012; Garbin et al., 2010; Luk et al., 2010; Rodríguez-Pujadas et al., 2013; Stocco & Prat, 2014), and older adults (Ansaldo et al., 2015; Borsa et al., 2018; Gold, Kim, Johnson, Kryscio, & Smith, 2013). Some studies report a greater degree of activation in specific regions for bilinguals over monolinguals recruited to handle the more cognitively demanding aspects of tasks (Garbin et al., 2010; Mohades et al., 2014). Others report decreased activation for bilinguals in similar regions to monolinguals for cognitively demanding sections of tasks (Abutalebi et al., 2012). Crucially, a difference in neural recruitment between bilinguals and monolinguals is more consistently found using MRI. Moreover, the differences in activation are not random; they are frequently found in regions implicated as part of the cognitive control network. This includes portions of the bilateral prefrontal cortex, anterior cingulate cortex, basal ganglia, thalamus, middle frontal regions, cerebellum, and parietal lobules (Abutalebi & Green, 2016; Green & Abutalebi, 2013; Pliatsikas & Luk, 2016). Several illustrative examples of studies finding differences in neural processes, but crucially not task performance, are discussed in detail.

One example of a divide between behavioral performance and neural activation patterns comes from Ansaldo, Ghazi-Saidi, & Adrover-Roig (2015) studied the neural bases behind the proposed cognitive advantage that bilingual speakers seem to exhibit in ageing. Twenty elderly (*m*age 74 years) participants were tested (10 bilingual and 10 monolingual). Participants completed a version of the Simon task during fMRI screening. Regarding the Simon task, no behavioral differences were found between groups. However, the incongruent condition related to activations in different parts of the brain for each language group- the right middle frontal gyrus (MFG) in the monolingual group and the left inferior parietal lobule (IPL) in the bilingual group. This difference can be taken as a change in how cognitive control is applied to given tasks. Another example of this comes from a study by Luk and colleagues (2010). This study examined neural responses to different costs: interference suppression, response inhibition and facilitation, in bilingual and monolingual young adults completing a modified flanker task. Here as well, behavioral patterns were not found to differ between groups, but bilinguals recruited markedly different neural response patterns for interference suppression (incongruent trials compared with neutral trials). Monolinguals were found to activate the left temporal pole and left superior parietal regions, whereas bilinguals were found to activate the bilateral frontal, temporal and subcortical regions.

Other studies report differences in the functional connectivity between these regions or networks for bilinguals and monolinguals while completing linguistic and non-linguistic executive function tasks (Becker, Prat, & Stocco, 2016; Costumero, Rodríguez-Pujadas, Fuentes-Claramonte, & Ávila, 2015; Kepinska, de Rover, Caspers, & Schiller, 2018; L. Li et al., 2015; Weber, Luther, Indefrey, & Hagoort, 2016). For example, Costumero and colleagues (2015) examined patterns of functional connectivity in monolingual and simultaneously acquired bilingual adults while completing a Go-NoGo task, which is designed to examine response inhibition (Chikazoe et al., 2009). No differences in task performance were found between monolinguals and bilinguals. Regarding functional networks (e.g. Smith et al., 2009), the connectivity increased left fronto-parietal network (FPN) more for bilinguals than monolinguals in the infrequent-go trials, but not the right FPN. The salience network was modulated in the no-go trials vs go-trials more for bilinguals than monolinguals. Correlation analyses between brain activation patterns and behavioral data showed a negative correlation between the salience network and the accuracy on the no-go trials for bilinguals only. RTs correlated negatively with the salience network in the no-go trials and the FPN in the infrequent-go trials only for the bilingual group as well.

Considered together, functional neuroimaging evidence shows a marked effect of bilingualism on the neurophysiological underpinnings of cognitive control processes, which crucially inconsistently patterns with results from the behavioral tasks used to tap into these processes. However, among this literature there is variability between studies, mainly in terms of how neural recruitment patterns on cognitive tasks are modulated by bilingual language use, and what can be interpreted from this. Some of this variability can be attributed to methodological differences between studies, and the relatively small group of studies that currently have examined this phenomenon with fMRI (García-Pentón et al., 2016b; Luk & Pliatsikas, 2016). However, bilingualism as a variable in its own right also needs to be further examined (Luk & Pliatsikas, 2016). Indeed, to date no study has examined what effects of individual differences in a range of bilingual language *experiences* have on neural recruitment patterns in non-linguistic tasks of executive function.

Evidence from structural MRI (stMRI) and resting-state functional MRI (rsfMRI)

In addition to affecting the functional recruitment of neural regions in language processing and cognitive control processes, aspects of bilingualism have also been found to relate to distinct neuroanatomical adaptations (García-Pentón et al., 2016b; P. Li et al., 2014; Pliatsikas, 2019). Structural plasticity related to bilingual language use has been found to occur largely within regions and pathways implicated in language processing and control (Pliatsikas, 2019). These include the including regions such as the bilateral inferior frontal gyrus (IFG), inferior parietal lobule (IPL), cerebellum, basal ganglia, and thalamus (Abutalebi & Green, 2016)

Studies have shown evidence of neuroanatomical changes in response to novel linguistic experiences within short time frames, from a matter of months (Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013; Mårtensson et al., 2012) to hours (Hofstetter, Friedmann, & Assaf, 2016). Moreover, these changes are specific to experience. Research has shown that the brain is highly adaptable in response to changing environmental stimuli and demands, to which it structurally adapts to be maximally effective at handling these (for review see Fuchs & Flügge, 2014). In the past decade, an small but growing number of studies have reported both neuroanatomical and physiological adaptations by the brain as an effect the bilingual language use (e.g. Grogan, Green, Ali, Crinion, & Price, 2009; Mechelli et al., 2004; Stein et al., 2012).

In this literature, effects of specific language experiences within bilingual language have been explored, however much of the evidence for this comes from cross-sectional studies with categorized groups. The most commonly studied language demographics are L2 age of acquisition (AoA) (e.g. Berken, Chai, Chen, Gracco, & Klein, 2016; D. Klein, Mok, Chen, & Watkins, 2014; Rossi, Cheng, Kroll, Diaz, & Newman, 2017), proficiency in the L2 (e.g. Grogan et al., 2009; Mårtensson et al., 2012; Stein et al., 2012), and more recently L2 immersion (Kuhl et al., 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017; Pliatsikas et al., 2015). While this direction is encouraging, the literature is still small, and inconsistencies exist between studies regarding location of specific effects and how they manifest.

Grey Matter

Differences or patterns of brain structure change related to bilingualism have been examined using a variety of indices. These include via grey matter (GM) volume using voxel-based morphometry (VBM) (Ashburner & Friston, 2000), cortical thickness (CT) (e.g. Ad-Dab'bagh et al., 2005) and surface displacement (via vertex analysis) (Patenaude, Smith, Kennedy, & Jenkinson, 2011).

Mechelli et al., (2004) were the first to examine structural effects of bilingualism. L2 AoA and proficiency in a second language were taken as specific variables on a gradient by which differences might be seen of grey matter density within certain regions of the brain. Results of VBM showed both early and late bilinguals exhibited a higher grey matter volume than monolinguals in the left inferior parietal lobule (IPL), which is a region often implicated in language selection processes (Abutalebi & Green, 2016). The authors also report a negative correlation between AoA of the L2 and grey matter density in the left IPL, which conversely positively correlated with L2 proficiency.

With respect to specific language-related factors, a handful of studies have examined effects of AoA on grey matter adaptation (Berken, Gracco, Chen, & Klein, 2016; D. Klein et al., 2014; M. Wei et al., 2015). The Klein et al (2014) study, as an example, examined GM adaptation in four groups, three categorized by age at which they learned their L2, and a control group. The four groups tested were 1) simultaneous bilinguals (mean age 23yrs, AoA 0), 2) early sequential bilinguals (mean age 26 years, AoA 5yrs), 3) late sequential bilinguals (mean age 28, AoA 10yrs), and 4) a monolingual control group (mean age 25). For the late sequential bilinguals, a reduction in CT in the RIFG was seen in comparison to simultaneous and early sequential bilinguals. Early sequential bilinguals also showed reduced CT in this area compared to monolinguals. Regression analyses showed, AoA and CT were positively correlated in the LIFG and negatively correlated in the RIFG. That is, the later the AoA, the thicker the LIFG and thinner the RIFG. CT in the left superior parietal lobule was also positively correlated with AoA.

Although technically an outcome of bilingual language use in its own right, effects of L2 proficiency on GM has also been examined, both from a cross-sectional (e.g. Grogan et al., 2009) and longitudinal perspective (Bellander et al., 2016; Mårtensson et al., 2012; Stein et al., 2012). The 2009 study (Grogan et al., 2009) examined neural correlates behind semantic and phonological processes in bilingual speakers. Participants completed a letter fluency task and a lexical decision task, both in English. Grey matter volume in both the left and right cerebellum correlated significantly with total fluency scores (semantic plus phonemic) over both languages. Pliatsikas et al. (2014b) compared grey matter (GM) volume in native and L2 speakers of English. The L2 speakers were all L1 Greek, were UK residents for an average of 4 years, and had an average AoA of English of 8 years old. GM volume was found to be highest in the posterior regions of the cerebellum for the L2 speakers in comparison the native English speakers. Areas in the brain with significant GM (between-subjects) differences were correlated to the subjects' performance on a grammatical processing task (Pliatsikas et al., 2014a); specifically, volume differences for the significant clusters identified were correlated with the participants' mean RTs from the grammatical processing task. A significant negative correlation was found between GM volume and reaction times for regular morphology on the grammatical processing task.

Effects of L2 proficiency on grey matter have also been found from longitudinal studies. One example of this comes from a training study by Mårtensson and collegues (2012) which examined neural structure effects in adults as a cause of intensive language learning. The participants were all young adults (n=14) in the Swedish military training as interpreters, which involves a 10-month total training process. Controls were also scanned (n=17) which were psychology and cognitive science students at the university. Both groups were scanned prior to, and after three months on the course. VBM analysis showed increased GM volumes in the superior temporal gyrus (STG), medial frontal gyrus (MFG), and right hippocampus (RHC) in the interpreters at the end of the three-month period. Within the interpreters, proficiency (as established by their course performance) was found to significantly correlate with GM volume the MFG, STG, and RHC, but not the left IFG.

Immersion in a non-native-language speaking context has also been shown to affect GM structure (Pliatsikas et al., 2017; Stein et al., 2012; Stein, Winkler, Kaiser, & Dierks, 2014). Pliatsikas and colleagues (Pliatsikas et al., 2017) examined the effect of sequential, immersive, bilingualism on the structure of the subcortical structures and basal ganglia. Two experimental populations were examined. The first used the participants from Pliatsikas et al., (2015). The second experiment used participants from Pliatsikas et al., (2014b), which included 17 advanced L2 English (L1 Greek) speakers (mean age 27.5; mean AoA English 7.7yrs), and 22 monolingual native speakers of English (mean age: 24.5). The bilingual participants had lived in England for 3.9 years at the time of scanning. To determine effects of linguistic experience, proficiency (QPT score), age of acquisition (years), and immersion (time in UK) were run as regressors in the model for the bilingual population only. For the immersed group, significant shape changes (expansions) were found in the thalamus, globus pallidus, and putamen for the bilingual group over the monolinguals. When regressions within group were run, only immersion was found to be a significant predictor for shape change, and this was in the globus pallidus bilaterally. No other significant effects were found. Comparing the non-immersed bilinguals to the monolinguals, shape changes (both expansions and contractions) were found, but only in the caudate nucleus bilaterally. None of the predictors in the regression analysis reached significance for this group.

White Matter

White matter integrity within tracts connecting language- and executive function-related regions have been reported in connection with the acquisition and use of an additional language (Anderson, Grundy, et al., 2018; Coggins, Kennedy, & Armstrong, 2004; García-Pentón, Perez Fernandez, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014; Hofstetter et al., 2016; Kuhl et al., 2016; Luk, Bialystok, et al., 2011; Mohades et al., 2012, 2015; Nichols & Joanisse, 2016; Pliatsikas et al., 2015; Rossi et al., 2017; Schlegel et al., 2012; Singh et al., 2017). Structural connectivity in white matter affected by bilingual language use has also been assessed using several measures including fractional anisotropy (FA), mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD). These values provide indirect indices of the degree of myelination in the white matter tracts of the brain by tracking degree of water flow, both along directional gradients and in general, within myelinated tracts (Smith et al., 2006; Yeatman, Dougherty, Myall, Wandell, & Feldman, 2012).

Specific language experiences have also been found to affect diffusivity patterns in bilingual subjects. L2 AoA has been found to relate independently to FA value differences by several studies, typically with earlier AoA correlating with increased structural connectivity in pathways connecting language-related regions (Mohades et al., 2012, 2015; Nichols & Joanisse, 2016; Rossi et al., 2017). Recently, length of immersion has also been implicated as showing a highly similar pattern of results to AoA (Kuhl et al., 2016; Pliatsikas et al., 2015). For example, Pliatsikas et al. (2015) examined a highly immersed bilingual group, which included 20 advanced L2 English speakers with various L1 backgrounds (mean age: 31.85), which had lived in the UK for an average of 91 months (range: 13-374 months) at the point of testing, and had an average AoA of English of 10.15 years. A monolingual control group (n=25; *m*age 28.16) had minimal to no exposure to an additional language. Results of DTI/TBSS analyses showed higher WM integrity in several regions of the brain bilaterally, including the genu, body, and the anterior portion of the splenium of the corpus callosum, which extended into the inferior fronto-occipital fasciculus (IFOF) and superior longitudinal fasciculus (SLF). The pattern of results for the immersed bilinguals, interestingly, was found to be highly to patterns of FA value effects in early-acquired bilinguals from other studies (Luk, Bialystok, et al., 2011; Olsen et al., 2015). The authors conclude that cognitive or structural effects linked to AoA are more likely an effect of immersion or relative length of time of continuous usage of the L2.

Effects on structural connectivity have also been found in longitudinal studies (Hosoda et al., 2013; Mohades et al., 2015). The study by Hosoda and colleagues (2013) examined effects of L2 instruction on structural connectivity. The participants were all students or graduates and native speakers of Japanese (L2 English learners). Participants were scanned and underwent a battery of English proficiency tests- a ‘pre’ condition. The participants then underwent an L2 training program of 16 weeks, each week learning 60 words/idioms and their proper use in English. A control group was selected to not complete the training. Both groups underwent scans and testing after the 16-week period. Finally, the test group underwent a final scanning session one year later without having any formal instruction during that time. Significant increases in test scores were noted between the pretest and post-test 1 (after training). Significant decreases were then observed at post-test 2, one year later (without any training), rendering similar scores between the pre-test and post-test 2. Regarding brain adaptations, no differences in structural connectivity were found between groups at the pretest. At post-test 1, increases in WM integrity in the sub-IFG region were seen between the test group and control group. Increases in structural connectivity were found in the IFG-caudate head pathway and dorsal pathway in the right hemisphere. These values significantly decreased for the test group at post-test 2.

Effects in the opposite direction have also been reported in this literature. For example, Cummine & Boliek, (2013) examined white matter integrity in 11 monolinguals and 12 bilinguals (mean age 28 and 24, respectively). The monolingual group had some exposure to an additional language (school instruction) but rated themselves as low or no proficiency in any language apart from English. The bilingual speakers were native Chinese L2 English learners, who started instruction in English around the age of 5. They rated themselves as fluent in both languages at the time of testing. Prior to scanning, all participants underwent a reading test in which they would read aloud three lists of 60 words. The words were either phonetic or irregular (e.g. mint vs pint). Reaction time and accuracy of pronunciation were recorded. Monolinguals exhibited higher FA values in the right IFOF, the superior portion of the right anterior thalamic radiation (ATR), and the inferior portion of the ATR bilaterally. Bilinguals were not found to exhibit higher FA values in any area. Negative correlations were found between FA values and word response time for both groups.

Resting-State Connectivity

Currently, relatively less evidence exists regarding the effect of bilingualism on resting-state (intrinsic) functional connectivity. While several networks are implicated in the resting state, including the Default Mode network (DM) and frontoparietal control network (Berken, Chai, et al., 2016; Chai et al., 2016; Grady, Luk, Craik, & Bialystok, 2015; Gullifer et al., 2018; Kousaie, Chai, Sander, & Klein, 2017; Luk, Bialystok, et al., 2011; Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010) the effect of the bilingual experience remains currently relatively understudied.

Luk et al. (2011), report changes to default mode network as functional correlates to white matter differences between bilinguals and monolinguals. The bilingual group was found to have higher FA values in the corpus callosum which extended to the superior longitudinal fasciculi, and anteriorly to the right inferior frontal–occipital fasciculus and uncinate fasciculus. Monolinguals were not found to exhibit higher FA values in any brain region. Resting functional activity patterns were then correlated to the FA values. Correlations with distributions of functional activity were found in WM tracts connecting the left inferior frontal gyrus to the bilateral middle temporal gyri, right inferior parietal lobule, precuneus, bilateral middle occipital gyri, and left caudate. The right inferior frontal region exhibited a similar pattern. Interestingly, the monolingual participants had stronger functional connectivity between the right inferior frontal seed and other frontal regions. Bilinguals had stronger functional connectivity between the seed and occipitoparietal regions. The increase in both FA values and functional connectivity is seen as a neurological index of the use and management of multiple languages by context.

Evidence for intrinsic functional connectivity changes have also been examined from initial exposure to the L2. A study by Veroude and colleagues (2010) examined connectivity differences as an immediate effect of the acquisition of/exposure to new words (in a different language). Participants in this study were native Dutch speaking monolingual adults. They were exposed to a weather report in Mandarin which contained 24 target words. Resting state functional scans were taken both before and after viewing the weather report. Participants were also given a word recognition task in which they would indicate whether they heard a given word during the video. They were divided into two groups (high-learner and low-learner) based on their performance on the word recognition task. Functional connectivity was found to be higher between the bilateral IFG, supplementary motor area, insula, SMG, STG, and middle temporal gyrus after viewing the report. Additionally, the high-learner group appeared to show stronger functional connectivity overall than the non-learners after exposure to the weather report.

1.2.5 Synthesis of neuroimaging research

Results from various neuroimaging methods (EEG, MEG, and MRI) have provided insights in to cognitive processing effects of bilingual language use, and their potential neurobiological underpinnings. Crucially, these effects have been often found in the absence of any behavioral effect (e.g. Ansaldo et al., 2015; Costumero et al., 2015; Luk et al., 2010). Furthermore, evidence from structural and resting-state MRI suggests that specific experiences within bilingualism are explanatory of patterns of adaptation. Here as well, though, there are discrepancies between studies regarding patterns of neural recruitment, magnitude of effects, and direction of effects. Arguments are made regarding methodological consistency, both in terms of experimental procedures and analytical methods (García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2016a; García-Pentón et al., 2016b). Specifically, greater methodological consistency and more longitudinal designs are needed to aid in the fine-tuning of existing models of bilingualism and its neural substrates. While this call is valid, an equally strong argument can also be made for more rigorously assessing what aspects of the bilingual experience differentially affect the structure and function of the brain. Some of the variability in neuroimaging evidence likely from underlying linguistic experience of the specific group of bilingual participants tested. Further research into the specific component factors that comprise the bilingual experience will likely result in greater convergence of evidence across studies.

1.3 The need to re-examine bilingualism as a spectrum of experiences

As has been discussed, the evidence surrounding an effect of bilingualism is inconsistent. Several review papers produced in recent years bring valid points about how to raise consistency, most of which include standardizing experimental procedures and analytical methods, testing greater numbers of participants (García-Pentón et al., 2016b; Valian, 2015a), and more investigation into neural substrates of bilingualism (Costa & Sebastián-Gallés, 2014; García-Pentón et al., 2016b; Valian, 2015a). However, a greater consideration for the linguistic experience is not among those usually considered, or how to view bilingualism. Bilingualism is known to be a complex and dynamic process (see e.g. Carroll, 2017; Grosjean, 1998, 2013; Romaine, 1995; among others), which is comprised of a number of experiential factors that potentially contribute to neurocognitive adaptations (Bak, 2016; Bialystok, 2016; Luk & Bialystok, 2013).

The majority of studies to date treat bilingualism as a categorical variable; that is, that one either has functional competence in more than one language or does not (Luk & Bialystok, 2013). Further categorizations within bilingual groups have been made on the basis of any given language use-related factors, such as L2 AoA (e.g. D. Klein et al., 2014; Mohades et al., 2015) and degree of L2 proficiency (e.g. Veroude et al., 2010), among others. However, grouping bilinguals based on arbitrary threshold criteria (e.g. early vs late-acquired) or examining only one language-related experience is problematic, as other language experience factors which also drive neurocognitive change are potentially collapsed across one another. This not only potentially skews, or obscures, results within a given study, but also lowers the degree to which meaningful comparisons can be made across studies regarding any specific effects of bilingualism. A similar situation that applies to monolinguals- there is not a consistent threshold at present which divides them functionally from bilinguals, and the majority of will have some exposure to other languages, registers, dialects, etc. (Luk, 2015; Rothman, 2008a). Some studies (e.g. Paap & Greenberg, 2013) note some degree of experience with an additional language for these, which in other studies might categorize them as early/low proficiency L2 learners.

The solution to the issue of categorization is not more stringent selection criteria (García-Pentón et al., 2016b); rather, to consider all individuals on the same continuum or spectrum of bilingual language use. Several calls for this type of research to be done have already been made (Bialystok, 2016; de Bruin & Della Sala, 2015; Green & Abutalebi, 2013, 2015; Luk & Bialystok, 2013; Luk & Pliatsikas, 2016). Moreover, recall that the existing models of neurocognitive adaptations to bilingual language use all make concrete predictions about neurocognitive adaptations to the nature, duration, and extent of bilingual language use, respectively. The adaptive control hypothesis (ACH) notes neural adaptations by context of use (Abutalebi & Green, 2016; Green & Abutalebi, 2013), whereas the BAPSS framework (Grundy et al., 2017b) and conditional routing model (Stocco et al., 2010, 2014) both predict changes with increased time spent using the L2, specifically related to increased efficiency of language processing and control.

Despite the calls for re-examining impacts of language-use factors within bilingualism, only a handful of recent studies have examined neurocognitive effects of specific language-related factors within the bilingual experience (Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015; De Leeuw & Bogulski, 2016; Gullifer et al., 2018; Kuhl et al., 2016; Mårtensson et al., 2012; Pliatsikas et al., 2017; Rossi et al., 2017; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016; Yamasaki, Stocco, & Prat, 2018). These factors include length of time in L2 immersion (Kuhl et al., 2016; Pliatsikas et al., 2017), proficiency (e.g. Mårtensson et al., 2012; Stein et al., 2012), age of acquisition (Abutalebi et al., 2015; Nichols & Joanisse, 2016; Rossi et al., 2017), language switching (Hofweber, Marinis, & Treffers-Daller, 2016; Verreyt et al., 2016), and frequency of use (De Leeuw & Bogulski, 2016; Yamasaki et al., 2018). These effects, however, are usually run post-hoc to any analyses run in between the predetermined between-group (bilingual vs monolingual) comparison.

Even fewer studies to date have considered the effects of a variety of factors related to bilingual language use and experience in their study designs (Gullifer et al., 2018; Hofweber et al., 2016; Pliatsikas et al., 2017; Rossi et al., 2017; Yamasaki et al., 2018). The study by Yamasaki and colleagues (2018) examined behavioral effects of individual differences in bilingual language use, with an attentional blink task and Simon task in bilingual adults. Factors used in their models included: typological distance between languages, L2 AoA, frequency of language use, frequency of language switching, and L2 proficiency. Frequency of language use was found to predict differences in the attentional blink task. Furthermore, attentional blink size was found to correlate with performance on the Simon task. Another study by Gullifer and colleagues examined effects of individual differences in bilingualism on resting-state functional connectivity and executive functions, specifically interference suppression in bilingual adults (Gullifer et al., 2018). Two language demographics were applied: L2 AoA, and a composite score, language entropy, which measured the variability in sources of bilingual language use. Resting-state connectivity between the bilateral IFG was inversely correlated with L2 AoA (controlling for language entropy). Degree of language entropy (social diversity of language use) correlated with higher connectivity between the ACC and clusters in the bilateral putamen, and between the left caudate and clusters in the bilateral STG.

The data from these studies suggest a dynamic and nuanced relationship between the various language experiences within bilingualism and neurocognitive adaptations. However, no study to date has considered and/or implemented both a range of linguistic experiences and their effects on both neuroanatomical and neurocognitive adaptations. In the present thesis project, we examine such a range of experiences and how they modulate neural and cognitive plasticity in bilinguals. In so doing we propose a change of mentality for future research to consider these experiences in greater detail and how they variably drive neurocognitive adaptations stemming from bilingual language use.

1.4 Principle Aims of the Thesis

The aim of this doctoral research project is to 1) identify the language-use related experiences within bilingualism which contribute to adaptations in brain structure, function, and cognition (and how these adaptations manifest), and 2) examine how these adaptations are modulated through time with continued bilingual language use. Three studies are run. A longitudinal study (Study 1) assesses the effects of longer-term linguistic immersion on brain structure in bilingual adults. A cross-sectional study (Study 2) examines the effect of specific language related factors, both static and experience-based (EBFs) within bilingualism, specifically related to duration and extent of L2 use, and their respective effects on brain structure and intrinsic functional connectivity. A final cross-sectional study (Study 3) examines effects of the same language use factors as Study 2 on neural recruitment while completing tasks tapping executive functions. Taken together, I aim to move practice in the field away from traditional binary (bilingual vs monolingual) designs and instead towards individual differences approach in assessing the neurocognitive effects of bilingualism.

1.4.1 Modulation of neural plasticity with continued bilingual language use

Study 1 addresses the second research aim. This examines the potential neuroanatomical effects of linguistic immersion over an extended period. In so doing this study outlines an aspect of what neurophysiological adaptations are incurred with prolonged, continuous bilingual language use. Furthermore, this study outlines a previously unexplored timeframe. Previous studies have examined structural effects of second language acquisition from a longitudinal perspective, however these were all training studies or examined structural plasticity in children (Hosoda et al., 2013; Mamiya et al., 2016; Mårtensson et al., 2012; Mohades et al., 2015; Stein et al., 2012). However, no study to date has examined the effect of naturalistic bilingual language use on neural plasticity in adults over a longer-term period.

Participants are scanned twice (MRI), with a three-year immersive period in between. All participants will be non-native speakers of English, who will have been living in the UK prior to the first testing session. Participants will also complete an English proficiency test (Oxford QPT; (Geranpayeh, 2003)), to assess if their general English proficiency increases during this period. With respect to neurological adaptations, a range of scanning protocols will be applied, which include a structural scan, DTI scan, and resting-state functional scan. Several neuroanatomical measures are assessed 1) Cortical GMV, 2) subcortical grey matter surface displacement, 3) indices of white matter diffusivity (FA, AD, RD, and MD), and 4) resting-state functional connectivity.

We predict that neuroanatomical adaptations here will be towards an increased efficiency in language processing and control over the three-year immersive period. Specifically, this will manifest as increases in regional GM in posterior and subcortical regions including the globus pallidus, thalamus, and cerebellum (Pliatsikas et al., 2017, 2014b), and tracts connecting these (Kuhl et al., 2016; Pliatsikas et al., 2015).

1.4.2 Effects of language-related experiences on brain structure, function and cognition

Studies 2 and 3 are meant to address the first aim. In these studies, we examine effects of a variety of language-related factors and their respective effects on a) neuroanatomical and b) neurocognitive adaptations. For both studies we assess the hypothesis that specific EBFs will confer distinct effects in regions specific to language/executive control processes.

Both studies are cross-sectional and recruit a large cohort of bilingual participants, with minimal exclusion criteria applied, such that a maximal range of linguistic demographic background can be represented. Participants will all speak English as an additional language, be living in the UK at the time of testing and have minimal to no exposure to- or competence in- any languages beyond their native language and English. Participants will undergo a variety of scan protocols including a high-resolution structural scan, DTI-weighted scan, functional scan at rest, and functional scan while participants complete a modified flanker task. The flanker task will contain both three mixed blocks (equal congruent and incongruent trials), a congruent block (only congruent trials), a control block, and a neutral block. In addition participants will complete an English proficiency test (Oxford QPT; (Geranpayeh, 2003)), and a detailed language use/background questionnaire- the Language and Social Background Questionnaire (LSBQ). Demographic information from the LSBQ will be used to predict neurocognitive adaptations. Several factors will be run in regression-based analyses assessing individual effects of each. The first two factors static factors related to the *duration* of L2 use: L2 AoA and length of immersion. Additionally, two experience-based factors (EBFs) will outline the *extent* of L2 use in two settings: 1) home settings and 2) social and community settings. These both are weighted factor scores from the LSBQ. These four factors will be run in one model to statistically control for the effects of each other such that we isolate specific effects of each. Finally, we run two EBFs examining the duration of *active* L2 use. These are the static factors from the first model, but accounting for extent of engagement with the

L2, such that they indicate the amount of time spent actively using the L2. The theoretical motivation for this is discussed in more detail in the papers. In brief this helps to assess what it is about duration of use that confers these changes and outlines a way to make such predictors maximally comparable across studies in future.

Study 2 specifically assesses neuroanatomical adaptations, and intrinsic (resting-state) functional connectivity patterns. Several neurophysiological measures will be assessed: 1) Cortical grey matter volume (GMV), 2) subcortical grey matter shape differences, 3) indices of white matter diffusivity (FA, MD, RD and AD), 4) functional connectivity at rest. Study 3 examines the effects of individual differences on both task performance (accuracy and reaction time (RT)), and neural recruitment modulations during the flanker task. These measures will be assessed across several task contrasts: 1) the congruency/flanker effect (incongruent > congruent trials), 2) a global switching or 'mixing' cost (mixed blocks > neutral block), and 3) the facilitation effect (congruent block > neutral block).

We predict that for both studies, specific language experiences will confer specific, distinct structural effects in the brain, in regions related to language processing and control (Abutalebi & Green, 2016; Grundy et al., 2017b). Furthermore, these will modulate neural recruitment patterns by task contrast (facilitation, congruency, and mixing cost). Specifically, we predict that factors related to duration of L2 use will confer structural adaptations towards increased efficiency in language processing and control, which will manifest in subcortical and posterior regions and pathways. This will also manifest as increased efficiency in non-linguistic cognitive control processes, specifically as activations in posterior regions. Extent of L2 use will confer a different pattern of effects- these will be adaptations towards increased cognitive demands of language control in frontal and temporal regions. This will also be present in recruitment patterns. Specifically, duration of L2 use will manifest as increased activations for the task contrasts in posterior and subcortical regions (Grundy et al., 2017b; Stocco et al., 2014). Extent of L2 use will manifest as increased activations in frontal and temporal regions (Green & Abutalebi, 2013).

CHAPTER 2: LINGUISTIC IMMERSION AND STRUCTURAL EFFECTS ON THE BILINGUAL BRAIN: A LONGITUDINAL STUDY

Abstract

Learning and using additional languages can result in structural changes in the brain. However, the time course of these changes, as well as the factors the predict them, are still not well understood. In this longitudinal study we test the effects of bilingual immersion on brain structure of adult sequential bilinguals not undergoing any language training, who were scanned twice, three years apart. We observed significant increases in grey matter volume in the lower left cerebellum, mean white matter diffusivity in the frontal cortex, and reshaping of the left caudate nucleus and amygdala and bilateral hippocampus. Moreover, both prior length of immersion and L2 age of acquisition were significant predictors of volumetric change in the cerebellum. Taken together, these results indicate that bilingualism-induced neurological changes continue to take place across the lifespan and are strongly related to the quantity and quality of bilingual immersion, even in highly-immersed adult bilingual populations.

2.1 Introduction

Since the early 2000s, an increasing amount of evidence has amassed suggesting that bilingualism has an impact on brain structure (Bialystok, 2017; Pliatsikas, 2019), with a smaller amount of studies even suggesting an impact on the brain’s default functionality (Pliatsikas & Luk, 2016). This impact has tended to be measured as a function of differences between bilingual and monolingual populations in cross-sectional designs. As might be expected given the nature of this type of research (see Bak, 2016 for discussion), results have been inconsistent across studies. Indeed, there is variability in terms of location of structural differences in the brain (e.g. hippocampus (Mårtensson et al., 2012), versus supramarginal gyrus (SMG) (Mechelli et al., 2004), versus the left inferior frontal gyrus (Mohades et al., 2012)), and directionality of changes (e.g., increased versus decreased grey matter volume (D. Klein et al., 2014) and/or white matter integrity (Gold, Johnson, & Powell, 2013)). García-Pentón et al. (2016) offer a convincing view of why such inconsistencies likely occur. Even allowing for the fact that the application of neuroimaging methodologies within bilingualism studies is relatively recent, and, therefore, not abundant, García-Pentón et al. argue that non-trivial issues emerge from the lack of standardized protocols across labs. For example, they highlight that higher sample sizes, a consensus of standard scanning procedures across labs and establishing more universal, and better vetting/selection criteria within subject populations are key factors contributing to the dearth of consistency. While we do not disagree with such suggestions per se, it is not clear that dealing with them alone would have the overall effect of teasing out the signal we aim to capture from the noise that muddies it (Bialystok, 2016). Others have argued that another major contribution to the inconsistency of findings in the literature likely stems from treating bilingualism as a monolithic variable. Acknowledging that bilingualism itself is a fluid, complex and dynamic experience is a necessary first step, but acknowledging this alone is not sufficient to deal its contribution to the constituency problem. The nature of the bilingual experience, comprising a dynamic continuum of co-varying factors, must be dealt with methodologically (Bialystok, 2017; Kroll & Chiarello, 2016; Luk & Bialystok, 2013). After all, if it is the experience of bilingualism that gives rise to adaptive change in the brain then it logically follows that various permutations of the bilingual experience should have measurably different outputs.

Although the link between structural changes in the brain and bilingualism is not fully understood, the pattern that emerges is becoming increasingly clear: bilingualism has some type of an effect on the structure of the brain. It seems reasonable that some aspects of the individual experience of being bilingual—factors that vary across individuals and/or whole subgroups—contribute to the ultimate explanation of the variance noted. Under such a view, we should assess specific factors within the bilingual experience—primarily the ones that differentiate types of bilinguals such as age of acquisition (AoA), immersion in the language(s), patterns of using the languages, level of code-switching, relative proficiency in both languages, the social milieu, etc.—with respect to potential effects on the brain. To date, exceedingly few studies have attempted to correlate experience-based factors to structural changes in the adult bilingual brain (e.g. Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017) and none have done so with a longitudinal design. Such a design will help determine whether these factors, and if so which, are likely to explain the observed variability among various bilingual subgroups. Doing so can: (i) reveal that the present literature is less messy than a current snapshot might suggest, (ii) uncover the mechanisms by which changes occur because of bilingualism, (iii) render more precise predictions for where in the brain we might find effects, if at all, and (iv) for which bilingual individuals/groups. In sum, we submit that the ultimate explanation for why replication is an issue in the field may be due to the fact that bilingual samples/cohorts are not adequately measured in terms of relevant experience-based factors that would provide the link between bilingualism and its neurological effects.

Given the above discussion, we used various experience-based variables as predictors of structural changes in the brain and we focus on one in particular—immersion in the L2 context—because it turns out to be (along with L2 AoA) predictive for individual differences in changes in the bilingual brain. Immersion is an excellent factor to begin the unpacking of the catch-all label “bilingual” as often used in the neuroimaging literature for several reasons. First, immersion is a valid proxy for many things such as access to high quantity of language input, the high quality of input (because a majority of it will come from native speakers), and crucially opportunity to use both languages. The proxy of immersion thus has a clear effect on the relative juxtaposition of activation of both languages relative to the inhibitory control needed to keep cross-linguistic influence to a minimum, which has been argued to be a likely contributor to ensuing changes in both bilingual behavior and anatomical changes to the brain (Marian & Spivey, 2003; Spivey & Marian, 1999; Thierry & Wu, 2007). Moreover, the study presented in this paper has an additional value. To our knowledge it is the first study to tackle this issue in a longitudinal manner in adults that do not undergo any kind of L2 training[1]; that is, testing the same individuals more than once

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[1] To our knowledge, there is only one other study that is longitudinal and not a training study, however, this was done with children and not adults. Mohades et al. (2015) is explained in greater detail below.

with no less than 3 years in between scans. Whereas other studies have used a cross-sectional methodology, we will be able to verify changes within the same bilingual brains over time as their period of active immersion in a naturalistic L2 native community increases.

2.1.1 Background literature

L2 AoA has often been used as a proxy for the total amount of time one is exposed to/uses the additional language, and has also been used to investigate optimal or critical periods in brain's plasticity with respect to L2 acquisition (see Berken, Gracco, & Klein, 2017 for review). L2 AoA has been found to relate to increased cortical grey matter (GM) volume, e.g. in the left SMG in bilinguals (Mechelli et al., 2004), cortical thickness in the left and right inferior frontal gyrus (IFG) and the superior parietal lobe in bilinguals (D. Klein et al., 2014), and GM density in the left putamen, posterior insula, bilateral occipital cortex, and right dorsolateral prefrontal cortex, and bilateral premotor cortex (Berken, Gracco, et al., 2016). Effects of L2 AoA have also been found to manifest as increased fractional anisotropy (FA), a common index for measuring white matter (WM) integrity, in various language related tracts including the left inferior fronto-occipital fasciculus (IFOF) (Mohades et al., 2012; Rossi et al., 2017). More recently, AoA has also been found to affect resting state connectivity (Berken, Chai, et al., 2016; Kousaie et al., 2017) (Table 1).

Table 2-1 summary of effects of L2 AoA on brain structure and resting-state connectivity.

Study	Participants	Measures	Findings
(Mechelli et al., 2004)	25 monolinguals 25 ‘early’ bilinguals (L2AoA ≤ 5yrs) 33 ‘late’ L2 AoA 10 and 15	Voxel-based Morphometry (VBM)	-Bilinguals greater GMV in left inferior parietal lobule (IPL) -GMV increase correlates with AoA and proficiency
(D. Klein et al., 2014)	12 simultaneous bilinguals; 25 early sequential bilinguals (mean AoA 5yrs), 29 late sequential bilinguals (AoA 10yrs) 22 monolinguals	Cortical Thickness (CT)	-LIFG (pars triangularis and orbitalis) higher CT for bilingual groups over monolingual. -Late sequential bilinguals, a reduction in CT in the RIFG compared to simultaneous and early sequential bilinguals. -Early sequential bilinguals reduced CT in this area compared to monolinguals. -AoA and CT were positively correlated in the LIFG and left superior parietal lobe; negatively correlated in the RIFG.
(Berken, Gracco, et al., 2016)	16 simultaneous bilinguals; 25 early sequential bilinguals (mean AoA 5yrs),	VBM (GM density)	-simultaneous bilinguals> sequential bilinguals, in the left putamen, left posterior insular cortex, left mid-occipital gyrus, right DLPFC, & right lateral occipital cortex -sequential bilinguals > simultaneous bilinguals in the bilateral premotor cortex
(Mohades et al., 2012)	15 simultaneous bilingual children, 15 sequential bilingual children, 10 monolingual children	TBSS/DTI	-monolingual group displayed the highest FA values for the corpus callosum to occipital lobe (AC-OL) -simultaneous bilingual group highest FA values in left IFOF.
(Rossi et al., 2017)	24 monolingual English speakers, and 25 native English speaking, late learners of Spanish (age range: 18–27)	TBSS/DTI	-L2 learners higher FA values in IFOF, ILF, ATR, UF -FA values correlate with AoA
(Berken, Chai, et al., 2016)	16 simultaneous bilinguals 18 sequential bilinguals (L2 AoA> 5 years)	Resting-state connectivity	-Simultaneous>sequential bilinguals connectivity in cerebellum, bilateral IFG, IPL, DLPFC from seeds in left and right IFG
(Kousaie et al., 2017)	11 simultaneous bilinguals 10 sequential bilinguals (avg. L2 AoA 7 years)	Resting-state connectivity	-vmPFC seed in default mode network (DMN), stronger anticorrelation in connectivity in DMN for simultaneous bilingual group -degree of anticorrelation relates to Simon task performance

Informative as it is, the use of L2 AoA as a predictor of brain changes might be insufficient, for two main reasons: First, cut-off points between early and late bilingualism, very common in earlier studies, are often defined on some arbitrary age criterion, with great variability among studies. Second, simply reporting AoA does not imply active and continuous L2 usage, which in turn might be crucial for any observed brain restructuring. Indeed, it is possible that brain reorganization in bilinguals is in part, if not fully, due to the continuous language switching demands for bilinguals, rather than the mere acquisition of an L2. To this end, L2 immersion, or the amount of time spent in a naturalistic L2 environment, has more recently been examined as a potential key factor (Stein et al., 2014), taken here as a proxy for continuous and intensive exposure to- and use of the L2 (Pliatsikas & Chondrogianni, 2015). Comparing highly immersed to non-immersed sequential bilinguals of comparable L2 proficiency, and to monolinguals, Pliatsikas, DeLuca, Moschopoulou, & Saddy (2017) reported expansions in the globus pallidus, putamen, and thalamus for the highly immersed bilinguals, but only some limited restructuring in the caudate nucleus for the bilingual group with limited immersion. L2 immersion has also been found to affect WM integrity in language-related pathways. Comparing late-acquired, immersed, L2 learners of English to a monolingual control group, Pliatsikas, Moschopoulou, & Saddy (2015) reported increased integrity in several WM tracts including bilaterally the corpus callosum, IFOF, uncinate fasciculus (UF), and superior longitudinal fasciculus (SLF). Crucially this group exhibited patterns of WM increase in a similar manner to elderly lifelong bilinguals (Luk, Bialystok, et al., 2011; Olsen et al., 2015), also pointing to effects of immersion that are independent of the L2 AoA. Kuhl and colleagues (2016), have also reported WM adaptations in response to L2 immersion: specifically mean diffusivity (MD) in anterior tracts of the left hemisphere were modulated by increased L2 exposure (listening), whereas production (speaking) was found to modulate FA values in the posterior section of the left hemisphere. Finally, volumetric increases in the cerebellum in bilinguals have been linked with increased exposure/proficiency in the non-native language, and were correlated with more efficient grammatical processing, which was also native-like in terms of functional activation of the cerebellum (Pliatsikas et al., 2014a, 2014b).

Although technically not a factor that *describes* the bilingual experience, but rather is a consequence thereof, L2 proficiency has also been examined as a potential predictor of neuroplasticity in bilinguals (Abutalebi et al., 2015; Nichols & Joanisse, 2016). Increased L2 proficiency has been found to relate to GM volume increases in regions such as the anterior cingulate cortex (ACC) in ageing bilingual populations (Abutalebi et al., 2015), and WM and functional adaptations in a variety of regions in bilingual adults (Nichols & Joanisse, 2016). Moreover, GM density in the cerebellum has been found to relate to levels of semantic and phonemic fluency in both languages for bilingual adults (Grogan et al., 2009). It is worth noting here that all results corresponding to different measures of proficiency are inextricably related to the measure itself, in the absence of an objective, or at least commonly agreed, way to measure proficiency. It is therefore possible that these effects only reflect the acquisition of the particular skill that the chosen proficiency measure taps on or is more reflective of the fact that increased proficiency is likely to correlate with multiple sub-factors of L2 language use and exposure.

Two proposals have attempted to model the processes of neural adaptation: the Adaptive Control Hypothesis (ACH) (Abutalebi & Green, 2016; Green & Abutalebi, 2013), and the Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model (Grundy et al., 2017b). The ACH discusses brain adaptation as a result of linguistic experience by proposing that the brain adapts to the conversational/linguistic contexts in which one is engaged routinely, including both single and dual language contexts (Green, 2011). These contexts call on varying subsets of cognitive control, including planning, inhibitory, and engagement processes (Green & Abutalebi, 2013). As modulated by changes to experience, a reshaping of cortical and subcortical structures occurs, including the left inferior frontal gyrus (LIFG) left caudate, putamen, and thalamus. The cerebellum is also implicated, forming part of the language control network with the LIFG, caudate, and putamen via the thalamus (Abutalebi & Green, 2016). The BAPSS model examines the overarching effect of bilingual/non-native language use through time. It states that initial stages of contact with an additional language incur reliance on frontal areas, due to increased demands on working memory and several language/executive control processes. As L2 exposure and proficiency increase, reliance on, and use of, the frontal regions shift to subcortical and posterior regions. Naturalistic linguistic immersion is an ideal environment in which to test the models, given the opportunity of continuous and sustained exposure to the additional language (Grundy et al., 2017b). However, both theories have mostly based their predictions on the synthesis of a huge variety of functional and structural brain data which have come either from cross-sectional studies comparing bilinguals to monolinguals, or from studies that report significant correlations between indices of brain structure and function and self-reported demographic variables. Longitudinal studies would be an ideal method to examine how specific experience-based factors of bilingualism manifest in the brain, and crucially how they change through time. Given the main comparison is within-subjects, changes to experience can be isolated and thus examined directly without necessarily collapsing other aspects of bilingualism across one another (Luk & Pliatsikas, 2016; Wong et al., 2016). A handful of studies in the past decade have examined neuroplastic effects of L2 acquisition and use from a longitudinal perspective. Notably, all the available longitudinal studies have focused on the brain outcomes of intensive training programs to participants that were newly acquiring an L2.

Several studies have found cortical GM volume to be affected during the acquisition of the L2 (Bellander et al., 2016; Mårtensson et al., 2012; Osterhout et al., 2008; Stein et al., 2012). For example Mårtensson et al. (2012) studied effects of initial stages L2 acquisition in military interpreters undergoing a 10-month intensive language training course. They report significant increases in GM volumes in the left superior temporal gyrus (STG), left medial frontal gyrus (MFG), and right hippocampus (RHC) after three months, the extent of which correlated with proficiency (subjects' course performance). Differences in WM integrity have also been found as a result of L2 acquisition and/or use over a range of time periods, from hours (Hofstetter et al., 2016) to 12-18 months (Hosoda et al., 2013). A recent study by Mamiya and colleagues examined the relationship of white matter tracts, immersion in an L2 environment, and genetic factors related to the growth of WM integrity (Mamiya et al., 2016). Regarding effects of immersion, increases in FA values in the right SLF were positively correlated with both time spent in the language course and proficiency measures. These values were also found to decline after the course was completed.

While the results are encouraging, available studies only present a partial picture in terms of relating structural change to L2 acquisition and use, for a variety of reasons: First, they primarily examine early stages of L2 acquisition or use (Mamiya et al., 2016; Stein et al., 2012); second, they examine the effects of intensive linguistic training (Hofstetter et al., 2016; Hosoda et al., 2013; Mårtensson et al., 2012), thus report brain adaptations to experiences that stem from a highly controlled linguistic environment.

Third, and perhaps most important, the majority of these studies focused on one aspect of L2 acquisition, very often vocabulary acquisition, so they do not account for the full repertoire of both L2 acquisition and L2 control (lexicon, grammar, phonology, pragmatics) which immersion in an L2-speaking environment brings about. To date, only one study has longitudinally examined the effects of naturalistic language use on the brain. Mohades et al. (2015) compared simultaneous bilingual with early sequential bilingual (mean AoA: 3 years) and monolingual children at two points, (two years apart) across several language-related WM pathways. They report that sequential bilinguals had the greatest increases in mean FA values in the left IFOF after the two-year period, while the simultaneous bilinguals displayed the highest overall FA values in this region at the second scan. Other than that, no study has longitudinally examined the effect of naturalistic immersion on neural plasticity, especially in already-proficient bilingual adults over a long-term period.

2.1.2 The present study

The aim of this study is to examine the effects of naturalistic linguistic immersion on brain structure in adult bilinguals over an extended period. Highly proficient non-native speakers of English were scanned three years apart while residing in the UK. Importantly, these participants did not undergo any linguistic training in their L2 or any other language during their immersion period but had been continuous residents in the L2-dominant environment. We specifically examined potential changes in language demographics, neural structure, and functional connectivity over the three-year period. We also assessed whether any changes in the brain were potentially predicted by differences in linguistic experience- specifically overall length of immersion, L2 proficiency, and L2 AoA.

Given results of previous studies showing effects of L2 immersion (e.g. Pliatsikas et al., 2017), we predict neuroplastic changes to occur, largely in either the cerebellum or subcortical regions, specifically the putamen, thalamus, and globus pallidus (Berken et al., 2016; Grogan et al., 2009; Pliatsikas et al., 2014b; Pliatsikas et al., 2017), as processing/production efficiency increases with prolonged, sustained, exposure to the non-native language (Grundy et al., 2017b). We would also predict higher FA values in WM tracts connecting the subcortical structures with posterior regions including the cerebellum (Abutalebi & Green, 2016; Grundy et al., 2017b). With respect to cortical GM, we do not predict any significant changes, given the majority of reported effects were seen in non-immersed bilingual subjects or those acquiring their L2 (e.g. Mårtensson et al., 2012; Mechelli et al., 2004; Osterhout et al., 2008). Finally, we wanted to test whether any observed changes in structural connectivity are related to changes in functional connectivity, as evidence suggests (Luk, Bialystok, et al., 2011), so we included a resting state fMRI scan.

2.2 Materials and methods

2.2.1 Participants

Twenty-six healthy bilingual participants that had already been scanned for previous projects were invited back three years later[2]. The inclusion criterion was

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[2] A group of monolingual native English-speaking participants (n=25, 14 female, *M*age 28.16, SD 5.3) were also scanned initially as a control group and were invited to this study. Of them, only six participants (4 female, *M*age 33yrs, SD 2.38) returned for Visit 2. The same analytical procedure was applied to this group as for the bilingual participants, and no significant neural changes across the longitudinal period were found for this group. Although this is not a surprise finding, and it would have indeed been our prediction, we do not discuss this cohort in detail primarily due to the small sample size, but also for several additional reasons, which are covered in the Discussion section.

continuous residence in the UK between the two testing points. Of these, nine participated in this study (8 females; *M*age 35.33 years, *SD* 8.12) and the two scanning sessions were approximately three years apart (average time between Visits 1 and 2: 3.22 years; *SD*= 0.12). At Visit 1, the participants had a variety of L1s, were already residing in the UK (*M*length residence: 134 months, *SD* 111.7 months, range= 4 months to 196 months), and they reported an average AoA of L2 English of 10.5 years (*SD* 4.6) (See Table 2 for details).

Table 2-2: Demographic information for subjects at Visit 1.

Subject	**Age**	**Sex**	**Education**	**Native Language**	**UK Residence (months)**	**QPT Score (%)**	**L2 AoA**
1	34	M	Graduate School	Greek	99	98	8
2	50	F	College (BA/BS)	Chinese	374	92	7
3	37	F	Graduate School	Polish	114	70	4
4	34	F	Graduate School	French	144	93	16
5	40	F	Graduate School	Polish	92	73	19
6	31	F	Graduate School	Italian	4	62	8
7	26	F	Graduate School	Greek	5	79	9
8	49	F	Graduate School	German	175	100	11
9	44	F	College (BA/BS)	Spanish	196	100	4

2.2.2 Procedure, Data Acquisition, and Analysis

In both Visits, prior to their scan participants were assessed for their English proficiency via the Oxford Quick Placement Test (QPT) (Geranpayeh, 2003). The same scanning protocol was implemented for both Visits 1 and 2. Brain images were collected with a 3.0-Tesla Siemens MAGNETOM Trio MRI scanner with Syngo software and 32-channel Head Matrix coil. T1-weighed MPRAGE (Magnetization Prepared Rapid Gradient Echo) images were collected from each participant (192 sagittal slices, 1 mm slice thickness, in-plane resolution 250 x 250, acquisition matrix of 246 x 256 mm, echo time (TE) = 3.02 ms, repetition time (TR) = 2020ms, inversion time = 900ms, flip angle = 9°). The scan lasted approximately 10 minutes. T2-weighted Diffusion-Tensor Imaging (DTI) images were also collected (60 transversal slices, 2mm slice thickness, acquisition matrix 256 x 256, in-plane resolution 128 x 128, 2 averages, TE= 93ms, TR= 8200ms). The scan lasted approximately 11 minutes. A resting-state Echo Planar Imaging (EPI) sequence was also run for each participant (200 volumes, 56 transversal slices, 3mm slice thickness, in-plane resolution 64x64, acquisition matrix of 192x192mm, TE= 30ms, TR= 3000ms, flip angle= 90°). This scan lasted approximately

10 minutes. The MRI scanning session did not involve any tasks. However, subjects were advised to keep their eyes open during the resting-state scan.

T1-weighted images were pre-processed with the FSL_anat software pipeline in FSL (Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012). Images were reoriented to the Montreal Neurological Institute (MNI)-152 orientation, automatically cropped, bias-field corrected, and non-linearly-registered to MNI space. Grey matter volume was calculated via the voxel-based morphometry (VBM) pipeline in FSL (Ashburner & Friston, 2000). Pre-processed images were brain extracted and grey matter segmented. A study specific template was then created using the average of the GM images. Native GM images were registered to this template and modulated to correct for local expansions and contractions due to the non-linear component of registration. They were spatially smoothed with an isotropic Gaussian Kernel of 3mm. A voxel-wise general linear model (GLM) was applied to test for differences between Visits 1 and 2, using permutation-based non-parametric testing. Two contrasts were examined: Visit 2>Visit 1 and Visit 1>Visit 2 to assess directionality of any significant differences; that is, whether any differences were increased or decreased GM volume between the two sessions. Corrections for multiple comparisons across the brain were done using threshold-free cluster enhancement (TFCE) (Smith & Nichols, 2009).

For the subcortical structures, a vertex-based analysis was applied via the FIRST software package of FSL (Patenaude et al., 2011). Several structures were extracted including the bilateral hippocampus, amygdala, thalamus, globus pallidus, putamen, and caudate nucleus. Although changes in the amygdala have not been reported in the bilingual literature, we decided to add them to this analysis due to the close proximity and relationship with the hippocampus (Schumann, 1990, 2001). Quality of the extractions was then assessed. No images were discarded. The resulting images were then submitted to vertex analyses. Per standard procedure, each structure underwent a 6 degrees of freedom rigid body transformation to study-specific template in standard space. The vertex coordinates of individuals were then projected onto the average coordinates of the two scanning scans. For each participant, this created maps signifying positive (outside the surface) or negative (inside the average surface) values for each structure. Finally, the values were analyzed using a voxel wise GLM (Smith & Nichols, 2009). The contrasts examined were Visit 2> Visit 1 and Visit 1> Visit 2, to examine what changes occurred (both expansions and contractions) between the two scanning points. Age and sex were included in the model as covariates of no interest. Corrections for multiple comparisons using were done via the Randomise pipeline within FIRST (Winkler, Ridgway, Webster, Smith, & Nichols, 2014). This created maps of within-groups differences, thresholded at $p \leq 0.05$.

For the analysis of structural connectivity, we looked at FA and MD values across the brain as the most commonly used indices of white matter integrity. FA and MD values were calculated using the FDT (Behrens et al., 2003) and TBSS (Smith et al., 2006) pipelines within FSL. Images were corrected for head motion and eddy-current distortions, then a diffusion-tensor model was fit for each voxel of the corrected data, using DTIFIT. This resulted in individual FA and MD images for each participant from Visits 1 and 2 respectively. Using TBSS, the FA images were (in a combined process) non-linearly registered to a standard space FA target image and affine-transformed to MNI standard space. This resulted in a 4D image which consisted of each FA image from the participants. An FA skeletonisation program was used to create an FA skeleton that included the voxels identified as white matter (WM) in each FA image, thresholded at 0.2. MD images were then nonlinearly registered to standard space and were then warped and registered into a single 4D file which was projected onto the mean FA skeleton. Finally, a within-groups voxel wise analysis was applied to test for differences between Visit 1 and 2 for the FA and MD data respectively. The contrasts examined were Visit 2>Visit 1 and Visit 1>Visit 2, to assess the directionality of the changes. Age and sex were included in the model as nuisance covariates. This resulted in a whole-brain t-statistical image of significant differences in FA and MD between the two scan points.

For the resting-state data, we conducted an independent components analysis (ICA), as this offers a data-driven approach to analysis, and mitigates the risks of potential biases in the data imposed by the more traditional seed-based resting state analysis (for discussion see Beckmann & Smith, 2004). The data were analyzed using the Multivariate Exploratory Linear Optimized Decomposition into Independent Components (MELODIC) pipeline within FSL (Beckmann & Smith, 2004, 2005). Resting-state data was preprocessed including motion corrections, corrections for field distortions, and registered to standard space. The processed datasets were then decomposed into spatial and temporal components using a multi-session temporal concatenation. This process involves the concatenation of all subjects' preprocessed 4D datasets, which subsequently are submitted to an independent components analysis. This generates a series of spatial maps which correspond to common components across each subject. Once components were established, these were submitted to group-level analysis via the dual_regression pipeline within FSL (Beckmann, Mackay, Filippini, & Smith, 2009). This involves a two-stage process in which the group-level spatial maps (common components) are regressed into each subject's 4D dataset to render a series of time courses. The time courses are in turn regressed into the same dataset to create a subject-specific set of spatial maps. These spatial maps are then compared across subjects via a within-subjects GLM, assessing Visit 2>Visit 1 and Visit 1>Visit 2, with age and sex included in the model as nuisance covariates. Correction for family-wise error was done with Randomise permutation testing (Winkler et al., 2014).

2.3 Results

2.3.1 Proficiency

We first looked at whether the participants' proficiency changed as a function of linguistic immersion. Results of a Wilcoxon's signed rank test showed that no significant change in the QPT scores occurred over the three-year period (*M*difference=3.481%, SD=12.03, p=.515). However, this is not surprising, as our participants were already at a proficiency ceiling at Visit 1, as measured by their performance on the QPT (Table 2). Spearman's Rho correlations between immersion (time spent in the UK at Visit 1), English (L2) proficiency (QPT score at Visit 1), and L2 AoA showed a marginally significant correlation for immersion and proficiency, r_s=.661, p=.053. None of the other correlations approached significance (proficiency and AoA: r_s=-.371, p=.325; AoA and immersion: r_s=-.017, p=.996). Finally, we also observed that the proficiency x immersion correlation disappeared at Visit 2 (r_s=.085, p=.753).

2.3.2 Grey Matter

Results of voxel-based morphometry (VBM) analysis showed a significant, corrected, increase in GM volume for Visit 2 over Visit 1 in the lower VIIb region of the left cerebellum (peak coordinates-32, -68, -58; 115 voxels; p=.033) (Fig 1). No significant decreases (Visit 1>Visit 2) were found. We assessed the normality of the distribution of the extracted volume changes within the cerebellum. This was done to ensure that the effect was not being driven artificially by a small portion of the participant sample. A Shapiro-Wilk test showed the changes in GM volume to be normally distributed (p=.887), with no outliers.

Figure 2-1: Results of VBM analysis. Significant grey matter volume change (orange) within the right cerebellum. Coordinates listed in MNI-space.

Our subcortical analysis produced no significant effects in the corrected results from the permutation analysis, which is not surprising given the sample size. Significant (uncorrected) contractions and expansions from the vertex analysis were thresholded at $p \leq 0.002$ to account for multiple comparisons (dividing the target significance threshold by the number of tests run (24- two tests per 12 structures). Expansions and contractions were found in several structures, including a contraction in the left caudate nucleus, a contraction in the left amygdala, a small expansion and larger contraction in the ventral anterior portion of the right hippocampus, and a contraction the dorsal anterior portion of the left hippocampus. Table 3 illustrates these effects. Changes in the putamen, globus pallidus or the thalamus did not survive thresholding.

Table 2-3: Results of vertex analysis corrected for multiple comparisons (thresholded p<.0021)

Structure	**Hemisphere**	**Expansion/ Contraction**	**Voxels**	**p**	**x**	**y**	**z**
Caudate	L	Contraction	597	0.002	-18	-8	21
Hippocampus	R	Expansion	15	<0.001	20	-29	-10
	L	Contraction	85	0.001	-27	-19	-13
	R	Contraction	138	<0.001	23	-22	-19
Amygdala	L	Contraction	83	<0.001	-28	-5	-18

2.3.3 White Matter

No significant differences of FA values (increase or decrease) were found between Visits 1 and 2 for any WM tracts. Significant, corrected, increases in MD values were found in two clusters in the left forceps minor (-20, 44, 3, cluster size: 174 1 mm^3 voxels; and -19, 34, 16, cluster size: 27 1 mm^3 voxels). These effects are illustrated in Figure 2.

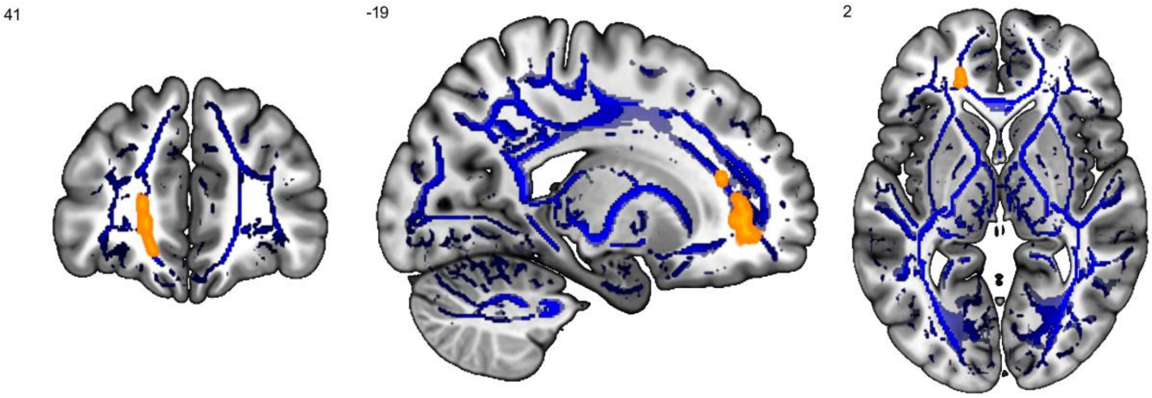

Figure 2-2: Results of MD analysis. Increases in MD values (yellow) in the left forceps minor (blue). Coordinates listed in MNI-space.

2.3.4 Resting-State Networks

No significant differences (increase or decrease) were found in functional connectivity for any resting state networks between Visits 1 and 2.

2.3.5 Regression Analyses

To determine the role of the subjects' language experience in shaping brain structure, we ran multiple regression analyses on the affected brain regions using immersion (months of residence in the UK at Visit 1) and L2 AoA as predictor variables, and age and sex as nuisance covariates. Specifically, the volumetric change in the cerebellum and the MD change in forceps minor were analyzed respectively with the above predictors. Given that proficiency at Visit 1 was found to correlate with length of immersion, it was not included in the final model to avoid issues of multicollinearity.

The model was found to significantly predict the longitudinal cerebellar GM increase, F(4,4)=10.73, $p<0.021$, $R^2=.829$. Specifically, L2 AoA was found to negatively correlate with the cerebellar increase (β=-.815, p=.0066) and length of immersion was found to positively correlate with it (β=1.391, p=.00815) suggesting that the greater the immersion, and the younger the AoA, the more plastic the cerebellum became. Figure 3 illustrates this. The model did not significantly predict the changes in MD values in forceps minor (all ps>0.1).

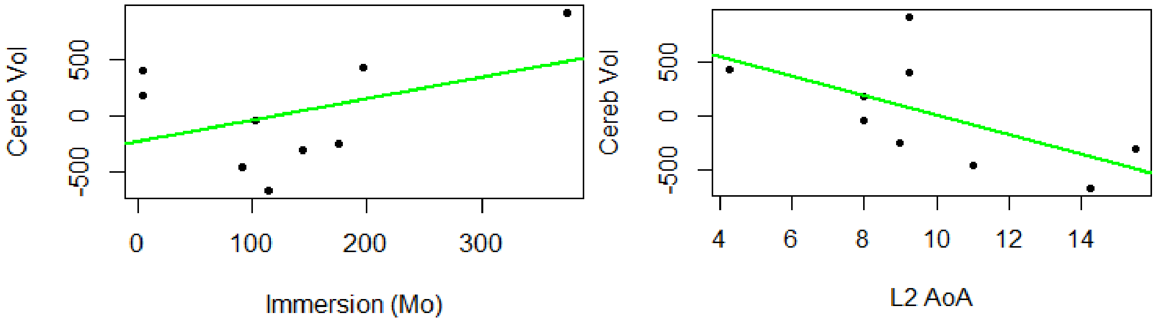

Figure 2-3 a,b: Relationship between cerebellar volume change and Immersion at Visit (a), and L2 AoA (b).

2.4 Discussion

The working hypothesis of this paper has been that it is not bilingualism *per se,* but potentially particular variables (and not others) related to the dynamics of the bilingual experience that induce anatomical brain changes. If on the right track, the interplay of certain experience-based variables and their relative weight should correlate to individual subject and cross-aggregate differences outcomes in individual studies and, by extension, explain at least some of the disparities across the literature. Herein, bilingual subjects were scanned twice with a three-year interval between scans while residing in the UK. Recall that there was a range of exposure in the same L2 immersion environment at Visit 1 (range= 4 months to 12 years), however, all subjects share a crucially common experience, that is, the same amount of time in between Visits 1 and 2. Also recall that our analysis was focused on change that took place from the point of each individual's own baseline (change between Visit 1 and 2), which crucially did not coincide to any major change in the lifestyle and/or experiences of our participants (e.g. arrival in the UK), or at least any change that applied to the entire sample.

Several changes were seen between the two scan points: a significant increase in grey matter volume was found in the lower left cerebellum, and reshaping in several subcortical structures including the (bilateral) hippocampus, left amygdala, and left caudate. Moreover, we observed a significant increase in MD values within the left forceps minor. These results add to a growing body of literature supporting the role of linguistic immersion in neuroplasticity related to bilingualism (Kuhl et al., 2016; Pliatsikas et al., 2017, 2015). Taken together, the grey matter adaptations support aspects of both the BAPSS model (Grundy et al., 2017b) and ACH (Abutalebi & Green, 2016). The changes in the cerebellum, forceps minor, caudate, and hippocampus show an overall adaptation within the language control network towards a more automated system of processing and production in the L2, as demonstrated below.

The increase in cerebellar GM volume partly replicates findings from previous work comparing bilinguals with limited immersion to age-matched monolinguals (Pliatsikas et al., 2014b) – specifically the same region of the cerebellum was found to expand for both studies. The cerebellar expansion over the three year period is in line with aspects of the BAPSS and ACH models- specifically that the increased reliance on subcortical/posterior structures in the language control network is commensurate with increased time spent intensively using the L2 (Abutalebi & Green, 2016; Grundy et al., 2017b), which in turn leads to increases in GM volume in these areas. It should be noted that the BAPSS model does not explicitly include the cerebellum in the posterior structures that are implicated in the shift with increased L2 exposure. However, the cerebellum has been implicated in several functions related to language including automated processing of grammatical rules in one’s non-native language (Pliatsikas et al., 2014b; Ullman, 2004), language control between the L1 and L2 (Filippi et al., 2011), and articulatory processes for bilinguals (Frenck-Mestre et al., 2005; Grogan et al., 2009). The connection with the time spent using the L2 is corroborated by the correlations with both L2 AoA and immersion seen in the multiple regression. The negative correlation with L2 AoA suggests that the earlier one acquires their L2 the greater plasticity in the cerebellum may be predicted. Similarly, the positive correlation between immersion and the cerebellar increase indicates that the longer one is immersed in the environment of the L2, the more likely they are to experience change in this region. The cerebellar expansion related to L2 AoA and immersion, appears to support an account of increased reliance on the cerebellum, as processing and production in the

L2 becomes more automated. In any case, the present pattern of effects suggests that the more experienced in an L2 one is, the more plastic the cerebellum becomes.

The reduction in the left caudate likely indicates a decreased switching cost between the participants' languages (Elmer, Hänggi, & Jäncke, 2014). The caudate has been implicated in a number of control processes in bilingual language processing and production (Abutalebi & Green, 2016; Luk, Green, et al., 2011). The reduction found in the caudate may thus reflect an optimization of the system to the language control demands within the immersion environment. An alternative explanation for this comes from the Conditional Routing model (Stocco et al., 2014), which suggests that increased automation in language switching and selection occurs in cortical regions, thus decreasing demand on the caudate, resulting in contractions. Similarly, recall that both expansions and contractions within the right hippocampus were found. It should be noted that the ventral anterior contraction in the right hippocampus overlaps with the expansion found by Bellander and colleagues (2016), who report the increased GM volume in the right hippocampus to be predicted by number of hours spent acquiring new words. In the case of the immersed bilinguals, the contraction likely indicates a return to baseline from an expansion at the first stages of L2 acquisition and/or immersion (e.g. Bellander et al., 2016; Mårtensson et al., 2012). The contraction in the right hippocampus may also be evidence for proceduralization within the L2 (Pliatsikas et al., 2014b; Ullman, 2004). Increased reliance on the procedural system in the processing and production in the non-native language, thus increased use on the cerebellum, would entail decreased use of the declarative memory systems, thus a decreased use of the hippocampus, leading to contractions in this structure.

The contraction in the left amygdala was not predicted, as it has not been typically reported in studies about bilingualism-induced structural changes, nor is it typically implicated in language processing and control in bilinguals (see e.g. Abutalebi & Green, 2016; Grundy et al., 2017; Stocco & Prat, 2014). The only exception is Li and colleagues (2017), who found increased GM volume in the left amygdala/hippocampus for older bimodal bilinguals who were active daily users of both languages. It has been proposed that the amygdala forms part of a corticofugal pathway for memory formation, and plays a role in regulation, stimulus appraisal, and motivation (based on emotional valence) in the formation of new memories in L2 acquisition (Schumann, 1990, 2001). The contraction in the amygdala, then, indicates a lower reliance on short-term/declarative memory formation procedures, in line with the contractions found in the hippocampus. However, a lack of neurolinguistic data currently exist to support this interpretation. It is also worth reiterating that the effects found in the hippocampus, caudate, and amygdala were found did not survive correction for multiple comparisons, thus should be interpreted with caution.

No differences were seen in the globus pallidus, putamen, or thalamus during the three year period, which is not in line with our predictions (Berken, Gracco, et al., 2016; Burgaleta, Sanjuán, Ventura-Campos, Sebastián-Gallés, & Ávila, 2016; Pliatsikas et al., 2017). This lack of difference between Visits 1 and 2 for these structures can be interpreted as no change in the reliance on them during this period. Demographically, our group is highly similar to the group in Pliatsikas et al. (2017), which reported structural changes in both structures for bilinguals vs. monolinguals. If the thalamus is crucial in selecting among lexical and semantic alternatives (Abutalebi & Green, 2016; Llano, 2013), the absence of any longitudinal structural changes probably reflects that the control needs did not change between Visit 1 and Visit 2, which is to be expected as in both cases our participants were immersed in the same environment. The putamen has been implicated in phonological monitoring in bilingual language production

(Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013). Similarly to the thalamus, the lack of change in the putamen indicates that the demands on the underlying system will not have changed. Finally, a similar explanation may also be given for the absence of change in the globus pallidus: that the demands on semantic control and selection would not have changed, even after periods of extensive immersion. An alternative explanation for the lack of changes in these structures might be that the selection and monitoring mechanisms were already optimized at Visit 1 and, as the relevant cognitive demands did not change between visits, the structure of the implicated regions remained stable. This would align with tenets of the ACH (Abutalebi & Green, 2016), specifically that continued plasticity of given brain regions would be dependent on changes in language use and/or exposure.

No significant changes in FA values were found in any region of the brain. This finding is not in line with the proposals of the BAPSS model (Grundy et al., 2017b), which would predict increased use of subcortical to posterior tracts, and thus increased myelination in those tracts linking the subcortical structures to those regions. It is important again to remember that our group in this study was demographically very similar to the group from Pliatsikas et al. (2015), meaning that higher levels of FA can already be assumed at Visit 1, as an effect of continuous prior exposure. What we didn’t find here is further FA increase *or* decrease *within* participants. An explanation for this lack of changes could be the same as the one for the absence of thalamic effects: the same needs for efficient communication between brain areas applied to both test points, so an already optimized system retained its structure. Not only would this explain the lack of FA *decreases* in Visit 2, but also reconciles with the fact that increased FA persists even in older bilinguals compared to monolinguals, while other effects typically disappear. In the same vein, the lack of *increases* in FA might reflect either that the system has reached and maintained the appropriate level of “reinforcement” needed to deal with the demands of the bilingual experience, or more simply, that there are physical constraints in white matter restructuring, that have now been reached. The small increases in MD in the forceps minor are less readily explainable. Forceps minor is the most anterior part of the corpus callosum, which projects to the frontal lobes, and has been associated with executive control (Kuhl et al., 2016). While several anterior and medial parts of the corpus callosum are shown to increase their FA and/or volume as a result of bilingualism (Coggins et al., 2004; Felton et al., 2017; Pliatsikas et al., 2015), changes in the MD of the forceps minor have only been reported in two studies: Cummine & Boliek (2013) reported decreased MD values for bilinguals vs. monolinguals in the left forceps minor, while Kuhl et al. (Kuhl et al., 2016) reported negative correlations between MD in this region and the bilinguals’ residence in the L2 speaking country, in that the smaller the immersion the larger the MD values. Higher MD values are typically explained as higher white matter diffusivity, which might signify reduced myelination. With this in mind, an interesting pattern emerges: the participants in both Cummine & Boliek and Kuhl et al. studies were at initial stages of L2 immersion, and showed increases in myelination, expressed as decreases in MD (but not increases in FA). On the other hand, our highly immersed participants showed small increases in MD but not decreases in FA. Although the exact correspondence between FA and MD is not fully understood, it appears that initial immersion causes changes in the MD of frontal areas, which are crucial for cognitive control. With increased immersion, it appears that overall diffusivity is also increased, possibly reflecting less reliance in the region because efficient control of languages has been achieved, while the directionality of the diffusivity, which is better expressed by the FA, remains unchanged. This suggestion is congruent with the BAPPS prediction of reduced reliance in frontal regions as an effect of L2 immersion. Nevertheless, more research is needed to understand the complex relationships between the FA and the MD, and how these are affected by the bilingual experience.

No significant differences in resting-state connectivity were seen between Visits 1 and 2. As this analysis was exploratory, we did not have any specific predictions about how the resting-state networks would change between Visits 1 and 2.

It is also worth noting that L2 proficiency was not found to increase between visits. Regarding change in proficiency, it is prudent to note a few things that render the lack of effects less surprising. Firstly, the participants were already highly proficient in English at the point of Visit 1 (see ‘participants’ section for details). Given that L2 learners tend to show ceiling effects in ultimate attainment that differ from typical monolingual acquisition (see Long, 2007; Rothman, 2008b for opposing views on how to interpret such finds), their initial proficiency was likely high enough that continued immersion effects would not result in changes as measured by the QPT. In this context then, we need to keep in mind what the QPT and measures like it are, and what its purpose is in our study. The QPT is designed to gauge so-called global proficiency and such measures tend to focus on properties of the formal grammar, especially lexical-semantic knowledge, as opposed to colloquial language, overall verbal fluency and other language aspects that are likely to be positively affected by continued immersion, even in the case someone has a highly proficient grammar at the outset. By *grammar* we are referring to the set of underlying mental representations and rules that form the computational system enabling an individual to comprehend (decode linguistic information received) and produce (encoding information onto language specific forms to be uttered) intended messages for any given language. The purpose of a proficiency measure is most crucial at Visit 1 to get an initial baseline, ensure a minimum level of proficiency for inclusion in a study, and for purposes of comparison across studies (present and future ones) who have similar subject profiles, including L2 proficiency. Were there to be a measure that could tease apart gains in the above-mentioned domains of language use for L2 learners, we might expect three additional years of immersion would show considerable gains. The fact that there is no observed increase in proficiency, despite clear changes to the brain in the same time span, already suggests that measures like the QPT are unable to capture the full picture of what is going on. Although L2 grammatical knowledge as measured by the QPT can reach a ceiling effect for such measurement, clearly continued exposure is still having significant effects that would otherwise not be captured, save for the use of different methodologies that are more fine-grained (such as MRI). For these reasons, and because linguistic immersion and proficiency are not independent to each other, as our results showed, we chose not to include proficiency as a predictor in our models.

This said, from a linguistic perspective it is not clear why proficiency per se would predict differences, provided that we are looking at individuals with at least a minimum level of exposure to and proficiency in the L2 (both serving as proxies for opportunity to develop a mental L2 grammar). This is evidenced by the correlation between length of L2 immersion and proficiency levels at Visit 1 and the fact that this correlation disappears after the three-year immersion period, as by then all would have surpassed the minimum threshold. Even more important, however, is the fact that when one has high degrees of verbal fluency in an L2, even if extremely different from what natives of the target grammar display, it is regarded as a complete grammar itself, referred to in the literature as *interlanguage* (Selinker, 1972). The basic idea is that at any given point in L2 development, the L2 grammar is a full grammar, much like it is for children developing their L1. If on the right track, then L2 proficiency is merely a measure of how native-like one is on a continuum, not a measure of how complete (in the sense of being considered a mental computational grammar itself) the developing system is. In this sense, the activation vs. inhibition tension that likely underlies changes to the bilingual brain (behavioral and anatomical) starts and is functionally much earlier than might otherwise be expected. The brain does not know when a grammar is target-like, it simply knows when there is a need to inhibit a competing system regardless of its stage of development. From such a perspective then, it is not clear that relative proficiency should matter. This is, of course an empirical question.

Taken together, our results show that immersive bilingualism continuously affects the structure of a dynamic system including the cerebellum, the hippocampus and the basal ganglia, as well as the integrity of the white matter, even after years of bilingual immersion. The reported patterns generally support the predictions of the BAPSS model and ACH, with some potential modifications. The expansions in the cerebellum and the reshaping/contractions in the caudate nucleus and hippocampus, and potentially the MD increase in the forceps minor, serve as neurological markers of increased efficiency and automation of processing and production in the L2 (Abutalebi & Green, 2016; Booth et al., 2007; Filippi et al., 2011; Pliatsikas et al., 2017), while the overall stability of the white matter diffusivity across the entire brain, paired with the structural stability of the thalamus and the putamen, suggest that the language control demands persist irrespective of the amount of L2 immersion. Future work should consider the cerebellum as a key structure in brain adaptation to L2 exposure and use, particularly at later stages of development.

An obvious limitation of our study was the high attrition rate of participants between Visits 1 and 2, thus our sample size ended up being fairly low (n=9). Nevertheless, the cerebellar and MD effects survived statistical corrections even with such a small sample, such that they are nonetheless reliable. A larger group at Visit 2 would have probably produced more robust findings in both cortical and subcortical regions. The GMV increase in the cerebellum would likely remain, along with decreases in GMV in frontal regions (Grundy et al., 2017). The contractions in the caudate and hippocampus would likely also remain. Finally, we might have expected to see modulation in white matter integrity in pathways connecting the cerebellum to the basal ganglia and frontal regions. However, these predictions require further investigation with an appropriate number of participants. Future longitudinal studies should strive to implement appropriate strategies in order to retain a greater number of participants in their final cohort. This of course likely requires a larger number of participants at the outset since attrition is common in studies like this, especially given a duration of three years between testing sessions. Future studies should also incorporate an extensive behavioral battery tapping at both executive functions and language abilities in L1 and L2, in order to study how these change as a factor of immersion, and whether they are linked with the observed structural changes.

Finally, a control group was not reported in this study, for several reasons. Despite our attempts to test a monolingual native-English speaking cohort as the control group (see footnote 1), we would still treat any findings with caution. Inclusion of such a cohort represents a comparative fallacy in examining specific neural effects of linguistic immersion, as these cannot be teased apart from any other effects related to the bilingual experience more generally. In other words, if we included a control group of this kind our null hypothesis would have been that the observed effects should appear in both language groups, or that the cerebellum continues to expand for everyone, no matter the language status. However, we certainly don’t have such a prediction, but we do have the valid prediction that the cerebellum reshapes as a result of the bilingual experience. Since our participants act as their own controls, we fail to see what the addition of a monolingual control group could add to the narrative. Conversely, the appropriate control group to use here, and the one we would suggest for future studies, would have been a highly-proficient bilingual cohort living in a country where their L2 (in this case English) is not the dominant language for communication, which would allow for the examination of effects of linguistic immersion independent of other potentially conflating experiences in bilingualism. Second- recall that the bilingual cohort in this was not homogeneous- they exhibited both a range of AoAs of English and length of immersion at Visit 1, and furthermore stemmed from a variety of professions. It is increasingly likely, then, that the one major commonality in their experiences (and thus neural outcomes) could be related to linguistic immersion within the three-year (longitudinal) period. Potential alternative explanations of our findings would include them being a result of major lifestyle changes in our participants' lives that might induce neural adaptations, such as taking up a sport or learning a musical instrument. To the best of our knowledge no such activity was taken up by all of our participants after Visit 1. Other potential causes of structural changes include ageing, which is hard to establish given the wide age range of our sample (and the fact that we added age as a covariate in our models), major changes of environment, such as recent migration, and the emotional imbalance it may bring about, which clearly does not apply to our already immersed participants, and major changes in general quality of life. The latter is a very broad concept encompassing a variety of factors (socioeconomic status, family experiences, education, general health), which is difficult (if not impossible) to test systematically; still, any changes to quality of life would have to apply to all of our participants (and to an entire control group for that matter) in order to produce these group effects.

2.4.1 Conclusions

In this study—the first to look at the longitudinal effects of L2 immersion in a group of highly proficient adult bilinguals—we showed that L2 exposure and use continue to impact brain structure beyond acquisition and initial stages of use. Crucially, bilingualism (and immersion where it applies) is a dynamic process in which brain adaptations are modulated through time by exposure and changes in efficiency of production and processing. Our approach and results also support current arguments that future research should move away from traditional cross-sectional comparative (bilingual vs. monolingual) designs and turn its attention to the experience of bilingualism itself, with a focus on experience-based factors to be used as predictors in assessing the specific impact of bilingualism on brain structure and function. Although exceedingly difficult to shift towards true longitudinal studies where change can be tracked within individuals as the dynamics of bilingualism unfold over time, the sacrifices (e.g., numbers of participants in light of attrition, the temporal length of the studies themselves, etc.) one will need to make will be overshadowed by the increased precision and comparability that intragroup comparisons provide.

CHAPTER 3: REDEFINING BILINGUALISM: A SPECTRUM OF EXPERIENCES THAT DIFFERENTIALLY AFFECT BRAIN STRUCTURE AND FUNCTION

Abstract

Learning and using an additional language is shown to have an impact on the structure of the brain, including in regions involved in cognitive control and the connections between them. However, the available evidence remains variable in terms of the localization, extent and trajectory of these effects. This variability likely stems from the fact that bilingualism has been routinely operationalized as a categorical variable (bilingual/monolingual), whereas in reality it is a complex and dynamic experience with a number of potentially deterministic factors affecting neural plasticity. Here we present the first study investigating the combined effects of several factors, both absolute and experience-based (EBFs), in bilingual language use on brain structure and functional connectivity. Our factors included an array of measures of everyday usage of a second language in different types of immersive settings (e.g., amount of use in social settings). Our analyses showed specific adaptations in the brain, both structural and functional, to individual factors and their combined effects. Taken together the data show that the brain adapts to be maximally efficient in the processing and control of two languages. This process of adaptation is modulated by differences in language use, thus, ultimately by the individual's particular language experience. Questions pertaining to bilingualism effects on the mind (cognition) and brain (neuroanatomical adaptation) are thus shown to not be amenable to yes/no dichotomies, highlighting the necessity of a detailed individual differences approach moving forward.

3.1 Introduction

Using more than one language has been found to impact both brain structure and function (García-Pentón et al., 2016b; P. Li et al., 2014; Pliatsikas, 2019). The use of an additional language is argued to create two active representations that compete for selection at several levels of language processing and production (Kroll et al., 2012; Luk et al., 2012). Resolution of that competition is required for successful communication. The process of selection places increased demands on both the linguistic and nonverbal executive control systems. The brain adapts both functionally and structurally to optimally handle these demands (Abutalebi & Green, 2016). Nevertheless, there is variability in specific effects of bilingualism across studies that we surmise is more systematic than might initially appear. A considerable portion of conflicting evidence likely stems, at least in part, from the inconsistency in how bilingualism is defined (Luk & Bialystok, 2013; Surrain & Luk, 2017) across studies. Reducing the dynamics of bilingualism to a discrete set of pre-defined aggregate groups collapses, and potentially obscures, factors that drive brain adaptation (Bialystok, 2016). Important differences clearly exist at the individual-to-individual level, and specific group-to-group levels, within the same and across subtypes of bilinguals. Thus, it is prudent to ponder why bilingualism is so often taken to be a monolithic variable in empirical studies seeking to assess what it conveys to brain structure and cognition.

Understanding the consequences of bilingualism on mind and brain requires a more nuanced examination of the predictive validity of various bilingual experiences (language use, exposure, etc. and their relative weights) to outcomes. This study tests this general line of reasoning, sidestepping the possible comparative fallacy inherent to a monolingual versus bilingual binary designs. To do so, we focus instead on how bilingual experiences impact brain structure and functional connectivity where bilingualism is examined as a continuum. Variables that situate individuals along that continuum are modelled to better understand how the dynamic nature of bilingualism affects the brain differentially. In turn, there is significant potential for this approach to shed light on the ongoing debate on the neurocognitive effects of bilingualism (R. M. Klein, 2016; Paap et al., 2015a).

Neural adaptations to bilingual language use are typically found in brain regions and pathways implicated in language processing and control. Discrepancies exist, however, between studies regarding where and how specific adaptations manifest in relation to bilingual language use, but also regarding the particular neuroimaging methods used (García-Pentón,et al., 2016; Luk & Pliatsikas, 2016). Effects of bilingualism have been reported as differences in cortical and subcortical grey matter volume (Mårtensson et al., 2012), shape differences via vertex analysis (Burgaleta et al., 2016), differences in diffusivity patterns (e.g. fractional anisotropy (FA)) (Schlegel et al., 2012), and more. While some studies include several measures of neural adaptations, such as both structural and intrinsic functional connectivity changes (Luk, Bialystok, et al., 2011), most examine only one type of adaptation, prompting calls for greater methodological consistency between studies (García-Pentón et al., 2016b) .

Two proposals have attempted to explain observed variance with respect to bilingual language experiences, insights used to understand results from our empirical study. The Adaptive Control Hypothesis (ACH) (Abutalebi & Green, 2016; Green & Abutalebi, 2013) states that language use context (single language, dual language, or dense code-switching) dictates the recruitment of the relevant networks best suited to handle the computational load. The Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model (Grundy et al., 2017b) states that reliance on specific networks changes from frontal regions to subcortical and posterior regions commensurate with increased L2 use. A growing number of studies have begun to examine neuroanatomical effects of experience-based factors (EBFs) within bilingualism, for example L2 Age of Acquisition (AoA) (Nichols & Joanisse, 2016; Rossi et al., 2017), length of immersion (Kuhl et al., 2016; Pliatsikas et al., 2017) and L2 proficiency (Abutalebi, Della Rosa, Ding, et al., 2013; Mamiya et al., 2016). However, the factors addressed in available studies are limited because they were examined in (a) relatively narrow ranges, and (b) in (relative) isolation from each other. Thus, potential combined effect shared between variables are unknown. For example, L2 immersion provides an environment of intensive exposure to native input in the L2 and opportunities to use the L2 in ecologically authentic contexts, which, in turn, facilitate inhibition of the L1 (Linck, Kroll, & Sunderman, 2009). However, L2 immersion does not guarantee the same degree of L2 exposure, nor opportunity for use, across all individuals. An analysis that is able to model the relative weight/contribution of various EBFs across a large enough cohort— capturing, for example, relationships between duration and quantity/quality of bilingual language use— could begin to uncover the underlying reasons for conflicting evidence in the literature.

The present study addresses this call by examining neuroanatomical impacts of two such factors and their combined effects; namely the duration and extent of bilingual language use. We examined effects of two absolute language factors related to duration of L2 use: *L2 AoA*, to examine overall length of bilingual language use, and length of *L2 Immersion*, to examine length of bilingual language use in settings where exposure to the

L2 is increased (Linck et al., 2009). We also examined measures related to the extent of engagement with the non-native language. These were composite factor scores derived from the Language and Social Background Questionnaire (Anderson, Mak, Keyvani Chahi, & Bialystok, 2018; Luk & Bialystok, 2013) detailing (i) L2 engagement in *social/community settings* and (ii) L2 use in *home settings*, to further isolate potentially explanatory patterns of language use and adaptation. Finally, we also examined the effects of *active* L2 use through time, both overall and in immersion. These factors were used as predictors in models assessing adaptation across a range of neuroanatomical measures. These included cortical grey matter volume (GMV), measures of white matter integrity including FA, mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD) values, shape adaptations in subcortical structures via a vertex analysis, and finally resting state functional connectivity.

Several hypotheses follow from each of duration and use of an L2. With respect to duration of L2 exposure, differences in specific experience-based factors will result in measurable neuroanatomical adaptations in regions and/or structural connectivity and functional networks involved in language processing and control. We predict that EBFs capturing duration of exposure and use (L2 immersion and L2 AoA) will predict adaptations related to increased efficiency in L2 processing and control in both cortical and subcortical regions. Cortical grey matter volume (GMV) will increase in posterior regions such as the cerebellum (Pliatsikas et al., 2014b), and decrease in frontal areas such as the left inferior frontal gyrus (LIFG) (Grundy et al., 2017b). Decreases in GM will also be seen in regions involved in short-term/declarative memory procedures, such as the right hippocampus (Ullman, 2004). Increased duration of L2 use will result in increases in several subcortical structures related to phonological monitoring and selection such as the globus pallidus and putamen (Pliatsikas et al., 2017), with decreases in structures used for language control such as the caudate and thalamus (Abutalebi & Green, 2016). Similarly, we predict increased FA values to relate to longer L2 use in language-related pathways, such as the IFOF, and SLF (Pliatsikas et al., 2015; Rossi et al., 2017). Moreover, lower connectivity is expected in the default mode network (DMN) (Kousaie et al., 2017).

With respect to greater extent of engagement with the L2, we predict adaptations commensurate with increased demands on language selection and control. Adaptations include cortical GMV increases in regions such as the LIFG and anterior cingulate cortex (ACC) (Abutalebi & Green, 2016). Increases in subcortical structures implicated in language selection and switching processes, such as the thalamus and caudate, will also correlate (Abutalebi & Green, 2016; Llano, 2013) as will increased FA (and decreased RD/MD) values in pathways connecting these regions such as the corpus callosum (CC) or anterior thalamic radiation (ATR) (Pliatsikas et al., 2015; Rossi et al., 2017).

With respect to EBFs related to length of active engagement to the additional language, these have not previously been examined, thus this analysis is exploratory in nature. Based on existing proposals, however, we may tentatively predict that any neuroanatomical adaptations will overlap with the duration-based predictors, specifically adaptations related to increased efficiency of language control processes (Abutalebi & Green, 2016; Grundy et al., 2017b).

3.2 Methods

3.2.1 Participants

Typically developing bilingual adults (n=65, 49 females, *m*age: 31.7yrs, SD: 7.24, range: 18-52) participated in the study. All participants were right handed and had no neurological damage/pathology. Participants spoke a variety of languages, but all spoke English as one of their languages (*m*AoA: 8.7 yrs., SD: 4.78), and had no to minimal exposure to a third (or additional) language. All participants were born in other countries and moved to the UK at varying ages, apart from 3 participants who were born in the UK to non-UK parents, moved away to their parent's country of residence in early childhood and returned in adulthood. All were living in the UK at time of testing (*m*length residence: 80.76 months, SD: 97.13) (Appendix A). Crucially, minimal exclusion criteria were applied to recruit as wide a range of linguistic experiences as possible. Specifically, participants were excluded from testing only if they spoke three or more languages proficiently and/or frequently, or if they learned English as a third language or further (L3/Ln).

3.2.2 Materials

Participants completed an English proficiency test, the Oxford Quick Placement test (QPT) (Geranpayeh, 2003). All were found to be high-intermediate to high proficiency speakers of English, based their performance on the QPT (avg. score 88.35%, SD 10%). Participants also completed a language history questionnaire, the LSBQ (Luk & Bialystok, 2013), which documents language use in the participants' known languages from early childhood to the present day in a range of settings (see Appendix B).

Scores from the LSBQ were entered into a factor score calculator developed by Anderson and colleagues (Anderson, Mak, et al., 2018), which is based on an exploratory factor analysis which loads variables based on relevant interpersonal interaction. The factor score calculator derives four scores based on scored responses to questions in the LSBQ based on responses to multiple questions regarding language use in specific settings and time points. The scores entered into the calculations are numerated Likert scale scores detailing amount of L2 use from 0 (only the L1) to 4 (only the L2). These scores are standardized and summed into one of three factor scores: 1) L2 use in home settings, 2) L2 use in Social/Community settings, 3) L1 proficiency, and 4) a composite score of the three factor scores- a "Bilingual Composite Score".

We used two of these in our model: 1) L2 use in home settings (L2_Home) and in social/community settings (L2_Social) and are derived as weighted aggregate scores from measures recorded within the LSBQ (Anderson, Mak, et al., 2018). For both factor scores, a higher score indicates more L2 use, a lower score indicates more engagement with the native language. We observed a mean score of 54.1 for L2_Social (SD: 11.74, range: 10.2-78.1), and a mean score of 3.29 for L2_Home (SD 6.03, range: -5.7-12.6) (Appendix A).

3.2.3 MRI data acquisition

Neuroimaging data were acquired on a 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil and Syngo software. Whole brain resting-state functional images were acquired (300 volumes, FOV: 192 x 192, 68 transversal slices, 2.0mm slice thickness, voxel size 2.1x2.1x2.0mm, repetition time (TR) =1500ms, echo time (TE) =30ms, flip angle 66°). Participants were asked to keep their eyes open during this scan. A high resolution anatomical scan using a MPRAGE sequence was carried out for purposes of registration and structural analysis (256 sagittal slices, 0.7 mm slice thickness, in-plane resolution 250 x 250, acquisition matrix of 246 x 256 mm, TE=2.41 ms, TR=2400ms, inversion time = 1140ms, flip angle = 8°). Finally, a diffusion-weighted echo planar imaging (EPI) scan was run (60 transversal slices, 2mm slice thickness, acquisition matrix 256 x 256, in-plane resolution 128 x 128, 2 averages, TE=70ms, TR=1800ms, 64 directions).

3.2.4 Data analysis

Neuroimaging data were pre-processed and analyzed with software pipelines in FSL (Smith et al., 2004). T1-weighted images were pre-processed with the FSL_anat software pipeline (Jenkinson et al., 2012). Due to artefacts from scanning, one participant was removed from the cohort for analysis.

Images were reoriented to the Montreal Neurological Institute (MNI)-152 orientation, automatically cropped, bias-field corrected, and non-linearly-registered to MNI space. Grey matter volume (GMV) was assessed via the voxel-based morphometry (VBM) pipeline in FSL (Ashburner & Friston, 2000; Good et al., 2001). Pre-processed images were brain extracted and grey matter segmented. A study specific template was then created using the average of the GM images. Native GM images were registered to this template and modulated to correct for local expansions and contractions due to the non-linear component of registration. They were spatially smoothed with an isotropic Gaussian Kernel of 3mm. A voxel-wise general linear model (GLM) was then applied to test for effects of language experiences.

The subcortical structures were assessed via a vertex analysis using the FIRST software pipeline (Patenaude et al., 2011). The following structures were automatically segmented for analyses: bilateral nucleus accumbens, hippocampus, amygdala, thalamus, globus pallidus, putamen, and caudate nucleus. These were then submitted to vertex analyses. For all participants, each structure underwent a 6 degrees of freedom rigid body transformation to study-specific template in standard space. The vertex coordinates of individuals were then projected onto the average coordinates of the template. This resulted in spatial maps signifying perpendicular displacement from the average structure including positive (outside the surface) or negative (inside the average surface) values. Finally, the values were analyzed for effects of language experience using a voxel-wise GLM (Smith & Nichols, 2009).

DTI data were pre-processed using the topup (Andersson, Skare, & Ashburner, 2003), and eddy (Andersson & Sotiropoulos, 2016) pipelines within FSL. White matter integrity was assessed via several measurements including FA, MD, RD, and AD values (Anderson, Grundy, et al., 2018; Singh et al., 2017). These values were calculated using the FDT and DTIFIT (Behrens et al., 2003) pipelines. Individual differences in WM integrity were assessed using the tract-based spatial statistics (TBSS) pipeline in FSL (Smith et al., 2006). The FA (and other diffusivity) images were non-linearly registered to a standard space FA target image and affine-transformed to MNI standard space. This resulted in a 4D image which consisted of each FA image from the participants. An FA skeletonization program was used to create an FA skeleton that included the voxels identified as white matter (WM) in each FA image, thresholded at 0.2. MD, RD and AD images were then also nonlinearly registered to standard space and were then warped and registered into a single 4D file which was projected onto the mean FA skeleton. Effects of language experience were then examined using the GLM tool in FSL.

Resting state connectivity was analyzed using the Multivariate Exploratory Linear Optimized Decomposition into Independent Components (MELODIC) pipeline within FSL (Beckmann & Smith, 2004, 2005). This data-driven approach mitigates potential biases associated with traditional seed-based analyses of resting-state fMRI data (Beckmann & Smith, 2004). The data were first pre-processed including motion corrections, corrections for field distortions, and registered first to the participant's anatomical scan, and then to MNI standard space. The processed datasets were then decomposed into spatial and temporal components using a multi-session temporal concatenation across participants. This results in a series of spatial maps containing components common across all participants. The total number of components calculated at the group level was limited to 20 (Smith et al., 2009). These components were then manually inspected and classified. Components classified as noise were excluded from further analysis. This included components with more than 50% power at greater than 0.1Hz, excessive spatial distribution in white matter and/or the brainstem, or spatial distribution indicative of motion or basal physiological activity (Seeley et al., 2007; Smith et al., 2009). Of the 20 components, 9 were classified as noise and were discarded. The remaining 11 components were compared and matched to existing resting-state networks including the default mode network, cerebellum network, executive control, network, sensorimotor, auditory, and frontoparietal network (Smith et al., 2009). The components were then subject to group-level analysis via the dual_regression pipeline (Beckmann et al., 2009). This involved regressing the spatial maps of the selected components into the 4D dataset for each participant, creating time courses for each component within each participant. The time courses were subsequently regressed into a single dataset creating spatial maps for each participant. Effects of language experiences were then assessed via a voxel-wise GLM. This resulted in a series of statistical maps detailing effects of each predictor on connectivity within each component.

Experience-based adaptations across participants were assessed via the GLM tool in FSL with demographics from the LSBQ used as predictors, with age and sex included as nuisance covariates. Two models were run. Model 1 included four EBFs as predictors testing duration and degree, respectively, of L2 exposure and use. These were 1) L2 age of acquisition (years), 2) L2 length of immersion (months), 3) L2 use in social/community settings (L2_Social), and 4) L2 use in home settings (L2_Home). The predictors in Model 1 were analyzed individually in the GLM, controlling for effects of the other predictors and nuisance covariates. This was done to test individual effects of duration and extent of L2 use in different contexts. L2 AoA and length of L2 immersion examined length of exposure and use of the additional language. We log transformed these variables for two reasons: first, the data were not normally distributed, and second, we did not expect a linear adaptation over time (Kuhl et al., 2016). The other two predictors (L2_Social, & L2_Home) examined the degree of bilingual or L2 use in various settings and were weighted factor scores derived from the LSBQ (Anderson, Mak, et al., 2018). English proficiency (participants' QPT performance) was found to correlate with both length of immersion ($r^2=0.35$, $p<.001$) and AoA ($r^2=-0.29$, $p=.03$), and thus was not included in the model.

Given that duration-based predictors may not account for the extent to which one engages with the additional language, we also sought to examine if *active* use of the additional language through time would modulate neuroanatomical adaptation. Essentially, we qualified the absolute duration-based predictor with the extent of engagement with the L2 during the timeframe specified (overall and in immersion) for each participant. Thus, Model 2, then, identifies the effects of duration of *active* engagement with the additional language. This was specified in two settings: 1) the total amount of time (of one's life) spent actively using the L2 (Years_Active_L2) and 2) the length of time in immersion spent actively using the L2 (Immers_Active_L2). Years_Active_L2 was determined by calculating the average percentage of English use in several stages, from the point the language was acquired through to the time of testing. The total number of years using the L2 was calculated by subtracting the reported L2 AoA from the participants' age at the date of testing. This percentage of L2 use was then multiplied by the total number of years spent using the L2. This resulted in a value per participant indicating the number of years spent actively using the L2 (English). Immers_Active_L2 was determined by first calculating an average percentage of daily use of English, from the contexts of reading, writing, speaking, and listening. The resulting percentage was then multiplied by the number of months of immersion. This resulted in values corresponding to the amount of time actively engaged with the L2 in immersion. As neither of the predictor variables were normally distributed, both were log transformed.

For all neuroimaging analyses, corrections for multiple comparisons were implemented with the Randomise pipeline (Winkler et al., 2014), in which a voxel-wise permutation analysis was performed with 5000 permutations. This created maps of areas of adaptations significantly predicted by a given factor, thresholded at $p<0.05$. For the resting-state analysis, a further correction was required. Given that the dual_regression pipeline does not correct for multiple comparisons between components, the significance values were further Bonferroni-corrected to a threshold of $p\leq0.0045$.

3.3 Results

3.3.1 Model 1: Independent effects of AoA, immersion, extent of L2 use in home settings, and L2 use in social/community settings

VBM Analysis

L2 age of acquisition, controlling for age, was found to negatively predict grey matter volume (GMV) in the left inferior frontal gyrus (pars opercularis) (IFG) (148 voxels; -58, 6, 2; p=.024) and left inferior frontal orbital cortex (IFOC) (58 voxels; -30, 30, -8; p=.044) (Fig 1), and a small region in the right parahippocampal gyrus extending into the amygdala (17 voxels; 28, -2, 18; p=.043). That is, longer exposure to the L2 related to a greater extent of GMV in these regions. No other EBFs significantly predicted GMV when corrected for multiple comparisons.

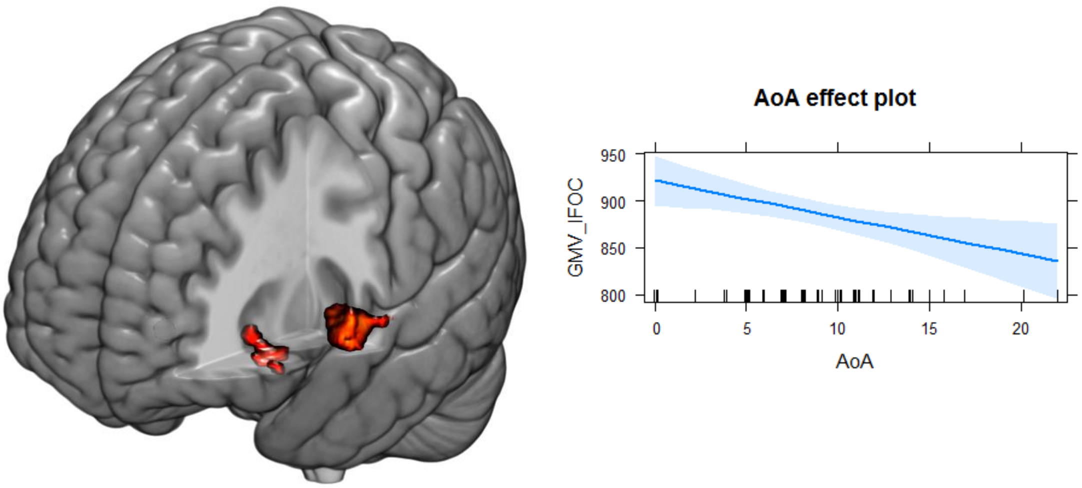

Figure 3-1: Results of VBM analysis. (Left) GMV increase (red) in left IFG and IFOC, (right) GMV correlating with L2 AoA.

Vertex analysis results

Several language factors relating to both duration and degree of bilingual language use were found to predict reshaping of the subcortical structures. Regarding duration of L2 use, L2 AoA was found to significantly predict contractions in the ventral anterior section of the left thalamus, and expansions in the medial section and contractions in the ventral anterior section of the right thalamus. Length of L2 immersion significantly predicted contractions in the bilateral globus pallidus and thalamus, the posterior section of the right caudate and in several regions of the right hippocampus (Fig 2) (Table 1). With respect to EBFs detailing degree of bilingual language use, L2_Social predicted expansions in several portions of the bilateral caudate nucleus (Fig 2) (Table 1).

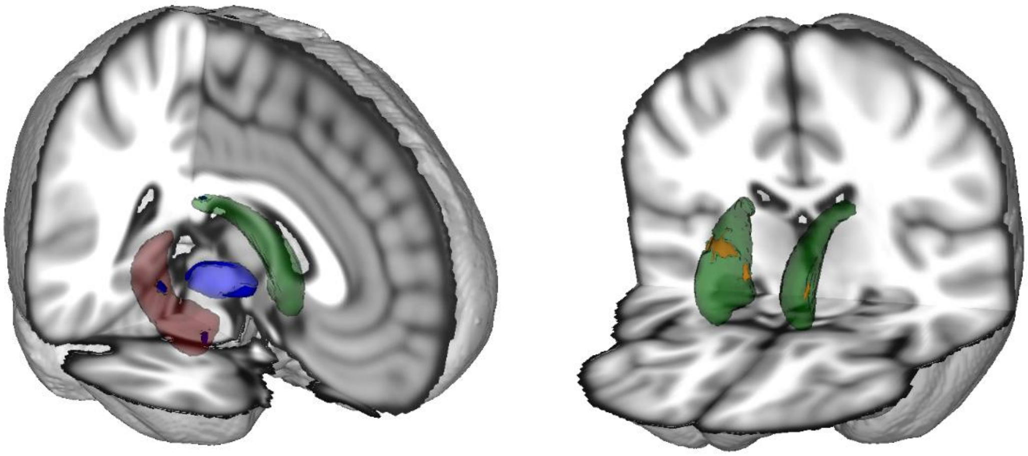

Figure 3-2: Results from vertex analysis. Left: effects of immersion as contractions (blue) on the right hippocampus (red), caudate (green), and globus pallidus (blue). Right: Effects of L2_Social as expansions (orange) on the bilateral caudate (green).

Table 3-1: Results of vertex analysis, Model 1. Coordinates are listed in MNI format.

Hemisphere	**Structure**	**Predictor**	**direction**	**Voxels**	**p**	**X**	**Y**	**Z**
L	Caudate	L2_Social	+	26	0.04	-18	22	7
	G Pallidus	Immersion	-	19	0.041	-18	3	-6
L	Thalamus	AoA	-	391	0.022	-6	-18	-2
		AoA	-	365	0.017	-14	-29	-4
		Immersion	-	23	0.047	-17	-26	14
R	Caudate	Immersion	-	67	0.026	18	-17	23
		L2_Social	+	206	0.031	18	6	15
			+	10	0.036	14	-10	19
	Hippocampus	Immersion	-	30	0.019	26	-25	-10
			-	19	0.037	19	-10	-25
	G Pallidus	AoA	+	7	0.044	13	1	-2
		Immersion	-	125	0.014	27	-14	-2
			-	117	0.014	20	3	-4
			-	37	0.039	14	0	-6
	Thalamus	AoA	-	136	0.023	10	-14	-1
			-	54	0.043	10	-27	12
		Immersion	-	111	0.028	15	-16	0

+: expansion; -: contraction

TBSS analysis

Both EBFs related to extent of L2 use (L2_Home and L2_Social) were found to relate to adaptations in axial diffusivity (AD) in several tracts. Specifically, increases in AD values were predicted by L2_Social in the anterior portion of the IFOF extending into the body of the corpus callosum (CC). A decrease in AD values in the genu, body, and splenium of the corpus callosum, extending into portions of the superior corona radiata in the right hemisphere, was predicted by L2_Home (Fig. 3) (Table 2). No significant effects of the predictor variables in Model 1 were found for FA, MD, or RD values.

Table 3-2: Results of TBSS analyses. All coordinates listed in MNI format

Hemisphere	**Structure**	**Predictor**	**direction**	**Voxels**	**p**	**X**	**Y**	**Z**
	Corpus Callosum	L2_Home	-	6610	0.021	18	-44	8
R	Anterior IFOF	L2_Social	+	1499	0.029	27	32	-1
R	Body corpus callosum	L2_Social	+	251	0.043	16	18	26
R	Superior corona radiata	L2_Social	+	132	0.045	28	-5	31
R	Anterior IFOF	L2_Social	+	122	0.048	46	24	18
R	SLF	L2_Social	+	99	0.048	36	17	19

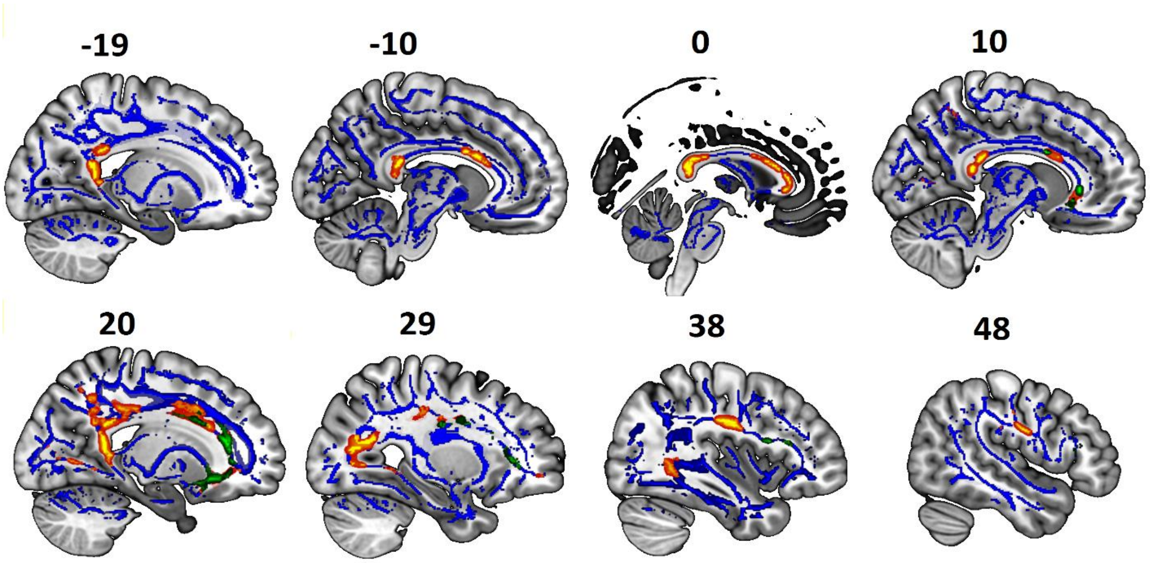

Figure 3-3: Results of TBSS analysis: effects of L2_Home (orange) and L2_Social (green) on AD values, overlaid on a standard-space mean FA skeleton. Coordinates are saggital in MNI format

Resting-state connectivity

L2 AoA was found to significantly predict resting state functional connectivity at the corrected significance threshold. Specifically, a negative correlation was found between L2 AoA and connectivity within the component related to the Executive Control network (-22, 14, 28; 2808 voxels; p<0.001) (Fig 4). That is, the earlier the L2 was acquired, the greater the connectivity within this network. No other predictors were found to predict functional connectivity when corrected for multiple comparisons.

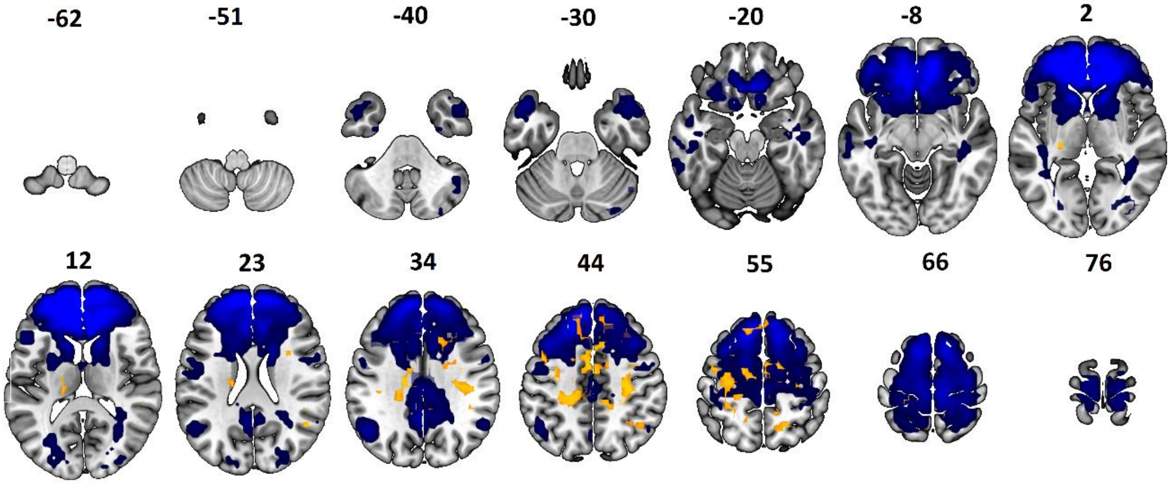

Figure 3-4: Results of resting-state analysis. Increases in connectivity (orange) in the EC network (blue).

3.3.2 Model 2: Duration of active L2 use

Model 2 revealed effects only in the vertex analysis. Both predictors, Yrs_Active_L2 and Immers_Active_L2, were found to predict reshaping within several structures. An expansion in the left nucleus accumbens was predicted by Yrs_Active_L2. Immers_Active_L2 was found to predict both an expansion and contractions in the right caudate nucleus (Fig 5), a contraction in the right hippocampus and right thalamus **(**Table 3). Neither predictor in Model 2 was found to significantly predict differences in GMV, white matter integrity or resting-state connectivity.

Table 3-3: Results of vertex analysis, Model 2

Hemisphere	**Structure**	**Predictor**	**Direction**	**Voxels**	**p**	**X**	**Y**	**Z**
L	Accumbens	Yrs_Active_L2	+	100	0.004	-14	16	-10
		Yrs_Active_L2	+	50	0.015	-7	14	-4
		Yrs_Active_L2	+	33	0.037	-7	6	-7
R	Caudate	Immers_Active_L2	+	56	0.021	18	-14	19
		Immers_Active_L2	-	72	0.021	18	-17	23
		Immers_Active_L2	-	51	0.042	14	24	-2
	Hippocampus	Immers_Active_L2	-	16	0.032	26	-25	-10
	Thalamus	Immers_Active_L2	-	58	0.037	15	-16	0

+: *expansion*; -: *contraction*

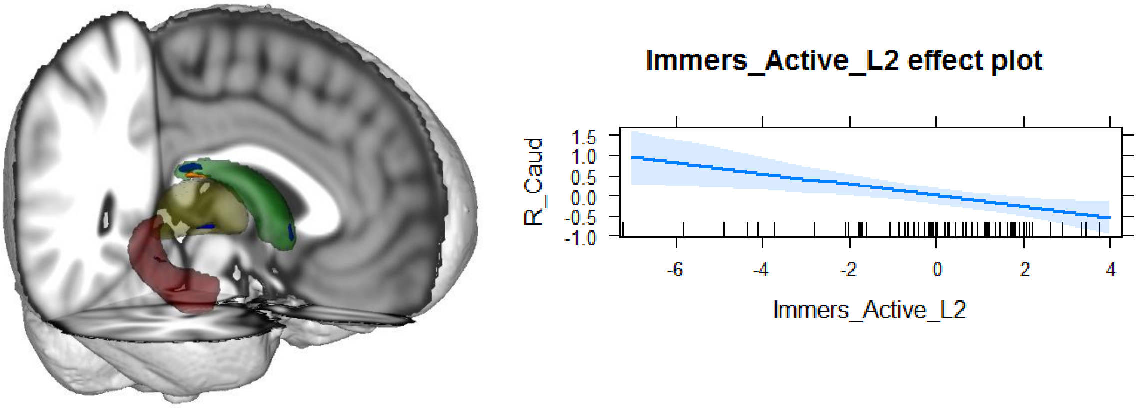

Figure 3-5: Results of vertex analysis (Model 2). Left: Effects of Immers_Active_L2 as expansions (red) and contractions (blue) on the caudate (green, and contractions in the right hippocampus (red) and thalamus (yellow). Right: effect plot of the surface displacement on the right caudate as predicted by Immers_Active_L2.

3.4 Discussion

This study examined the effects of bilingualism on the structure and connectivity of the brain by accounting for the influence of particular language-use factors, both absolute and experience-based (EBFs), in order to highlight the nuances that give rise to a continuum of neuroanatomical effects in bilingual individuals and groups. The factors examined in the study were found to incur specific effects on brain structure and structural and functional connectivity. In Model 1, the neural adaptations differed between overall factors related to duration of L2 use (L2 AoA and Immersion) and quantity (L2_Social, and L2_Home) of L2 use respectively. Model 2, which examined the effects of the length of time one was actively engaged with the additional language, produced some similar results to the duration-based predictors of Model 1, but also several distinct, specific effects. Considered together, the results highlight the need for further consideration of specific language experiences/individual differences in examining the neuroanatomical effects of the bilingual experience. In the remainder of this Discussion we will present our findings for each model and examine the implications for bilingualism-induced neuroplasticity.

3.4.1 Model 1- Independent effects of AoA, Immersion, L2 use in social/community settings, and L2 use in home settings

The first model revealed independent effects of language use factors related to duration and degree, respectively, of bilingual language use. This is in line with our predictions. The effects of duration of bilingual language use reflected adaptations towards increased efficiency in L2 processing and control, whereas effects of extent of use reflected adaptations towards increased cognitive cost of language selection and monitoring processes.

With respect to measures of absolute duration of bilingual language use, L2 AoA was negatively predicted GMV increases in the left inferior frontal gyrus (IFG), left frontal orbital cortex (lFOC), and left thalamus with a reshaping (expansion and contraction) in the right thalamus. Recall that a lower L2 AoA entails longer exposure to the L2. The thalamus has been implicated in language control processes, specifically language selection, given its extensive connections to the basal ganglia (particularly caudate, putamen, and globus pallidus) and IFG (Abutalebi & Green, 2016; Ford et al., 2013). The reshaping in this structure then reflects part of an optimized system to handle demands related to language selection at several levels of processing and production. Similarly, the IFOC has also been previously implicated in conjunction with the IFG in syntactic computations involving increased working memory load (Kepinska, de Rover, Caspers, & Schiller, 2017; Prat & Just, 2011), and is connected to a variety of language-related brain regions, including the thalamus, IFG and cerebellum, via the IFOF (Sarubbo et al., 2013). The increase in GMV in these regions then may reflect adaptations towards increased efficiency of syntactic processing in the L2.

The increases in functional connectivity in the Executive Control network likely reflect an optimized system to handle the language control demands. Increased resting state connectivity in the Executive Control network has been associated with more efficient computations of stimuli related to identified salience and executive function processes (Kousaie et al., 2017; Seeley et al., 2007). Furthermore, several regions encapsulated by this network, such as the ACC and paracingulate gyrus (Smith et al., 2009), are known to be functionally recruited in language control and switching processes (Luk, Green, et al., 2011). Given that the participants were all proficient speakers of English at the time of testing, the increased connectivity in the EC network related to L2 AoA indicates an optimized system to handle the control of the additional language. The results found for AoA are also consistent with findings (Gullifer et al., 2018) showing increase in connectivity in regions implicated in executive control processes with a longer duration of L2 use, controlling for variability of input.

The thalamic and functional connectivity adaptations related to L2 AoA are consistent with predictions from the BAPSS model (Grundy et al., 2017b) and the ACH (Abutalebi & Green, 2016). Specifically, according to BAPSS, these effects indicate an increased reliance on the subcortical and posterior structures commensurate with increased L2 experience. Similarly, the thalamic adaptations may be understood as an optimization to increased language control demands as predicted by the ACH. Considered in combination, the structural and functional adaptations with AoA reflect specific adaptations to changing processing demands with the acquisition and use of the additional language.

The functional and structural adaptations related to length of L2 immersion seem to reflect an increased automation or proceduralization, and optimization for L2 processing. The right hippocampus is often implicated in short-term and working memory functions associated with language acquisition and increases in hippocampal GM have been reported by several studies following L2 acquisition in the initial stages (Bellander et al., 2016; Mårtensson et al., 2012). The right hippocampus has also been implicated as part of a network involved in the acquisition of novel grammar (Kepinska et al., 2018). The contractions seen in this structure, then, probably reflect decreased reliance on short-term, declarative memory processes (Ullman, 2004) commensurate with increased duration of immersed L2 use. Similarly, the contraction seen in the right caudate (RCN) would suggest a return to baseline from prior expansions earlier in L2 immersion (Pliatsikas et al., 2017), given increased efficiency in language switching. An interpretation of increased efficiency in switching is supported by the contractions seen in the bilateral thalamus, which indicates a decreased reliance on this structure with increased efficiency in language selection (Green & Abutalebi, 2013; Llano, 2013). The left caudate nucleus (LCN) is more often implicated in language and task-switching cognitive demands (Abutalebi & Green, 2016), however several studies report recruitment of the RCN for more demanding language switching tasks (Luk, Green, et al., 2011; Ma et al., 2014). However, given the role of the LCN in language control and switching (Abutalebi & Green, 2016), an alternative explanation for the contractions seen in the RCN would be that the majority of language control demands have been taken by the LCN, causing decreased use of its right hemisphere counterpart. The caudate has been found to play a monitoring role in language control processes (Seo et al., 2018). The lack of change in the LCN may reflect an optimization of the system with respect to language control in the face of sustained language control demands from the immersive environment.

The contractions found in the bilateral globus pallidus are not in line with our predictions. Previous findings show expansions in this structure relative to increased length of immersion for highly immersed bilinguals (Pliatsikas et al., 2017). This was interpreted as adaptation to increased phonological and semantic monitoring costs of an immersive environment. This difference between the Pliatsikas et al. study and the present study is especially intriguing, given that both the age ranges and the variables related to duration of bilingual language use (AoA and L2 immersion) are highly similar between the respective participant groups. One potential difference between the groups is the relative quantity of L2 use during immersion. Although the two cohorts completed different language background questionnaires, the cohort included in the Pliatsikas et al. study was qualitatively more L1-dominant based on reported degree of L2 use at the time of testing, whereas the participant cohort in the present study was more L2-dominant. A tentative explanation, then, for the contractions in the globus pallidus is that the present cohort had already achieved peak efficiency in L2 phonological processing and semantic selection, at point of testing. The contractions, then, may reflect a return to ‘baseline’ from prior expansions commensurate with decreased recruitment of these structures in language switching and L2 production. This discussion highlights the need to unpack EBFs in the future. The difference between the otherwise seemingly comparable groups possibly reflects a conditioning factor on language use. If we are on the right track, this serves as a quintessential example of how nuances can translate to relatively important differences in neuroanatomical effects across aggregate groups, and by extension, across different studies.

With respect to extent of engagement with the L2, L2_Social was found to relate to specific neuroanatomical adaptations, L2_Social was found to predict expansions in the bilateral caudate nucleus. The right caudate (RCN) is not typically implicated in models covering language control (Abutalebi & Green, 2016), as language selection processes are more often facilitated by the left caudate (LCN). Under some proposals, however, increased demands on language selection procedures incur recruitment of the right hemisphere counterparts of regions and structures associated with language control (Luk, Green, et al., 2011). Under such an interpretation, the expansion in the RCN reflect an adaptation towards the increased demands on both language selection processes commensurate with increased engagement with the L2. This interpretation is supported by the expansion seen in the LCN, which also likely reflects adaptations to increased language control demands (Abutalebi & Green, 2016; Luk, Green, et al., 2011). These effects also highlight the importance of assessing the extent of engagement with the L2, even in immersion settings where potential for L2 exposure and use is thought to be increased (Linck et al., 2009).

L2_home and L2_Social were also found to predict effects within axial diffusivity (AD) values in several pathways. Specifically, recall that L2_Social predicted increases in AD the anterior portion of the right IFOF, extending into genu of the CC, whereas L2_Home predicted decreased AD across the genu, body, and splenium of the corpus callosum (CC). These adaptations are not in line with our predictions related to language control demands in the L2, as FA, MD, and RD values were not found to change. Nevertheless, these adaptations may provide further support for the interpretation of increased language selection demands. The decreased AD values related to L2_Home may reflect an increase in myelination of the axonal pathways within the CC. Previous research has shown decreased AD values commensurate with increased FA values (Qiu, Tan, Zhou, & Khong, 2008), indicating an inverse relationship between AD and degree of myelination along the principle direction of water flow in axonal tracts. The CC connects analogous cortical structures across the two hemispheres, and has been found to be modulated in structural connectivity by bilingual language use (Coggins et al., 2004). Under such an interpretation, the decreased AD values also partially replicate findings of previous studies who report increased FA values for bilingual subjects in this region (Pliatsikas et al., 2015; Schlegel et al., 2012). The increase in AD related to L2_Social may reflect increased efficiency in communication along right hemisphere structures. It has been proposed by others that increases in AD may reflect a restructuring in tract geometry to facilitate more efficient communication (Singh et al., 2017). Taken together, the AD modulations indicate the increased extent of L2 use in immersion may necessitate recruitment of right hemisphere structures to assist in the language control and processing load. However, very little evidence currently exists regarding effects of AD in relation to bilingual language use.

As such, we must be cautious in over-interpreting these effects. More research is required to fully ascertain the effects of bilingual language use on specific diffusivity patterns.

The effects found for Model 1 show a specificity in brain adaptations to individual language use factors. Absolute factors related to duration of L2 use predict adaptations towards maximized efficiency of L2 processing and control. EBFs related to extent of L2 use predicted adaptations to increased language processing and control demands. Together, the data indicate that individual language experiences are indeed explanatory of the variance in neurocognitive outcomes in bilinguals and should be considered in greater detail.

3.4.2 Model 2- effects of the duration of active L2 use

Model 2 revealed effects of the amount of time spent actively using the additional language. Some similarities in terms of neural effects were found between the predictors in this model and the EBFs from the first model, however, distinct neural adaptations were also found. The results here indicate that specific effects related to proportions of language use manifest differently through the time course of L2 use.

The total amount of time spent actively using the L2 (Yrs_Active_L2) was found to relate to expansions in the left nucleus accumbens. This effect was not predicted, as the accumbens is not typically implicated in language processing and control. However, the reshaping in this structure may reflect an adaption to prediction-error processing, or learning, associated with language processing and production (Botvinick & Braver, 2014) as the use of the additional language continues. The nucleus accumbens forms part of the ventral striatum which is typically implicated in processes related to reward-based decision making, specifically to reinforcement and motivational salience in learning, and prediction-error processing (Botvinick & Braver, 2014; Chase, Kumar, Eickhoff, & Dombrovski, 2015). Given this, the expansions seen in the accumbens may reflect adaption to the increased cognitive demands of processing and production in the L2. Like the first model, both EBFs were log transformed. Thus, the differences here reflect a gradual slowing in adaptation with increased time using the L2 as the system optimizes. However, this interpretation is speculative and requires more evidence to assess its validity.

The length of active L2 use in immersion settings (Immers_Active_L2) was found to relate to several neuroanatomical adaptations. The contractions in the right hippocampus replicate the contractions found for length of immersion found in Model 1. As such, the contractions found for the hippocampus for Immers_Active_L2 likely also indicate a decreased reliance on short term memory processes, as efficiency in L2 processing increases (Ullman, 2004). The contraction in the right hippocampus also overlaps with the area of expansion found by Bellander and colleagues, which correlated with length of time spent acquiring novel vocabulary (Bellander et al., 2016). Recall that the values for Immers_Active_L2 represented the amount of time *actively* using English in the immersive environment, thus use on this structure likely decreased with as short-term memory needs for L2 processing decrease. The reshaping (expansion and contractions) in the RCN can be taken as an indication of adaptation to continued intensive language control demands in the immersion. The LCN has been proposed as assisting in controlling the non-target language in processing and production (Green & Abutalebi, 2013). However, recall that several studies report recruitment of the right caudate in language control processes to assist in the increased computational load (Luk, Green, et al., 2011; Ma et al., 2014). The reshaping in the RCN in the right caudate may then reflect an optimization towards increased efficiency of language control processes stemming from continued intensive L2 use in the immersive environment. Finally, the contractions in the right thalamus indicate decreased reliance on this structure commensurate with greater efficiency in language control and selection processes with increased time using the L2 in immersion. The corresponding structures (thalamus and caudate) in the left hemisphere were not found to change. The lack of change in these structures indicates that language control and processing demands are relatively unchanged, thus the system has optimized to handle them. These data support an interpretation of increased intensive L2 exposure in immersion relating to changing recruitment of the affected structures, as the system optimizes through time to more efficiently handle the language control demands.

The data from Model 2 indicate adaptations to both learning and increased efficiency in language control respectively. Total length of specific L2 use predicted increased adaptations to learning. Length active L2 use in immersion was found to predict adaptations related to increased efficiency of language processing and control. Data considered together, Model 2 indicates that sustained, active L2 use drives specific neural adaptations towards maximal efficacy in L2 processing and control.

3.4.3 General Discussion

Bilingualism is a multifaceted experience comprised of various proportions of language use factors that present themselves differently to groups and individuals over time. If individual factors matter in predicting specific changes to the brain, then it stands to reason that treating 'bilingualism' as single variable does not always reveal the important adaptations. This is not to suggest that there is nothing to be gained from the monolingual vs. bilingual comparison from the past and moving forward. Data of the type we presented here, however, suggest caution is needed with respect to what can be claimed from such comparisons alone. A bilingual-centric approach that seeks to unpack how and why EBFs in bespoke proportions confer differences in adaptations is in a privileged position to reveal the dynamicity of the bilingualism-mind/brain relationship. Such an approach should be able to deal with all data from well-designed, well-executed studies, even and especially when they are seemingly in conflict with each other. In principle, when a replication fails, factoring in and modelling language use factors can potentially resolve the apparent quandary. The effect of bilingualism on the mind/brain need not be conceived of in binary terms; rather, studies like the present provide the evidence that permits a shift away from binary answers towards: "how much" and "under what (language use factor) conditions".

Experiences are individualistic, although certain experiences cluster together in non-random ways by bilingual type, geographic location and other societal factors. Consider a scenario where the same languages (English and Spanish), relative proficiency in both, and age at time of testing are held constant yet apply to different individual bilinguals. Notwithstanding crucial commonalities, some absolute factors will necessarily be different at the group level (e.g. AoA). Other EBFs will tend to trend in clusters differently by specific group depending on various external factors. In our view, one should not be surprised if Hispanic-American simultaneous bilinguals who grew up in Hispanic-majority areas of California are different from those raised in English-dominant Iowa. It is not necessarily reasonable to expect that either group (or all individuals in either) would be the same as compared to successful adult English-native second language learners of Spanish residing in Madrid. Should we anticipate that the same results of the previous groups would apply to native Spanish speakers who moved to California as teenagers and have resided there for decades and/or in successful English-native acquirers of L2 Spanish who have never left the US? We submit that the answer is “no”. Patterns in language use will distribute differently across all five groups. Opportunities to use the language, factors affecting language choice, differences in code-switching proportions, and more will affect how these factors distribute. In line with what we have shown for language use factor effects in neuroanatomical differences across bilinguals, we expect differences in all bilingual neurocognitive adaptations. Denying the veracity of existing data simply because it cannot be replicated under what are different conditions runs in disaccord with scientific prudence. It is more likely that differences relate to tendencies of how such factors distribute in certain cohorts of bilinguals as compared to others. Minimally, it is a strong and relatively easily testable hypothesis that should be exhaustively pursued.

Modelling the general weighting of specific factors of language use has a good chance not only of explaining variable outcomes across studies, but also embodies a major step towards uncovering the dynamic nature of how bilingualism translates into mind/brain adaptations. In this same vein, it is important to keep in mind that proxies such as ‘bilingual type’ themselves, while useful especially when they reduce the likelihood for vast differences in individual EBFs across members, can conflate too many variables. Taking again the example of ethnic Hispanic-American simultaneous bilinguals, AoA is ubiquitously early. Nevertheless, factors related to exposure to both languages, use/preference of both languages (likely changing dynamically over time), and more will differentiate individuals. Unless we are sure none of this matters, we need to move towards models that take these factors seriously and can place individuals on a discernible continuum. Doing so will increase ecological validity in our field and move us closer to understanding variability in findings.

The goal of this study was to test the hypothesis that specific language use factors, both absolute and experience-based (EBFs) related to bilingualism predict specific adaptations in the brain. We found specificity in neuroanatomical adaptations in regions responsible for language and cognitive control to respective language use factors. This suggests the brain optimizes to be maximally effective in handling cognitive demands of the communicative environment. In relation to bilingual language use, this neurocognitive optimization is a dynamic process which is modulated by both duration and extent of language use, and their combined effects. Taken together, the data support the notion that specific language experiences should be considered in detail in future research examining bilingualism and related neurocognitive adaptations. The factors we examined do not comprise an exhaustive list. The data herein highlight a promising program where an increasingly comprehensive cohort of individual factors and their combined effects will add to unraveling the complexity of language experience with its ensuing bilingual cognitive and neurological consequences as well as explaining the dynamic interaction that bilingualism has in mind/brain adaptations.

CHAPTER 4: BILINGUALISM IS A SPECTRUM OF EXPERIENCES THAT VARIABLY AFFECTS NON-LINGUISTIC NEUROCOGNITIVE PROCESSES

Abstract

The effects of bilingualism on executive control have been heavily debated, given variable results across studies. However, much of the discrepancies between bi- and monolinguals likely correspond to how bilinguals are treated as a monolithic group. We address this by examining several language experience factors on brain activity related to executive control processes. Healthy bilinguals were scanned (fMRI) while they completed a Flanker task. Behavioral data showed robust Flanker effects, which were not modulated by language experiences across participants. However, language experiences did predict activation in distinct brain regions indicating differences in neural recruitment across conditions that were calibrated to both amount of time of the bilingual experience and extent/engagement of bilingual language use. This approach highlights the need to consider specific bilingual language experiences in assessing neurocognitive effects. It further underscores the utility of neuroimaging evidence, especially for younger adult populations that might display ceiling effects behaviorally given their peak-levels of cognition juxtaposed against the granularity of traditionally used tasks. By beginning to unpack the dynamics of the bilingual experience, and how this manifests in adaptations to specific cognitive functions, this approach contributes to a better understanding of the variability reported in the behavioral literature.

4.1 Introduction

The effect of bilingualism on domain-general cognition, particularly executive functions, has come to the fore of significant debate in recent years (Bialystok, 2017; Paap, Johnson, & Sawi, 2015; Valian, 2015), not least due to concerns regarding issues of replication. Variability of results between studies, however, is to be expected when one considers the multifarious nature of the bilingual experiences of individuals and groups (Bak, 2016). Failure to replicate findings is thus not inherently a critical problem, at least to the extent we can begin to reveal the systematic nature of when effects are more and less likely to occur. Bilingualism is a complex and dynamic process within which there is a range of experiences that may drive neurocognitive adaptations (Bak, 2016; Bialystok, 2016; Luk & Bialystok, 2013). Nevertheless, the neurocognitive effects of individual language experiences remain understudied despite very compelling reasons for studying them.

The acquisition and use of more than one language create a situation in which there are two active and competing mental representations. This competition must be resolved for successful communication to take place (Kroll, Dussias, Bogulski, & Kroff, 2012), a process that places demands on the executive control system. In turn, the brain adapts to these demands to more effectively facilitate this process of conflict resolution (Luk, Bialystok, Craik, & Luk, 2012). These adaptations have been found to affect domain-general cognitive control in several of its aspects, including behavioral evidence for suppression of interfering information, cognitive cost of task switching, and use of facilitatory information in performing a task (Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010; Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010; Zhou &

Krott, 2018). However, some studies find significant effects of bilingualism only in aspects or sub-sections of cognitive tasks tapping cognitive control (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Hernández, Martin, Barceló, & Costa, 2013). Others report no significant effects of bilingualism on cognitive control (Antón et al., 2014; Kirk, Fiala, Scott-Brown, & Kempe, 2014; Paap & Greenberg, 2013), leading to recent claims that bilingualism has no meaningful effect on executive functions overall (Klein, 2014; Paap et al., 2015). Understanding the variability of cognitive adaptations across studies has significant impact for the field beyond adjudicating between contrasting claims. We confront this challenge in the present paper, seeking to identify specific language experiences within bilingualism that contribute to domain-general neurocognitive adaptations and assess how and why these adaptations manifest differentially.

In recent years, focus has been given to the neural mechanisms underlying bilingual language control and how these modulate neural recruitment in completing executive function tasks (Pliatsikas & Luk, 2016). A growing number of studies show adaptations in brain network activity and structure to accommodate the increased control and processing demands commensurate with bilingual language use (Pliatsikas, 2019). For example, language and executive control/processing are served by overlapping neural regions and networks (De Baene, Duyck, Brass, & Carreiras, 2015; Green & Abutalebi, 2013), such that increased demands on the language control system have been found to affect domain-general control.

An important issue in the neurocognitive study of bilingualism is to reconcile disparities in results between studies of the same type (task, population, design, etc.) across the mind-brain divide. It would be logical to presume that changes in behavior (executive functions) would have neurocognitive correlates, yet greater consistency exists in terms of neurocognitive differences between bilinguals and monolinguals in the neuroimaging literature than in the cognitive literature. That is, whether or not a behavioral difference emerges, the neuroimaging data show that bilinguals employ different neural recruitment patterns to monolinguals on tasks of executive function, indicating a difference in processing strategy to handle the same cognitive demand (Abutalebi et al., 2012; Ansaldo, Ghazi-Saidi, & Adrover-Roig, 2015; Costumero, Rodríguez-Pujadas, Fuentes-Claramonte, & Ávila, 2015). However, inconsistencies exist between studies with respect to exactly how bilingualism affects neural recruitment in cognitive control processes (García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2016; Pliatsikas & Luk, 2016). Differences between bi- and monolinguals in terms of in neural recruitment typically manifests in one of two ways. The first type of difference is an equivalent degree of activation occurs for both groups completing an executive function task, but with a different spatial distribution (Ansaldo et al., 2015; Luk, Anderson, Craik, Grady, & Bialystok, 2010), indicating an alternative processing strategy. The other common type of difference is decreased activation for bilinguals in the same regions (Abutalebi et al., 2012), indicating lesser cognitive demands in completing aspects of the task. Crucially, these differences in neural recruitment are often found in the absence of any task performance differences between groups (Costumero et al., 2015; Luk et al., 2010).

A likely source of the inconsistencies in findings, in both behavioral and neural data, is how bilingualism itself is examined. Neurocognitive adaptations to the bilingual experience are very likely determined by a series of experiential factors including duration of use, extent of engagement with each language, etc. However, most studies examining this phenomenon to date have operationalized ‘bilingualism’ in binary terms- that is, one is ‘bilingual’ or not, or is a ‘type’ (e.g. early- or late-acquired) of bilingual. These groups are then compared to matched ‘monolingual’ control groups (Bak, 2016; Surrain & Luk, 2017). Grouping bilinguals against monolinguals will collapse specific language experiences across one another, thus obscuring their related effects. Indeed, several proposals argue that individual bilingual language experiences confer varied language control demands to which the brain accordingly adapts (Green & Abutalebi, 2013; Grundy, Anderson, & Bialystok, 2017). The adaptive control hypothesis (ACH) (Abutalebi & Green, 2016; Green & Abutalebi, 2013) states that communicative context contributes to the nature of the adaptation. The bilingual anterior to posterior and subcortical shift (BAPSS) framework (Grundy et al., 2017) claims that reliance on certain brain structures will shift from frontal to subcortical and posterior regions as exposure and automation of L2 processing increases. Despite these calls, relatively few studies to date have examined effects of specific experience-based factors (EBFs) within bilingualism on domain-general cognitive processes. Furthermore, none has done so with the granularity we present herein; related to how bilingual experiences are treated and across the cognitive (mind/brain) divide.

Results from the few studies which examine language experiences support the argument that specific (bilingual) language experiences confer distinct neurocognitive adaptations (Gullifer et al., 2018; Yamasaki, Stocco, & Prat, 2018). These studies report individual effects of extent and duration of bilingual language use on measures of attentional control and intrinsic functional connectivity respectively, which crucially are found to correlate to the amount/degree of bilingual language experience. For example, the study by Gullifer and colleagues found earlier AoA to translate to increased interhemispheric connectivity and increased reactive control reliance. Greater diversity of L2 input translated to increased ACC-putamen connectivity and increased reliance on proactive control strategies. The study by Yamasaki and colleagues did not include a neuroimaging measure but found increased performance (accuracy and blink size) during an attention control task correlated with frequency of L2 use. While the results from these studies are promising, no study to date has examined the both the individual and combined effects of multiple EBFs on neural recruitment patters for executive control demands in bilinguals. This is a shift in practice we believe is necessary and to which the present study speaks.

We address this issue by defining and examining several language experience factors known to be related to cognitive control adaptations. Specifically, we examined how such factors modulate task performance and/or neural recruitment during executive function tasks, both independently and in combination. These factors can be reduced to two general domains: *duration* and *extent* of bilingual language use. With respect to independent effects of individual language experience, we used four distinct variables to asses these. *Duration* of L2 use was assessed with two variables. These were: L2 Age of Acquisition (AoA), the absolute length of bilingualism and Length of L2 immersion, that is- length of bilingual language use in settings where exposure to, and use of, the L2 is increased (Linck, Kroll, & Sunderman, 2009). *Extent* of L2 use was also assessed using two variables. These were weighted factor scores (Anderson, Mak, Keyvani Chahi, & Bialystok, 2018) derived from the Language and Social Background Questionnaire (LSBQ) (Luk & Bialystok, 2013), which detail (a) extent of L2 engagement in home settings and (b) extent of L2 use in broader social/community settings. These variables were assessed together to further isolate their respective contributions to neurocognitive adaptations.

In addition to assessing the independent neurocognitive effects of duration and extent of bilingual language use, we also examined the combined effects of such factors. Given the dynamic nature of bilingual language use, adaptations to duration and extent of bilingual language occur together. Considering duration-based factors (e.g. L2 AoA) in isolation would then be inadequate for any meaningful cross-study comparisons precisely because they are absolute numbers that do not necessarily reflect the degree to which the second language was used. As such, we sought to combine the factors of duration and extent in a separate model, to assess the duration of *active* L2 use. We essentially converted the variables of AoA and Immersion into experience-based variables, by factoring in the degree to which one reported being actively engaged with their L2 during that respective timeframe (overall or in immersion).

In summary, two models were run to examine effects of language use on neurocognitive adaptations. The first model assessed independent effects of duration (L2 AoA and length of immersion in the L2 environment) and extent of L2 use in home settings and social/community settings respectively. The second model assessed combined effects of duration and extent of L2 use both overall and in immersion. These factors were used as variables in models assessing whether they affect task performance (accuracy and reaction time (RT)) and/or neural recruitment for bilingual participants while completing a flanker task, using fMRI. We examined aspects of executive control that can be derived from this task and which have previously been found to be affected by bilingual language use: 1) interference suppression, 2) facilitation, and 3) global switching cost (Luk et al., 2010; Wiseheart, Viswanathan, & Bialystok, 2016).

The hypothesis is that specific EBFs will be associated with the recruitment of distinct neural regions for different executive control demands. We predict that accuracy and RT will not significantly relate to language experiences across participants (Luk et al., 2010, 2012), but that the neural recruitment within the task will differ by task contrast and that neural recruitment will be modulated by different EBFs. Specifically, increased duration of bilingual language use will correlate to increased activation in posterior regions, including the cerebellum, for all tested contrasts (Filippi et al., 2011; Grundy et al., 2017; Pliatsikas, Johnstone, & Marinis, 2014). Greater extent of L2 use will predict increased activation in frontal and lateral/temporal regions including the anterior cingulate cortex (ACC) and inferior parietal lobule (IPL) (Abutalebi & Green, 2016; Green & Abutalebi, 2013). The two factors from our second model have not previously been examined thus our analyses here are exploratory. However, we predict that duration of active bilingual language use will relate to activation increases in posterior and temporal regions such as the cerebellum and IPL (Abutalebi & Green, 2016; Grundy et al., 2017).

4.2 Methods

4.2.1 Participants

Healthy bilingual adults (n=65, 49 females, *m*age: 31.7yrs, SD: 7.24, range: 18-52) participated in the study. All participants were right handed and had no neurological damage/pathology. Participants were native speakers of a variety of languages, and all spoke English as an L2 (*m*AoA: 8.7 yrs., SD: 4.78). All participants moved to the UK at various ages, apart from three participants who were born in the UK to non-UK parents, then moved away to their parent’s country of residence in early childhood and returned in adulthood. Finally, all were living in the UK, with varying lengths of residence at time of testing (*m*length residence: 80.76 months, SD: 97.13). Minimal exclusion criteria were applied to recruit the widest possible range of linguistic experiences. Participants were excluded from testing if they learned English as a third (or later) language, or if they spoke three or more languages proficiently and/or frequently (Appendix A).

4.2.2 Materials and Procedure

In addition to the Language and Social Background Questionnaire (LSBQ, Anderson et al. 2018), participants completed the Oxford Quick Placement Test (QPT) (Geranpayeh, 2003) for general English proficiency and Raven’s Standard Progressive Matrices task (Ravens) (Raven, 1998) to control for intelligence/nonverbal spatial reasoning ability. Participants scored an average of 70.56% on the Ravens (SD: 8.38%, range 53.3-90%) and were found to be high intermediate to high proficiency speakers of English via the QPT (avg. 88.4%, SD 10.8%, range: 52%-100%). The LSBQ documents language use in the participants’ known languages from early childhood to the present day in a range of settings in both home/familial settings and broader social and community settings.

Scores from the LSBQ were entered into a factor score calculator developed by Anderson and colleagues which, based on an exploratory factor analysis, groups similar language experience variables into factors (Anderson et al., 2018). The factor score calculator derives three individual factor scores and a composite factor score (from the individual factor scores) based on scored responses to questions in the LSBQ based on responses to multiple questions regarding language use in specific settings and time points. The scores entered into the calculations are numerated Likert scale scores detailing amount of L2 use from 0 (only the L1) to 4 (only the L2). These scores are standardized and summed into the relevant score of the three factor scores: 1) L2 use in home settings, 2) L2 use in Social/Community settings, 3) L1 proficiency, and 4) a composite score of the three factor scores- called a “Bilingual Composite Score”. Two of these factor scores were adapted and used as variables in our behavioral and neuroimaging analyses. The first, L2_Social, detailed L2 exposure and use in societal and community settings. The other, L2_Home, detailed the extent of L2 proficiency and use in home settings. As our participants were all highly proficient L1 speakers (average self-reported proficiency: 8.7/10, SD: 1.9), the factor score for L1 proficiency was not meaningful to our analyses, thus we did not use it. For the two factor scores we used (L2_Home and L2_Social), a higher score indicates more L2 (English) use, whereas a lower score indicates more engagement with the native language. We observed a mean score of 54.1 for L2_Social (SD: 11.4, range: 10.2-78.1), and a mean score of 3.29 for L2_Home (SD 6.03, range: -5.7-12.6).

Participants completed a version of the Flanker task (Eriksen & Eriksen, 1974; Luk et al., 2010) in the MRI scanner. The task was presented with E-Prime 2.0 Professional (Psychology Software Tools). Participants were instructed to respond to the direction of a red target arrow, surrounded by other white colored symbols (Fig. 1), presented against a black background.

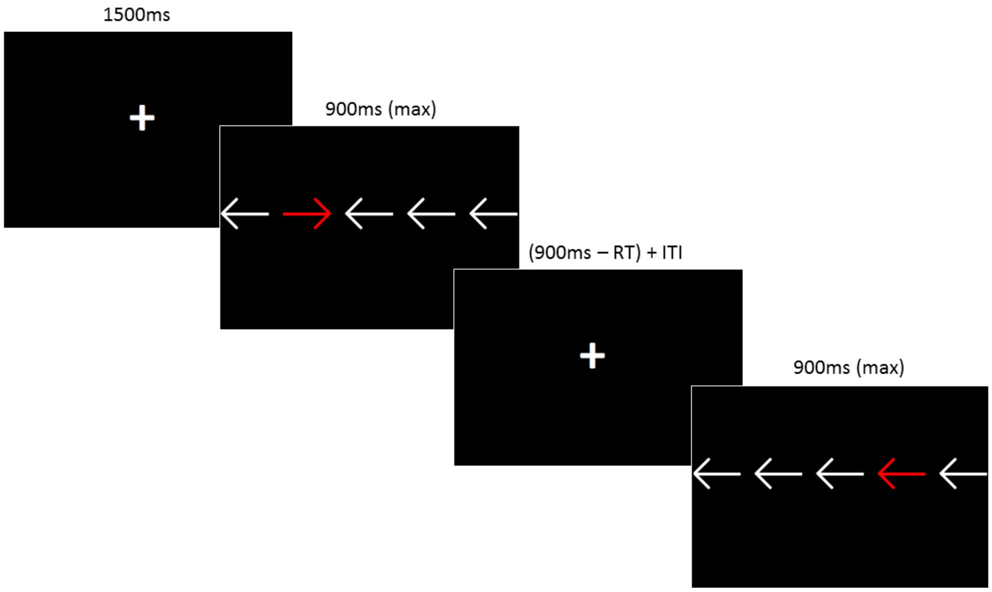

Figure 4-1: Presentation order and stimulus/ITI timings for the flanker task.

The task included 6 blocks: three ‘mixed’, one ‘congruent’, one ‘control’ and one ‘neutral’. In the control block, the arrow was presented alone in the middle of the screen. In the neutral block, the arrow was surrounded by double-sided arrows, such that the trial had the same number of items as the other (non-control) trials but contained no conflicting or facilitating information. A congruent block contained only trials where the flanking arrows were in the same direction as the target arrow. Finally, the mixed blocks contained an even number of both congruent and incongruent trials, in which the flanking arrows were pointed in the same or opposite direction of the target arrow. In all blocks, the order of presentation for individual trials was randomized. The mixed blocks were presented in an interspersed order with the other blocks, such that participants never saw the same block type sequentially. Blocks were presented on a Latin-square design to control for any potential effects of the order of block presentation. Target arrow direction was randomized across all trials within each block. Each block contained 72 trials.

The starting trial for each block began with a fixation cross presented for 1500ms. The stimulus was then presented for up to 900ms. This screen was followed by a fixation cross which lasted for the remaining amount of time for the trial length and the ITI (Fig 1). The remaining time for the trial was recorded/calculated as the difference between the trial reaction time and 900ms. For the mixed blocks, stimuli were presented with a jittered inter-stimulus interval (ISI) of 1500 ± 500ms (minimum ISI 1000ms, maximum ISI 2000ms). The average trial length was 2400ms, but this varied from 1900 to 2900ms. The neutral, control, and congruent blocks had a consistent ITI of 1500ms.

Breaks between blocks lasted 9 seconds. During this time, two screens were shown. The first was gave instructions for participants to take a brief break, which lasted 3 seconds. This was followed by a screen instructing participants to get ready for the next block; this lasted 6 seconds.

4.2.3 MRI Data acquisition

Neuroimaging data were acquired with a 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil and Syngo software. Whole-brain functional images were acquired during the flanker task (735 volumes, FOV: 192 x 192, 68 transversal slices, 2.0mm slice thickness, voxel size 2.1x2.1x2.0mm, TR= 1500ms, TE= 30ms, flip angle 66°). A high-resolution anatomical scan using a MPRAGE sequence was carried out for purposes of registration (256 sagittal slices, 0.7 mm slice thickness, in-plane resolution 250 x 250, acquisition matrix of 246 x 256 mm, echo time (TE) = 2.41 ms, repetition time (TR) = 2400ms, inversion time = 1140ms, flip angle = 8°).

4.2.4 fMRI data analysis

Neuroimaging data were processed and analyzed using the FEAT pipeline in FSL (Smith et al., 2004). Non-brain tissue was removed using the brain extraction tool (BET) (Smith, 2002). Functional data were motion-corrected using MCFLIRT, and slice-time corrected using Fourier-space time-series phase shifting. Image distortion corrections were applied using field map-based echo-planar imaging (EPI) with PRELUDE+FUGUE (Jenkinson, 2003). Functional images were registered to high resolution structural images using FLIRT (Jenkinson, Bannister, Brady, & Smith, 2002; Jenkinson & Smith, 2001). Registration from high resolution structural to standard space was then further refined using FNIRT nonlinear registration (Andersson, Jenkinson, & Smith, 2007). The images were also spatially smoothed using a Gaussian kernel with a Full Width and Half Maximum (FWHM) value of 4mm, and grand-mean intensity normalization of the entire 4D dataset by a single multiplicative factor was applied. Highpass temporal filtering was then applied (Gaussian-weighted least-squares straight line fitting, with sigma=50.0s).

FMRI data were first analyzed by task contrast at the subject level. Individual subject data were analyzed using the GLM package within FEAT (Woolrich, Ripley, Brady, & Smith, 2001). The four experimental conditions modelled as separate EVs. Incorrect and/or missing responses and breaks between blocks were modelled as covariates of no interest in the analysis. Three task contrasts were specified to tap into specific cognitive demands. The first of these was the Flanker effect, which was run to assess neural correlates of interference suppression (Luk et al., 2010). This was assessed by contrasting incongruent against congruent trials and vice versa (incongruent>congruent and incongruent<congruent) within the mixed blocks. We also assessed neural correlates for the

facilitation effect by contrasting the average activation for the congruent block against the neutral block (congruent>neutral and congruent<neutral) (Luk et al., 2010). Finally, we examined global switching cost or ‘mixing cost′ (Wiseheart et al., 2016) which was assessed by contrasting the congruent trials from the mixed blocks with the congruent trials in the Congruent block (Congruent mixed>Congruent and Congruent mixed < Congruent).

Cross-subject analyses were carried out with mixed effects models using the FMRIB's Local Analysis of Mixed Effects (FLAME) pipeline in FSL (Woolrich, 2008; Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004). Contrast Parameter Estimates (COPEs) for all the task contrasts (Flanker effect, mixing cost, and facilitation effect) from the subject-level analyses were entered into the models. The cross-subject model specified group mean, age, sex, and Ravens score as nuisance covariates, and then the language use factors of interest. The resulting statistic images from the higher-level analyses were thresholded using images determined using Z>2.3 and a corrected cluster significant threshold of p=0.05. The Flanker effect, facilitation effect, and mixing cost were analyzed individually. We ran two separate models for the different language factors, aiming to capture individual effects of extent- and duration-based language use factors, and then their combined effects on neurocognitive adaptation.

Model 1 included four variables of interest, which assessed independent effects of absolute duration and extent of L2 exposure/use respectively. Duration of L2 use was measured as two absolute factors: 1) L2 age of acquisition L2 AoA)) and 2) length of L2 immersion (months). We log transformed the variables of L2 AoA and Immersion for two reasons: first, the data were not normally distributed, and second we did not expect a linear adaptation over time (Kuhl et al., 2016). The final two predictors in Model 1 assessed effects of extent of L2 use. These were two of the factor scores derived from the LSBQ (Anderson et al., 2018): 1) L2 use in home settings (L2_Home), and 2) L2 use in social/community settings (L2_Social). The four language use factors were included in the same model to allow us to control for their respective effects and isolate the individual neural effects of each language experience.

As discussed earlier, Model 2 assessed effects of the duration of *active* engagement with the additional language, thus combined effects of duration and extent of L2 use. This was specified in two settings: 1) the total amount of time (of one's life) spent actively using the L2 (Years_Active_L2) and 2) the length of time in immersion spent actively using the L2 (Immers_Active_L2). Years_Active_L2 was determined by calculating the average percentage of English use in several stages, from the point the language was acquired through to the time of testing. This percentage was multiplied by the total number of years spent using the L2. This resulted in a value per participant indicating the number of years spent actively using the L2 (English). Immers_Active_L2 was determined by first calculating a percentage reflecting the daily use of English, including contexts related to reading, writing, speaking, and listening. The resulting percentage was then multiplied by the number of months of immersion. This resulted in values corresponding to the amount of time actively engaged with English in immersion. As neither of these predictor variables was normally distributed, both were log transformed.

4.3 Results

4.3.1 Behavioral

The participants were all highly accurate on the Flanker task (Table 1), so we focused on the reaction time (RT) data. These data were submitted to a linear mixed-effect regression analysis using the *lme4* package in R (Bates, Mächler, Bolker, & Walker, 2015).

Table 4-1: Performance on the flanker task (accuracy and reaction time) globally and by condition.

Measure		**Whole task**	**Congruent (Mixed)**	**Incongruent (Mixed)**	**Neutral**	**Congruent**	**Control**
Acc (%)	Mean	97.82	98.79	95.39	97.97	98.69	98.98
	SD	1.44	2.08	2.90	2.24	1.65	1.3
RT (ms)	Mean	450.6S1	455.03	525.47	468.79	421.41	382.36
	SD	38.1	39.77	40.4	41.92	46.98212	42.1

A base model was first specified including main effect of condition, Ravens scores, and random effects of participants. The optimal random effects structure for the base model was assessed via an analysis of variance using the *anova()* function within the *lmerTest* package using Satterthwaite's method (Kuznetsova, Brockhoff, & Christensen, 2017).

The three task contrasts of interest, namely facilitation, mixing cost, and flanker effect, were assessed separately. For the flanker effect, Congruent Mixed was set as the reference level and was contrasted with Incongruent Mixed. For the mixing cost, congruent mixed was set as the reference level and was contrasted against the Congruent block. Finally, for facilitation effect, Neutral was set as the reference level and contrasted against Congruent. For all three contrasts, we found a significant effect of condition. For the Flanker effect: F(1,64)=1479.29, p<.0001), incongruent (Mixed) trials were slower than congruent (Mixed): (*est*=70.44, *SE*=1.83, *t*=38.462, p<.0001). For the mixing cost

(F(1,64)=102.188, p<.0001), congruent trials were faster than congruent (Mixed) trials (*est*= -33.62, *SE*=3.325, *t*=-10.109, p<.0001). Finally, for the facilitation effect, F(1,64)=118.839, p<.0001), neutral trials were slower than the congruent (*est*=47.37, *SE*=4.34, *t*=10.901, p<.0001).

Two follow up models were run for each task contrast, specifically interaction terms between language experience factors and condition, to assess if these factors modulated RTs on the flanker task. As with the neuroimaging analyses, Model 1 included AoA, Immersion, and the two factor scores L2_Home and L2_Social. Model 2 included the factors detailing duration of active use of the L2, Years_Active_L2 and Immers_Active_L2. None of these models were found to significantly improve model fit over the base model (all ps >.05), indicating no modulatory effect of language experience on task performance.

4.3.2 Neuroimaging

Both Models 1 and 2 showed modulations in brain activation across contrasts, which differed by language use factor/EBF. Results are presented by model and task contrast, respectively.

Model 1: Independent effects of AoA, immersion, and extent of L2 use in home settings and in social/community settings

Flanker/Congruency effect

Length of Immersion negatively correlated with activations in several frontal and parietal cortical regions, including the right MFG and ACC, and bilateral IPL (Table 2), and the cerebellum. L2_Social positively correlated with activations in left lateral occipital cortex (LOC) (Fig 2).

Table 4-2: Model 1 results for the congruency effect. Coordinates listed are in MNI space

EBF	**Direction**	**Hemisphere**	**Region**	**Voxels**	**Z Score**	**X**	**Y**	**Z**
Immersion	-	L	ACC	254	4.04	-4	28	42
	-	L	IPL	193	3.32	-56	-54	34
	-	R	IPL	1042	4.39	52	-50	40
	-	R	MFG	212	4.3	50	18	40
	-	R	Cerebellum	182	3.65	4	-54	-26
L2_Social	+	L	LOC	217	3.83	-40	-80	-2
	+	L	LOC	202	3.89	-20	-66	44

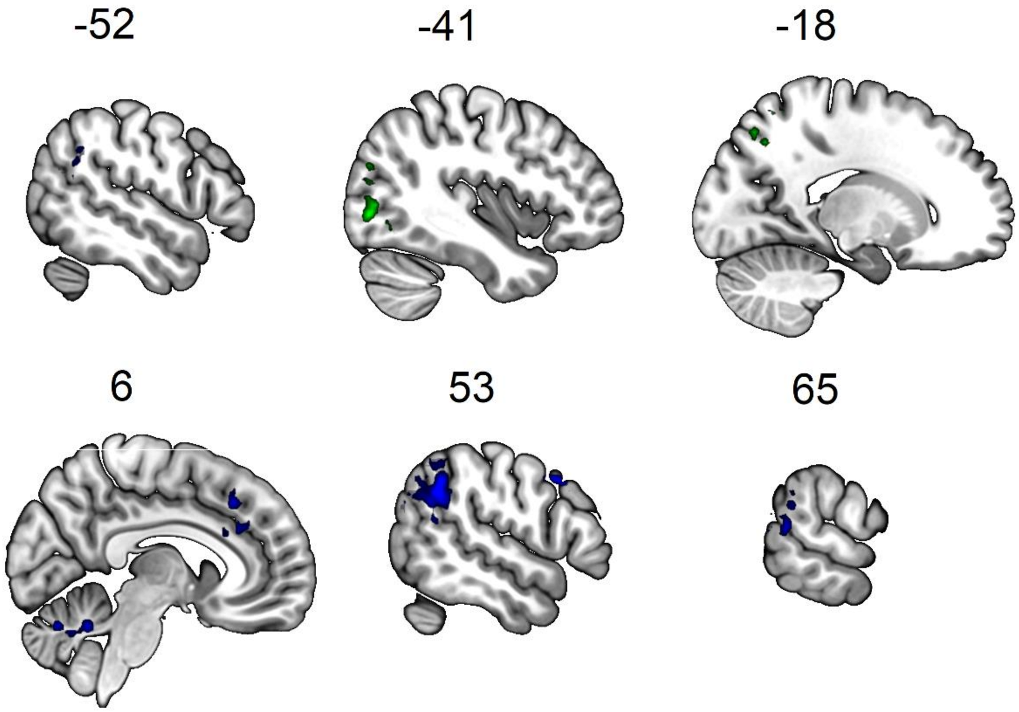

Figure 4-2 Neural correlates for Flanker effect. Negative correlations for Immersion (blue,) and positive correlations for L2_Social (green). Coordinates are in MNI space.

Facilitation effect

AoA negatively correlated with activation in the frontal pole for facilitation. That is, the longer one spoke the L2, the greater the degree of activation in this region for the facilitation effect. Similarly, the length of immersion positively correlated with activation in the precuneus. Finally, L2_Home negatively correlated with activations in several parietal and posterior regions including the regions of the occipital cortex and cerebellum (Table 3; Fig 3).

Table 4-3: Model 1 results for the facilitation effect.

EBF	Direction	Hemisphere	Region	Voxels	Z Score	X	Y	Z
AoA	-	R	Frontal Pole	270	4	32	48	-2
Immersion	+	L	Precuneus	322	3.73	-6	-60	6
L2_home	-	L	Occipital gyrus	1061	4.18	-12	-66	-10
	-	L	LOC	212	3.57	-50	-72	8
	-	L	LOC	206	3.88	-6	-86	46
	-	R	Superior parietal lobule	574	4.41	24	-46	62
	-	R	Cerebellum (Vermis/Crus II)	473	4.25	2	-72	-34
	-	R	Occipital cortex	203	3.16	24	-54	-12

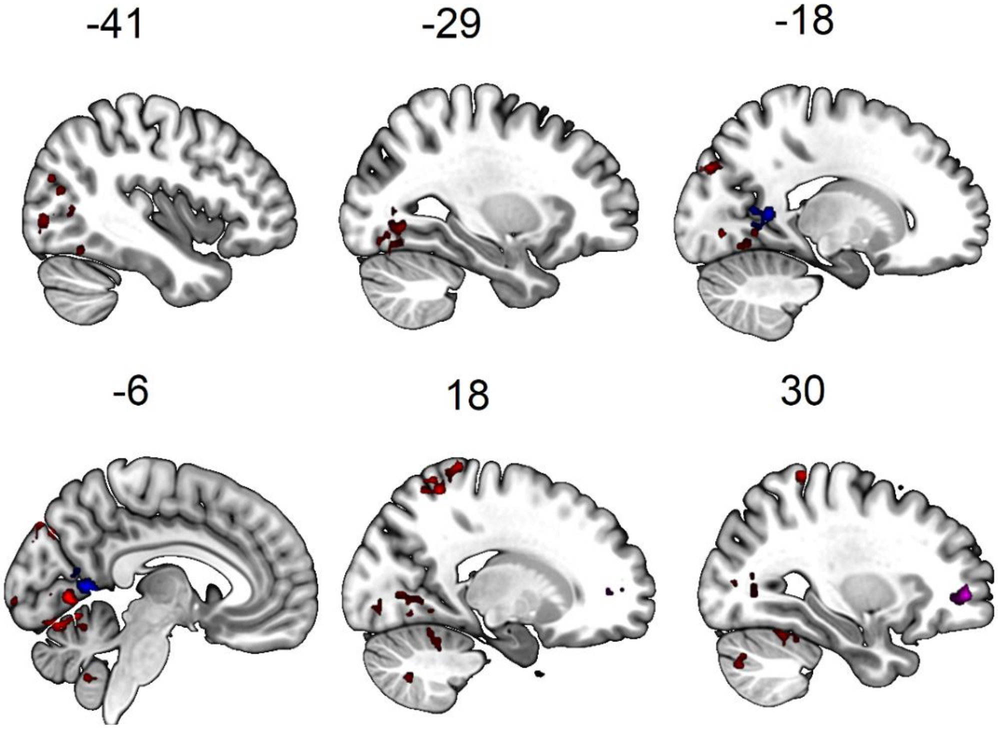

Figure 4-3Neural correlates for the facilitation effect. Positive correlations for Immersion (blue), and negative correlations for AoA (purple), and L2_Home (red).

Mixing Cost

All four language-use factors related to activation patterns for this effect. AoA correlated with activation in the ACC; that is, longer use of the L2 incurred lower degrees of activation in this region. Length of immersion negatively correlated with activation in the precuneus (Fig 3). L2_Home correlated with activation in wide area over posterior regions including the postcentral gyrus and cerebellum (Table 4; Fig 5). Conversely, L2_Social negatively correlated with activations in posterior regions including the IPL/LOC and cerebellum (Table 4; Fig 4).

Table 4-4: Model 1 results for the mixing cost.

EBF	**Direction**	**Hemisphere**	**Region**	**Voxels**	**Z Score**	**X**	**Y**	**Z**
AoA	+	R	ACC	199	3.82	16	46	14
Immersion	-	R	Precuneus	189	4.06	22	-60	12
L2_home	+	R	IPL/LOC	17591	5.07	46	-62	22
	+	R	Postcentral gyrus	720	4.03	68	-2	26
	+	R	Cerebellum (VIIIa/b)	268	3.52	24	-58	-50
L2_Social	-	L	Cerebellum (V)	246	4.03	-16	-62	-12
	-	R	IPL/LOC	366	4.04	48	-62	22

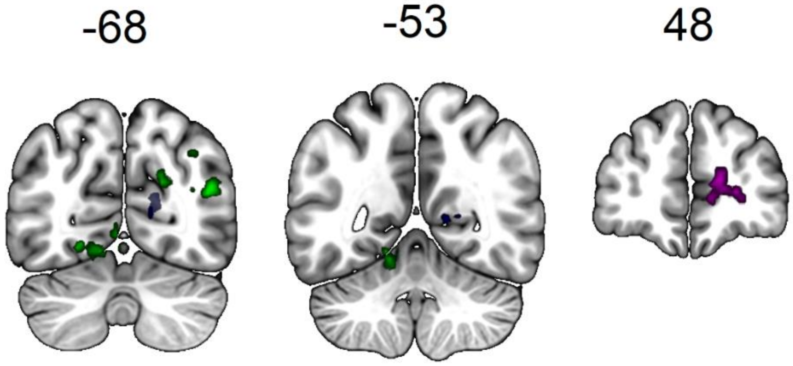

Figure 4-4Neural correlates for the mixing cost. Negative correlations of L2_Social (green) and immersion (blue), and positive correlations for AoA (purple).

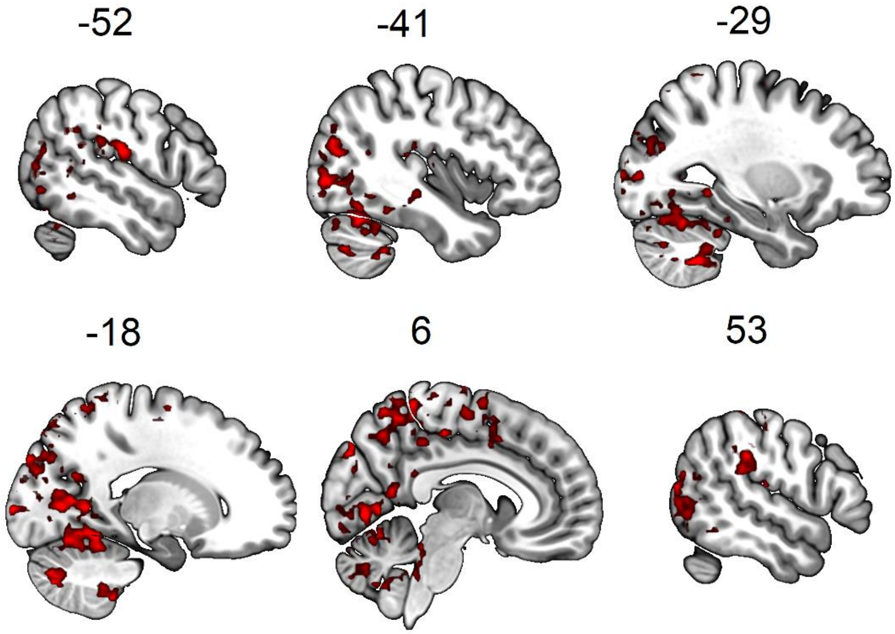

Figure 4-5 Regions showing significant positive correlations for L2_Home (red) for the mixing cost

Model 2: Duration in light of active L2 use overall and in immersion

Flanker/Congruency effect

Both EBFs related to activations, but in distinct regions. Years_Active_L2 predicted activation in several regions including sections of the cerebellum, and bilateral occipital pole. Immers_Active_L2 negatively predicted activation in several regions including in the paracingulate gyrus extending into the anterior cingulate cortex (ACC), within the inferior parietal (angular gyrus and SMG), and lateral occipital cortex (LOC) (Table 5) (Fig 5).

Table 4-5: Model 2 results for the congruency effect

4.4 Discussion

This study examined how different language-use factors in bilinguals affect behavioral performance and neural recruitment in several aspects of executive function as measured by a Flanker task. It is worth reiterating here that this study, by design, did not include monolinguals as a control group. As a result, it is not meant to be interpreted directly within the bilingual advantage debate precisely because this debate has focused extensively on the monolingual versus bilingual comparison. However, data from this study clearly speak to several aspects of the debate and provide a basis for a call to change the direction of research in this field. The debate itself has emerged from studies that have largely treated bilinguals *and* monolinguals as monolithic groups, in the absence of the nuances that potentially give rise to variability within and across these groups. We maintain that an experience-based approach is the crucial next step to understanding potential neurocognitive adaptations related to bilingual language use.

Given this, several general findings from the present study are key. First, behavioral performance on the Flanker task was not significantly affected by the language experiences of individuals. Second, participants' bilingual language experiences did affect patterns of neural recruitment; longer duration of bilingual language predicting adaptations towards increased efficiency of executive control processes, and extent of L2 use showing adaptations towards automation in handling these cognitive demands. Crucially, these neural effects were calibrated to both the extent and duration of bilingual language experience of the participants. This discussion will examine how these results reconcile some contentiously debated issues, while maximally informing our understanding on the effects of bilingualism on neurocognition.

Although our participants showed the expected behavioral task effects for all measured contrasts (interference suppression, facilitation, and mixing cost), these were not modulated by their language experiences. This is likely because all participants were near to ceiling in terms of both accuracy and RT. Thus, the task may not have been sufficiently granular to capture trends in performance (e.g. RT and/or accuracy) resulting from language experiences across the group, at least in our highly functioning group of young adults. This finding echoes several previous studies showing no differences in task performance for highly functioning young adults with different language experiences (i.e. bilinguals vs. monolinguals) on executive function tasks (Bialystok et al., 2005; Costumero et al., 2015; Luk et al., 2010; Paap & Greenberg, 2013). However, if there are behavioral or cognitive constraints related to task granularity/sensitivity (potentially for a subset of bilinguals- young adults at peak cognitive functioning (Bialystok, 2016, 2017)), they do not necessary apply to brain activity. Thus, if an effect of bilingual language use exists at the neural level but does not manifest in task performance, we cannot attribute a lack of group/individual differences in task performance as evidence of no neurocognitive effects. Although such a conclusion may be correct, coming to it in the absence of feasibly corroborative experimental evidence is precipitous.

The results from the present study show that the extent of neural activation across each task contrast was modulated by the respective language-use factors examined in our study. While these adaptations did not translate into comparable behavioral patterns, the neural recruitment patterns found here overlap with previous work showing differences in brain activation between bilinguals and monolinguals (Abutalebi et al., 2012; Ansaldo et al., 2015; Luk et al., 2010). That is, even in the absence of a monolingual control group, the previously reported bilingualism-induced adaptations are documented *within* a bilingual group and are modulated by both the extent and duration of bilingual language experience.

Generally, greater *duration* of L2 use related to decreased cognitive load in interference suppression and switching, and increased engagement with facilitation. For interference suppression, measured here via the flanker effect, longer duration of L2 use (specifically, length of immersion) related to decreased cognitive demands. This is evidenced by negative correlations between duration based predictors and activations in several regions including the MFG, ACC, and IPL, which have previously been implicated in selection and conflict monitoring processes (Abutalebi et al., 2012; Abutalebi & Green, 2016; Ansaldo et al., 2015). A similar effect was found for the mixing cost, in which longer duration of L2 use (both AoA and immersion) translated into decreased recruitment of regions involved in conflict monitoring, again indicating lessened cognitive engagement to maintain a similar level of task performance. These results are also in line with existing models which propose decreased use of frontal regions commensurate with decreased active cognitive engagement in language and cognitive control processes as one continues to use an additional language (Abutalebi & Green, 2016; Grundy et al., 2017). Interestingly, the pattern of results differed for the facilitation effect, in which longer duration of L2 use resulted in increased recruitment of specific regions. For overall duration of L2 use (AoA), this occurred in the frontal pole, indicating increased engagement with current tasks and goal maintenance (Koechlin, 2011; Koechlin & Hyafil, 2007). Longer duration of immersion related to greater activation in the precuneus, which has been implicated in guiding goal-directed activity (Cavanna & Trimble, 2006) and in pattern recognition (Skosnik et al., 2002; Watanabe, Yagishita, & Kikyo, 2008). Under such a view, we may interpret this relationship as an increase in sensitivity to the facilitation effect with increased duration of L2 use.

Functional adaptations related to extent of additional language use showed a differing pattern to duration. Recruitment patterns related to these reflect increased automation in interference suppression and global switching processes, and decreased engagement with facilitation. For interference suppression, greater engagement with the L2 in community settings related to increased activation in the lateral occipital cortex (LOC), bilaterally. This supports aspects of the BAPSS framework (Grundy et al., 2017), specifically increased reliance on posterior structures with increased L2 use, which reflects increased efficiency and automation in language control and processing. For mixing costs, increased engagement with the L2 in home settings related to increased activation in a wide network of parietal and posterior regions. For example, the right cerebellum serves as a hub in the language control network (Abutalebi & Green, 2016), given extensive connections to both frontal regions and the basal ganglia/thalamus (Abutalebi & Green, 2016; Llano, 2013), and has been implicated guiding inhibitory control, through planning and execution (Tyson et al., 2014). The increased recruitment of this structure then indicates greater automation in global switching costs. Increased L2 use in home settings related to lessened activations in several posterior regions. This pattern indicates a decreased cognitive load of task execution with increased L2 use. The SPL and cerebellum have both been implicated in processes related to planning and execution in both linguistic and non-linguistic cognitive processes (Abutalebi & Green, 2016; Chen & Desmond, 2005; Pliatsikas et al., 2014; Reverberi et al., 2015). The negative correlation to facilitation, then, reflect a decreased necessity for cognitive engagement with facilitation in linguistic domains, which in turn affects said engagement in non-linguistic contexts.

Finally, the duration of active L2 use also related to activation patterns indicating increased neural efficiency and automation in handling non-linguistic cognitive control demands. Several effects patterned with those derived by the absolute duration-based factors, with some distinctions. This further indicates a dynamic relationship between extent and duration of bilingual language use regarding associated neurocognitive adaptations. The years actively using the L2 positively related to activations in several posterior regions. This supports tenets of the BAPSS framework (Grundy et al., 2017), specifically increased automation in interference suppression processes. The increased activations in these regions for the congruency effect thus more automated and efficient interference suppression with prolonged active L2 use. Active use of the L2 in immersion settings negatively related to activations in a range of regions in frontal and lateral regions involved in language/executive control. The majority of these spatially converged with regions implicated in the congruency effect for absolute length of immersion. This similarity in effects is not necessarily surprising as both immersion and length of active L2 use in immersion were highly correlated. As such, the negative relationship with activations for active use of the L2 in immersion likely also indicates decreased cognitive demands for interference suppression.

While there is a degree of overlap between the absolute duration-based variables and those accounting for extent of use, several distinctions exist between the two. Comparing length of immersion and its EBF corollary (Immers_Active_L2), for example, the EBF version revealed changes in the lateral occipital cortex and middle temporal gyrus for the Flanker effect that did not emerge from just considering time alone. In other words, not all immersion values in absolute terms X are qualitatively the same, and these experiential differences relate to measurable differences in neurocognitive function. A stronger case in point can be made between L2 AoA and its EBF corollary Years_Active_L2 where there was no overlap, but the more nuanced EBF version revealed activations for the Flanker effect that AoA did not predict. Therefore, the effects of absolute values are clearly modulated by what happens experientially within these periods.

Concluding remarks

This study examined neurocognitive effects of different language use factors within the bilingual experience, across domain general cognitive processes. The study was framed within the contemporary debate regarding the extent to which bilingualism may be associated with adaptations to the executive function system. The present data provide crucial insights pertinent to further examination of bilingualism and related neurocognitive adaptations.

Related to the debate of neurocognitive effects of bilingualism, the asymmetry of our results between task performance and neural recruitment underlines a further important point. Although executive functions tasks themselves target measurable behavior at a specific level, they are used as a tool to make claims about what is happening in the black box of the mind/brain. However, behavioral data does not reliably capture the whole picture such that it can be used—in the absence of converging data of higher granularity also showing no effects—to negate an effect found by other studies. The test-retest reliability of a number of executive function tasks is known to be relatively low (Soveri et al., 2018), yet data from them are often used to make claims about certain neurocognitive adaptations/differences in absolute terms. In principle, to ensure that what is claimed from behavioral results is not precipitous, the data should not run in contrast to simultaneously collected neurological function (correlate) data. The asymmetrical pattern revealed in our study provides a crucial example to this cautionary tale, precisely because they show that behavioral measures can fail to capture differences in neurocognitive processing that are captured by a more fine-grained modality of neuroimaging. This is crucial, as it highlights a potential limitation of the behavioral tasks tapping executive control, especially in healthy young adults. Considering the above, null results from purely behavioral modalities should not (necessarily) be interpreted as absolute evidence against neurocognitive adaptations to bilingual language use, as much as not all positive results necessarily confirm bilingual cognitive effects either. Regardless, the present data strongly suggest a utility in following up what is found behaviorally with complementary, more granular modalities, to ascertain the whole picture of potential neurocognitive adaptations.

Furthermore, the continuum of experiences that comprise bilingualism do indeed confer distinct, measurable neurocognitive outcomes. Moreover, these outcomes manifest as adaptations in neural recruitment patterns that occur in regions in the executive control network that are also found by studies comparing bilinguals to monolinguals. Crucially, as has been discussed, these adaptations are dynamic: the degree to which said neurocognitive adaptations occur is modulated by the language experience of the participants. That is, although the participants all performed essentially at ceiling in terms of task performance, the degree of bilingual language use was commensurate to the efficiency and/or automation by which participants arrived at this level of task performance. It should also be reiterated here that the language use factors examined in the present study are by no means an exhaustive list. Exploring other factors and their dynamic relationship with the present ones would better delineate the dynamic nature of bilingual language use and related neurocognitive adaptations.

The distinction of results between the absolute duration-based factors (AoA and Immersion) and their experience-based (EBF) corollaries also have consequences for comparisons of results across a broader group of studies. If, for example, AoA can encompass any extent of usage—e.g. 10 years of L2 use in a group of 20 bilinguals could comprise 20 different levels of active engagement—then comparing adaptations for equivalent ages of acquisition across studies would be an inadvertent red herring. It is possible, in context of the replication debate, that studies showing no effects have greater variability between the AoA and EBF corollary levels than other studies that show effects. Precisely because the present study and similar ones recently have shown that quality of the bilingual experience matters, we should consider replacing absolute scores with EBF composites. Then, instead of claiming there is no effect whatsoever because a study in San Francisco failed to replicate the findings of a study in London, we can check what the quantity of the experience of the individuals was in both locations and determine if such a comparison is justified. Even if in both cases, absolute measures of time such as L2 AoA or immersion are equivalent, we might see that the patterns of language use in that time are vastly different, and thus give rise to the disparity in findings.

As we have discussed, bilingualism is a complex and dynamic process, which is comprised of a range of experiences that shape distinct neurocognitive adaptations. The brain constantly adapts and updates to be maximally effective at handling the cognitive load of the communicative environment. Modulations to that environment, specifically the language experiences it entails, will thus confer measurable and distinct outcomes for the mind and brain. Specific language experiences must be considered in more detail in future research examining the neurocognitive effects of bilingualism. As such, we propose that future studies move away from categorically distinguishing bilingualism/monolingualism and treat bilingualism not as a *label* but as a *spectrum* of related experiences that variably affect neurocognition.

CHAPTER 5: GENERAL DISCUSSION AND FUTURE DIRECTIONS

At initial review, the effects of bilingualism on the mind/brain are variable and tenuous, based on what is reported by the studies examining this relationship (García-Pentón et al., 2016b; Valian, 2015a). Indeed, as has been noted previously in this thesis, this disparity of results has incited questions over what exactly the effect of bilingualism is on the mind/brain, to the extent one exists (Baum & Titone, 2014; Bialystok, 2016; Bialystok, Kroll, Green, MacWhinney, & Craik, 2015; de Bruin et al., 2015; R. M. Klein, 2014; Paap et al., 2015b; Paap, Sawi, et al., 2014; Titone & Baum, 2014). The effect of bilingualism is not uniform, and these effects are likely modulated by several factors. As some have argued (Valian, 2015b), the disparities in results between studies are in part due to methodological inconsistencies between them. However, this is not the only factor which affects the outcomes reported. It is widely acknowledged that bilingualism is a highly dynamic process with many factors determining both patterns of language acquisition, processing and use (e.g. Carroll, 2017; Cunnings, 2017; Grüter, Lew-Williams, & Fernald, 2012; Kaan, 2014; Kroll & Bialystok, 2013; Rothman & Guijarro-Fuentes, 2010; Slabakova, 2016; Wei, 1994; White & White, 2003; among others). Under such a view, it would be inaccurate to expect uniformity of results across studies examining neurocognitive effects of the bilingual experience, even if more rigorous measures were put in place to maintain consistency in methodology across studies. Many would agree that it would be inaccurate to consider equally the neurocognitive effects of (for example) sequential bilinguals residing in London with simultaneous bilinguals living in Montreal.

However, such a comparison would become more valid when appropriately accounting for the contributions of language engagement/exposure proxies, including where and to what extent the languages are used, language dominance, and access to each language, among others. Indeed, very few studies to date have employed an approach which considers such a range of experiences regarding their relative contributions to neurocognitive adaptations.

Given the above, this thesis project represents a departure from the canonical methodology applied in research examining neurocognitive effects of bilingual language use. The primary goals of the project were twofold. First, I aimed to identify factors within the bilingual experience that contribute to neurocognitive adaptations, and how these adaptations manifest. Second, I aimed to assess how these adaptations are modulated through time with continued bilingual language use. These aims were subsumed under a general goal, which was to assess the validity of examining individual differences in bilingualism on neurocognitive adaptations in future research, as has been called for previously (Bialystok, 2016; Green & Abutalebi, 2015). The results from each of the three studies support the argument that individual language experiences confer distinct effects to the mind/brain. Additionally, the data support an account of continuous neurocognitive adaptation, such that the brain is maximally effective and efficient at handling stimuli from the surrounding environment. Furthermore, these adaptations seem to have several implications for non-linguistic cognitive processes. The contributions of each study to this conclusion are discussed.

The first study of the thesis (DeLuca, Rothman, & Pliatsikas, 2018) showed neuroanatomical adaptations in bilingual adults to longer-term, naturalistic, L2 immersion over a three-year period. Given the longitudinal (within-subjects) nature of the study, examining effects of immersion using this methodology allows for us to better control language use-related factors across the group and isolate effects of duration of intensive exposure to the L2 (Linck et al., 2009). With respect to aims of this project, the results show that neuroplasticity is continuously modulated with continued bilingual language use, which here include adaptations towards automation of processing and decrease in cognitive load of controlling the two languages. Results from the second study of this thesis (DeLuca, Rothman, Bialystok, & Pliatsikas, (a) under review) showed independent and distinct effects of specific language related factors, both static (absolute numbers of years related to L2 AoA, and immersion) and experience-based (EBF) (extent of engagement with the L2 in the same time periods) home and ii) social settings) on brain plasticity in bilingual adults. Factors related to duration of language experience (controlling for extent of L2 use) showed neuroanatomical adaptations towards increased efficiency in language processing and control. EBFs related to extent of engagement with the L2 (controlling for duration) show adaptations towards the increased cognitive, language control, demands associated with more intensive L2 use. Finally, experience-based factors related to duration of active L2 use suggest adaptations towards increased efficacy in learning reinforcement and increased efficiency in language control processes. A similar pattern of results can also be seen for Study 3 (DeLuca, Rothman, Bialystok, & Pliatsikas, (b) submitted) in which we found neurocognitive adaptations to vary by individual language use factors and by each cognitive demand. Similar to Study 2, the results seen here suggest neurocognitive adaptations towards maximal efficiency and efficacy in cognitive control, which relates to both extent and duration of L2 use (both categorically and active). More cognitively demanding processes (interference suppression and global switching cost) became more automated with increased extent and duration of L2 use. Less cognitively demanding tasks (facilitation) showed more automatic processing with increased extent of L2 use, and more attention to the effect with increased duration of L2 use.

Further to their individual contributions to our understanding of bilingualism and neuroplasticity, the data support efficacy of a bilingual-centric approach to studying the effects of bilingualism on the mind/brain. This approach has two main benefits for future work. Primarily, it serves as a basis for experimental and analytical designs in future studies. Secondly, such an approach also provides a potential basis by which to adjudicate between the results of past and present studies which find differing outcomes of bilingualism.

The primary argument of this thesis is that the field should move away from examining the effects of bilingualism as patterns of behavior and brain structure and function that are compared to an ill-defined monolingual ‘baseline’. The consideration of bilingualism as a spectrum is beneficial as it allows a step away from typical, binary, terms of ‘yes’ and ‘no’ to ‘to what extent or degree’ and ‘considering what conditions?’. The data from the present study support such an account going forward. The regions and pathways identified in the analyses from the three studies overlap with areas previously identified in the literature for which monolinguals and bilinguals differ. Moreover, the degree to which these adaptations manifest was found to be calibrated to factors of the bilingual experience. These results thus establish the validity of such an approach.

It should be noted that this approach does not attempt to directly address the debate in the literature regarding a ‘bilingual advantage’, as monolinguals were not tested in any of the three studies. However, the data do contribute to the debate, in that they do directly call into question its central premise. The current controversy is argued to revolve around a wholesale question: “does bilingualism confer an advantage in executive functions?” As discussed above, the results from the three studies suggest varying degrees of adaptation which are tied to the degree of bilingual language experience, from both an extent-based and durative perspective. Thus, at the level of individual studies, the grouping or categorization of bilinguals into a comparable group to monolinguals would then average out the adaptations tied to these respective experiences, and at the very least obscure the results. At the level of generalizations across studies, this suggests potential issues with comparisons between groups of bilinguals when the various factors related quantity, quality, and duration of L2 use are not adequately considered. Instead, the observed effects should be evaluated in connection with the individual language experiences of the bilinguals, which will help to build a comprehensive theory to explain observations across all bilingual groups.

5.1 Future Directions

This field is in its relative infancy, and as such the body of literature is small. A number of avenues can be taken in future to better understand the effect of bilingualism to brain structure, function, and cognition. As such, there are several underexplored areas/questions which seem promising to further tune our understanding of the cognitive and neurological effects brought on by the bilingual experience. Several such directions are discussed in the following section.

5.1.1 Further factors and their interrelatedness

This direction is a clear follow-up from the results of the present thesis. We are just scratching the surface of accurately modelling the dynamic nature of bilingualism in terms of what regressors can be applied. Work from two other studies provides key examples of other language variables that should be accounted for or examined in their own right in future research (Gullifer et al., 2018; Yamasaki et al., 2018). Recall from the introduction (Section 3) that the study by Yamasaki and colleagues examined behavioral effects of individual differences in bilingual language use, with an attentional blink task and Simon task in bilingual adults (Yamasaki et al., 2018). The factors used in the models included: typological relatedness between languages, L2 AoA, frequency of language use, frequency of language switching, and L2 proficiency. Additionally, recall that the study by Gullifer and colleagues examined effects of individual differences in two measures on proactive vs reactive control and resting-state connectivity. The factors examined here were: L2 AoA, and language entropy, a composite score which measured the variability in sources of bilingual language use (Gullifer et al., 2018).

There are overlapping factors examined by both this thesis and the above studies. These include static factors (L2 AoA), and EBFs (frequency of language (L2) use). However, the above studies and those in this thesis diverge on other factors including frequency of language switching, language typology, and the social diversity of language use.

The typology of one's respective languages in bilingual and multilingual language use has been considered more extensively in language acquisition (Gonzalez Alonso & Rothman, 2017; Håkansson, Pienemann, & Sayehli, 2002; Kellerman, 1986; Rothman, 2010, 2011, 2015; among others). However, the implications this has for neural plasticity is relatively understudied in the current literature (see e.g. Zhu, Nie, Chang, Gao, & Niu, 2014), leaving much more to be understood about the neurological implications for typological relatedness effects in language acquisition. In this light, the role of language typology is an empirical question, particularly with regards to the how typological relatedness between languages shapes the processes of acquisition and representation neurologically. For reasons of cognitive economy, full transfer of a language to the target language occurs (Gonzalez Alonso & Rothman, 2017; Rothman, 2015; Schwartz & Sprouse, 1996). As such, languages which are typologically more closely related have a greater chance of facilitating acquisition overall (Rothman, 2015; Schwartz & Sprouse, 1996), although this process is not linear (Håkansson et al., 2002; Lardiere, 2008, 2009) and non-facilitation can also occur, especially in multilingualism, as a result of the same economical push for full transfer early on (Gonzalez Alonso & Rothman, 2017; Rothman, 2015). The varying trajectories in language acquisition and control would have implications for the neural networks involved in language processing, in that more or less stress (with varying cognitive demands) would be placed on regions and pathways implicated in specific language processes, for example the phonological/auditory loop or networks involved in the processing of morphology and syntax (Abutalebi & Green, 2016; Friederici & Gierhan, 2013; Pliatsikas et al., 2014a; Ullman, 2004). However, understanding the specific role language typology plays in this process requires more consideration and research.

Another variable to consider is the diversity of language use across various domains, how this interacts with language use patterns, and what implications this has for neurocognitive adaptations (Green & Abutalebi, 2013; Gullifer et al., 2018; Hartanto & Yang, 2016; Hofweber et al., 2016). As was noted by both the Gullifer et al study and the Hartanto and Yang (2016) study, exposure to a greater diversity of domains in which both languages were used related to adaptations towards greater language control demands, and in both cases were found to affect domain general cognitive processes. The results are intriguing, but more work can be done in this domain. In both cases, the variables used were general overviews of the diversity of language use. To some extent, this diversity was captured in the variables in studies 2 and 3 of this thesis, specifically those related to extent of L2 use in social and home settings. However, future work should consider this factor in greater detail and more accurately map the contributing sources of diversity in language use.

It should also be noted that while the variables are individually partially explanatory, the experiences they measure do not occur in isolation. The combination and interaction of language use variables should also be considered in future research- a better understanding of any potential relationships between these variables and how this relationship relates to neurocognitive adaptations. A poignant example of this is the relationship between language background/environment and language switching (Hartanto & Yang, 2016; Hofweber et al., 2016). Language environment and background will very likely play a role in determining language use patterns (Green & Abutalebi, 2013; Green & Wei, 2016; Heller, 1978; L. Wei, 1994). Results from these studies support this notion. Language background (in this case immigration status) and language environment (single vs dual language context) was found to determine the degree and density of code switching, which in turn was found to relate to modulations in task switching costs. Similarly, in the case of the above example with language diversity, it follows logically that greater opportunities for use of both languages will facilitate individuals in doing so. From these and other examples, I propose that more consideration needs to be given to the interaction between various environmental and experiential factors to most accurately model language use patterns and their neurocognitive effects. In so doing, we aim to model the experience of bilingualism as a multidimensional continuum in which a range of distinct but interrelated factors which place individuals.

Finally, I should reiterate that the variables specified here, and in this thesis, are by no means an exhaustive list of explanatory factors. However, their inclusion in future studies will likely further delineate the nature of neurocognitive adaptations as the complexity of the bilingual experience is further unpacked into its respective components.

5.1.2 Effects of individual differences in predisposition- genetics and neural morphology

In addition to considering language experience, taking account of individual differences in predisposition, genetics and pre-existing neural morphology, can help to better outline the relationship between bilingual language use and neurocognitive outcomes. Only select studies to date have examined the role of individual differences in genetic phenotypes and their effects on capacity or bilingual language use (e.g. Vaughn & Hernandez, 2018), and how this affects neurocognitive adaptation (e.g. Mamiya et al., 2016). With respect to effects on neuroanatomical adaptations, recall that the study by Mamiya et al. (2016) found that participants with Met/Val and Val/Val polymorphisms of the COMT gene exhibited higher FA values during immersion, whereas those with

Met/Met genotype did not exhibit this relationship. Further to this, expressions of the COMT gene have been linked to individual differences in executive function processes (Kasparbauer et al., 2015). The study by Vaughn and Hernandez (2018) examined both L2 AoA and the ANKK1/TaqIa and Val158Met polymorphisms, and their effects on language proficiency in bilingual adults. Language proficiency was found to relate both to AoA and genetic variants within the studied polymorphisms. Specifically, in earlier AoAs, expressions of the genetic variant associated with higher levels of subcortical dopamine (Val/Val and Met/Met polymorphisms) related to higher proficiency. For later AoA, individuals with the genetic variant associated with cortical dopamine levels that are balanced between stability and flexibility (Val/Met) were found to relate to higher language proficiency (Vaughn & Hernandez, 2018).

Genetics is one potentially key factor of predisposition towards acquiring a novel language. The role of pre-existing brain morphology has been suggested to predict the capacity for one to more effectively acquire a non-native language (Cachia et al., 2017; Deniz Can, Richards, & Kuhl, 2013; Golestani, 2014; Golestani, Molko, Dehaene, LeBihan, & Pallier, 2007; Marie & Golestani, 2017; Sebastián-Gallés et al., 2012). The connection of brain morphology and behavioral pattern may be a chicken-and-egg relationship given the relative timings of acquiring each measure (Golestani et al., 2007; Sebastián-Gallés et al., 2012). Nevertheless, the pattern of results from the above studies suggests that existing predisposition in genetics and brain structure is an empirical question and as such should be considered in study designs in future research.

5.1.3 Relating structural adaptations to function/cognition

Bilingual language use has been found to affect neural structure, function and domain-general cognitive processes individually and in combination. However, relatively less research has been devoted to what specific connections exist between structural plasticity and functional/cognitive outcomes related to domain-general cognition, as a function of bilingual language use. Previous work has shown a link between linguistic outcomes and neural structural plasticity (Grogan et al., 2009; Mårtensson et al., 2012; Osterhout et al., 2008; Pliatsikas et al., 2014b; Rodriguez, Archila-Suerte, Vaughn, Chiarello, & Hernandez, 2018; Stein et al., 2012). Results from recent work also show that plastic changes related to bilingual language use are related to individual differences in executive function capabilities (Cachia et al., 2017; Mamiya, Richards, & Kuhl, 2018). In the case of both studies, a greater degree of brain plasticity in brain regions and pathways implicated in cognitive control functions related to increased performance on executive function tasks. The study by Mamiya and colleagues found increased myelination in the anterior thalamic radiation (ATR) to predict lower reaction times on a Stroop task. The study by Cachia and colleagues (2017) found the degree symmetry of sulcation between hemispheres in the anterior cingulate cortex (ACC) to relate to lower congruency effects in a flanker task in bilingual participants. The results of these studies are highly interesting but need to be explored further with respect to the specific effect of bilingualism on this relationship. Future research should incorporate the language experience of bilingual participants, and how this modulates the connection between neurophysiological adaptation and cognitive performance (e.g. Gullifer et al., 2018).

5.1.4 Longitudinal Studies

The majority of research examining neurocognitive effects of bilingualism comes from cross-sectional studies. Results from these can have issues, given the number of factors that must be addressed when regressing effects of EBFs of interest across a large, complex cohort. This is particularly true when attempting to assess effects of any duration-based factors. This considered, longitudinal studies would thus be especially useful in examining effects of specific EBFs in bilingual language use. By virtue of their within-subjects design, they allow for greater control over extraneous variables; these variables are then are not necessarily confounded as they might be in a cross-sectional design (Luk & Pliatsikas, 2016; Wong et al., 2016). As such, longitudinal designs allow us to practically isolate effects of specific EBFs of interest and what effects they have on the mind/brain. Essentially, these allow us to more directly examine effects of specific language use patterns over time.

It should be noted that longitudinal designs themselves are not novel in this field. Several studies have examined the effects of language learning, and later stages of use, on the brain from a longitudinal perspective (Bellander et al., 2016; Hosoda et al., 2013; Mamiya et al., 2016; Mårtensson et al., 2012; Osterhout et al., 2008; Stein et al., 2012). However, these only examine a handful of language-use factors, last for a maximum of three years (with most studies lasting a matter of weeks), are typically training studies examining vocabulary acquisition (thus not particularly ecologically valid), and the majority only employ two or three scan points. Thus, there is a great deal of room for greater contributions of studies employing a longitudinal design. Specifically, any future longitudinal studies would do well to employ designs with more scanning points, and over longer time periods, practically considering (where possible) a range of experience-based factors and their individual effects. In so doing, they would allow us to outline effects of specific EBFs through time, without the risk of inadvertently confounding other variables in the process. Furthermore, they will allow us to directly answer whether some of the variability of the effects found in the literature is due to different studies having captured different time windows of a larger overall trajectory in neurocognitive adaptation.

5.2 Conclusions

As has been noted several times within this thesis, bilingualism is a complex and dynamic process which is comprised of a number of language-related experiences that play a role in determining linguistic and domain-general neurocognitive outcomes. As the brain strives to be maximally efficient at handling its surrounding environment, it logically follows that differences to individual bilingual language experiences would confer distinct, tailored neurocognitive adaptations to the past and ongoing experiences. This is precisely what the results of this thesis show. Furthermore, these adaptations were found to be modulated with ongoing bilingual language use. Overall, the results from this thesis highlight the necessity of an individual differences approach in future neurocognitive research examining the various effects of the bilingual experience.

It should be noted that the results and methodology from this thesis project are not the complete answer to the ongoing debate. What this thesis does is support the departure from binary/categorical distinctions and comparisons so prevalent in the field at present, towards a program of using bilingualism as a continuous predictor and considering/regressing a sufficient number of contributing factors. As discussed before, doing so has two benefits. First, it allows a more nuanced understanding of the relationship between bilingual language use and neurocognitive adaptations, how these adaptations manifest, and how they are modulated with continued bilingual language use. Second, it allows for maximal comparability between studies, both past and future, examining different populations, and can create a much greater breadth and depth in understanding of the consequences of bilingualism.

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APPENDIX A: Demographic information- Participants

Subject	Age	Sex	Native Language	QPT Score	AoA English	UK residence (months)	L2_Home Score	L2_Social Score	Yrs_Active_L2	Immers_Active_L2
201	33	F	European Portuguese	54	10	0.26	-5.74	10.27	1.44	0.10
202	33	F	Italian	55	5	1.32	4.03	45.77	14.00	0.99
203	35	F	German	55	11	11.38	3.14	52.44	4.80	8.54
204	28	F	Polish	50	5	105.86	8.00	63.90	12.46	105.86
205	29	M	Greek	58	0	44.01	10.29	58.56	13.41	33.01
206	25	M	Japanese	52	21	7.17	-5.15	42.76	2.00	3.59
207	34	M	Turkish	56	12	18.49	3.55	68.33	13.06	13.87
209	29	F	Turkish	55	17	38.72	2.19	49.71	4.88	31.46
210	22	F	Romanian	41	7	28.65	16.70	56.01	5.25	28.65
211	18	F	Italian	57	2	36.15	-1.09	64.39	12.80	33.89
212	30	F	Italian	43	14	47.17	14.89	62.66	7.50	35.38
213	23	M	Swiss-German	58	0	43.88	4.04	64.49	14.38	32.91
214	38	F	German	58	10	165.13	3.58	62.07	11.38	165.13
215	39	F	Dutch	57	6	85.16	7.48	56.48	10.83	74.52
216	39	F	German	58	11	240.33	2.31	44.83	14.00	210.29
217	32	F	Italian	57	0	395.03	-2.56	34.44	12.00	395.03
218	26	F	Latvian	47	6	2.93	1.59	59.60	5.00	2.20
219	38	F	French	60	12	172.11	11.47	47.86	8.67	129.08
220	35	F	Spanish	60	0	408.05	-2.20	52.46	24.79	315.72
221	26	M	Spanish	58	6	68.29	-1.75	61.46	4.69	68.29
222	26	F	Spanish	55	4	11.22	7.39	66.06	5.50	7.01
223	34	F	Polish	55	6	118.68	2.35	62.09	5.95	89.01

224	22	F	Bulgarian	57	14	36.91	-1.14	42.41	4.67	36.91
225	44	F	Mandarin	54	13	91.25	1.36	55.36	4.65	68.44
226	28	F	French	55	7	85.76	6.17	72.27	6.23	64.32
227	34	F	Polish	57	10	127.37	11.80	53.38	11.00	103.49
228	23	M	Czech	56	4	34.84	8.06	51.42	7.13	34.84
229	47	F	Dutch	55	8	8.98	12.69	78.07	26.00	6.74
230	27	F	Urdu	59	5	134.67	11.59	68.85	11.55	134.67
231	23	F	Swedish	57	0	46.22	8.28	71.13	14.38	34.66
232	26	M	Dutch	57	4	5.53	6.17	48.21	9.97	4.14
233	37	F	Greek	59	6	36.28	-1.48	33.77	12.92	27.21
234	52	F	German	59	10	21.12	5.78	55.93	15.75	10.56
235	26	F	Polish	56	11	59.64	3.05	61.69	6.56	44.73
236	30	F	Spanish	40	22	87.50	5.01	46.56	4.00	82.03
237	43	M	German	58	5	459.05	0.89	39.90	30.08	459.05
238	41	F	Spanish	50	14	52.53	0.41	73.72	11.81	32.83
239	21	F	Portuguese	57	5	31.81	2.18	49.83	6.67	31.81
241	38	F	Russian	59	11	180.56	1.99	60.53	7.88	135.42
242	50	F	Spanish	48	7	23.65	3.40	51.92	8.36	19.22
243	43	F	Finnish	56	9	289.90	-1.46	65.13	16.06	217.43
244	25	M	Dutch	57	5	11.84	0.60	51.79	7.50	9.62
245	27	M	Italian	50	8	12.53	1.58	55.39	7.52	8.62
246	27	F	Spanish	33	9	12.70	6.52	61.79	7.50	6.35
247	38	F	Greek	52	7	38.42	-1.79	32.41	10.33	24.01
248	29	F	German	57	10	34.28	1.39	62.10	8.97	25.71
249	23	M	Spanish	39	7	0.69	-4.78	41.19	4.33	0.43
250	39	M	Greek	56	6	131.78	7.94	73.35	13.06	131.78
251	29	F	Spanish	45	10	58.52	-3.93	41.92	7.92	43.89
252	32	M	Greek	54	8	61.61	-0.54	66.52	18.00	61.61
253	29	M	Spanish	38	10	24.64	5.91	54.15	5.94	15.40

254	31	F	Spanish	48	6	84.93	-0.82	35.31	11.46	63.70
255	24	F	German	52	8	9.51	-0.34	46.54	5.00	6.54
256	22	F	German	49	7	2.27	1.52	39.55	4.38	1.70
257	38	F	German	56	12	146.32	6.29	52.58	10.56	109.74
259	35	F	German	53	11	125.43	-1.11	50.00	8.00	94.07
260	30	F	Norwegian	50	7	1.91	2.89	52.48	11.50	1.43
261	29	M	German	53	11	38.16	1.39	55.78	10.69	26.23
263	28	F	Turkish	47	9	26.74	2.84	62.79	6.86	18.39
265	40	F	German	57	11	98.98	2.29	51.97	13.29	74.24
266	39	F	Polish	55	15	162.83	4.42	46.00	10.50	122.12
267	25	F	Spanish	53	20	32.24	2.00	60.89	3.13	20.15
268	46	F	German	60	12	154.93	3.28	55.03	17.00	154.93
269	26	F	Spanish	31	16	39.51	5.17	51.59	3.44	29.63
270	29	M	Romanian	53	11	75.46	2.16	49.94	8.25	56.60

APPENDIX B: The Language and Social Background Questionnaire

Language and Social Background Questionnaire

Lifespan Cognition and Development Laboratory

Ellen Bialystok, Ph.D., Principal Investigator

Language and Social Background Questionnaire

Today's Date: ______________________

Day **Month** **Year**

1. Sex: Male ☐ Female ☐

2. Occupation/Student Status (i.e. FT/PT, current year of study): ______________________

3. Handedness: Left ☐ Right ☐

4. Date of Birth: ______________________

Day **Month** **Year**

5. Do you play first-person shooting (FPS)/action video games? **Yes** ☐ **No** ☐

If **yes**, on average how many hours do you play per week? ______________________

6. Do you have hearing problems? **Yes** ☐ **No** ☐

If **yes**, do you wear a hearing aid? **Yes** ☐ **No** ☐

7. Do you have vision problems? **Yes** ☐ **No** ☐

If **yes**, do you wear glasses or contacts? **Yes** ☐ **No** ☐

Is your vision corrected to normal with glasses or contacts? **Yes** ☐ **No** ☐

8. Are you colour blind? **Yes** ☐ **No** ☐

If **yes**, what type? ____________________

9. Have you ever had a head injury **Yes** ☐ **No** ☐

If **yes**, please explain: ____________________

10. Do you have any known neurological impairments? (e.g., epilepsy etc) **Yes** ☐ **No** ☐

If **yes**, please indicate: ____________________

11. Are you currently taking any psychoactive medications? **Yes** ☐ **No** ☐

If **yes**, please indicate: ____________________

12. Please indicate the highest level of education and occupation for each parent:

Mother	Father
1. _____ No high school diploma	1. _____ No high school diploma
2. _____ High school diploma	2. _____ High school diploma
3. _____ Some post-secondary education	3. _____ Some post-secondary education
4. _____ Post-secondary degree or diploma	4. _____ Post-secondary degree or diploma
5. _____ Graduate or professional degree	5. _____ Graduate or professional degree
Occupation: ____________________	Occupation: ____________________
First Language: ____________________	First Language: ____________________
Second Language: ____________________	Second Language: ____________________
Other Language: ____________________	Other Language: ____________________

13. Were you born in the UK? **Yes** ☐ **No** ☐

If **no**, where were you born? ______________________________

When did you move to the UK? ______________________________

Year

14. Have you ever lived in a place where English is not the dominant communicating language? **Yes** ☐ **No** ☐

		From	**To**
If **yes**, where and for how long?	1. ______________________	__________	__________
	2. ______________________	__________	__________
	3. ______________________	__________	__________
		Year	**Year**

Language Background

15. List all the language and dialects you can speak and understand including English, ***in order of fluency***:

Language	Where did you learn it?	At what age did you learn it? (If learned from birth, write age "0")	Were there any periods in your life when you did not use this language? Indicate duration in months/years.
1.__________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ______________________		
2.__________	☐**Home** ☐**School**		

	☐Community ☐Other: ________________		
3.__________	**☐Home ☐School** **☐Community ☐Other:** ________________		
4.__________	**☐Home ☐School** **☐Community ☐Other:** ________________		
5.__________	**☐Home ☐School** **☐Community ☐Other:** ________________		

Relative to a highly proficient speaker's performance, rate your proficiency level on a scale of 0-10 for the following activities conducted in English and your other language(s).

16.1 **English**

No Proficiency		High Proficiency
0	5	10

Speaking

Understanding

Reading

Writing

16.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in English?

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

17.1 **Other Language:** ______________________________

No Proficiency High Proficiency

0 5 10

Speaking

Understanding

Reading

Writing

17.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

Community Language Use Behavior

18. Please indicate which language(s) you most frequently heard or used in the following life stages, both inside and outside home.

		All English	Mostly English	Half English half other language	Mostly the other language	Only the other language
18.1	Infancy	☐	☐	☐	☐	☐
18.2	Preschool age	☐	☐	☐	☐	☐
18.3	Primary School age	☐	☐	☐	☐	☐
18.4	High school age	☐	☐	☐	☐	☐

19. Please indicate which language(s) you generally use when speaking to the following people.

		All English	Mostly English	Half English half other language	Mostly the other language	Only the other language
19.1	Parents	☐	☐	☐	☐	☐
19.2	Siblings	☐	☐	☐	☐	☐

19.3	Grandparents	☐	☐	☐	☐	☐
19.4	Other Relatives	☐	☐	☐	☐	☐
19.1	Parents	☐	☐	☐	☐	☐
19.2	Siblings	☐	☐	☐	☐	☐
19.3	Grandparents	☐	☐	☐	☐	☐
19.4	Other Relatives	☐	☐	☐	☐	☐
19.5	Partner	☐	☐	☐	☐	☐
19.6	Roommate(s)	☐	☐	☐	☐	☐
19.7	Neighbours	☐	☐	☐	☐	☐

20. Please indicate which language(s) you generally use in the following situations.

		All English	Mostly English	Half English half other language	Mostly the other language	Only the other language

20.1	Home	☐	☐	☐	☐	☐
20.2	School	☐	☐	☐	☐	☐
20.3	Work	☐	☐	☐	☐	☐
20.4	Social activities (e.g. hanging out with friends, movies)	☐	☐	☐	☐	☐
20.5	Religious activities	☐	☐	☐	☐	☐
20.6	Extracurricular activities (e.g. hobbies, sports, volunteering, gaming)	☐	☐	☐	☐	☐
20.7	Shopping/ Restaurants/ Other commercial services	☐	☐	☐	☐	☐
20.8	Health care services/ Government/ Public offices/ Banks	☐	☐	☐	☐	☐

21. Please indicate which language(s) you generally use for the following activities.

	All	Mostly	Half English	Mostly the	Only the

		English	English	half other language	other language	other language
21.1	Reading	☐	☐	☐	☐	☐
21.2	Emailing	☐	☐	☐	☐	☐
21.3	Texting	☐	☐	☐	☐	☐
21.4	Social media (e.g. Facebook, Twitter etc.)	☐	☐	☐	☐	☐
21.5	Writing shopping lists, notes, etc.	☐	☐	☐	☐	☐
21.6	Watching TV/ listening to radio	☐	☐	☐	☐	☐
21.7	Watching movies	☐	☐	☐	☐	☐
21.8	Browsing on the Internet	☐	☐	☐	☐	☐
21.9	Praying	☐	☐	☐	☐	☐

22. Some people switch between the languages they know within a single conversation (i.e. while speaking in one language they may use sentences or words from the other language). This is known as “language-switching”. Please indicate how often you engage in language-switching. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Never	Rarely	Sometimes	Frequently	Always
22.1	With parents and family	☐	☐	☐	☐	☐
22.2	With friends	☐	☐	☐	☐	☐
22.3	On social media (e.g. Facebook, Twitter)	☐	☐	☐	☐	☐

Thank you for participating!