Bachelor Degree Project

UNIVERSITY OF SKÖVDE

THE NEURAL CORRELATES OF BILINGUAL LANGUAGE CONTROL

Lifelong Bilingualism and its Mitigating Effects on Cognitive Decline

Bachelor Degree Project in Cognitive Neuroscience
Basic level 22.5 ECTS
Spring term 2019

Sofia Ramos Knudsen

Supervisor: Stefan Berglund
Examiner: Paavo Pylkkänen

Abstract

Speaking a second language requires the ability to keep the two languages apart so that language interference can be avoided, allowing the target language to be used fluently. As such, cognitive control systems are used more extensively in bilinguals compared to monolinguals, a process referred to as bilingual language control (BLC). In the past few decades, the cognitive and structural effects of this lifelong language control experience have been of great interest among researchers within the field of cognitive neuroscience. The present thesis reviews current knowledge on the neural correlates of bilingual language control in high proficient bilingual speakers who actively use both languages in their everyday lives. Language proficiency and frequency of use are important aspects to consider since they both modulate brain activity and structure. Indeed, some studies fail to provide this information. Neuroimaging studies reveal consistent brain activity in a network of cortical and subcortical areas in bilingual speakers during non-verbal and verbal executive control tasks. These brain areas include the anterior cingulate cortex (ACC), prefrontal cortex (PFC), inferior parietal lobes (IPLs), basal ganglia (BG) and the cerebellum. Research also indicates that bilingualism serves as a protective variable against age-related cognitive decline. Studying the effects of lifelong bilingualism on the brain has therefore proven to be important since it can influence an individual's ability to cope with age decline at a cognitive level.

Keywords: bilingualism, language control, cognitive reserve, neural reserve

CONTENTS

1. INTRODUCTION

1.1. INTRODUCING BILINGUALISM

Language is a large part of our identity, culture and everyday lives, allowing us to communicate our thoughts and feelings. In a global society, it is very likely to encounter languages other than one's own. For some, the exposure to two languages is present even from birth and continues throughout the lifespan. It has been estimated that to this day, the majority of people in the world speak two or more languages. In fact, bilingualism is a worldwide phenomenon that exists in practically all countries of the world, in all social classes and all age groups. The fast-growing globalization has left very few societies completely monolingual (Grosjean François, 1982; Grosjean, 2013). There are even entire nations that have adopted two languages and are therefore officially considered bilingual. In these bilingual (or trilingual) nations, including for e.g. Canada, Spain, Switzerland and Finland, the governance is bilingual, meaning that public administration, political environments and publication of laws consist of two languages. However, most monolingual nations consist of bilingual and multilingual populations within different regions with some monolingual nations having high percentages of bilingual populations.

There are multiple factors that contribute to the establishment of bilingual societies. One of the most important factors is migration, that for numerous reasons such as economic, political, educational, religious and environmental, forces and/or drives people all over the world to move and adapt to new environments where another language is spoken. Historically speaking, there are numerous cases where military invasions, occupations and colonization have lead to the spreading of languages, such as Latin, Greek, Spanish, English, Arabic and French, beyond their original borders. The search for food, work and better living conditions after World War II, leading to mass migration from multiple countries in Europe to the United States is only one case describing how bilingualism has developed. In these cases, the immigrant eventually acquires the new language, but continues to use his or her native language at home and/or with other immigrants of the same native language (Grosjean François, 1982). To this day, migration is a highly ongoing reality for millions of people in many parts of the world, contributing to the establishment of bilingual societies and populations.

1.2. DEFINING BILINGUALISM

A common question is whether for e.g. immigrants, who adopt a language later in life are considered bilingual. In order to empirically study bilingualism, it is essential to understand how the concept is defined as well as understand the criteria used to determine the degree of an individual's bilingualism. According to the Oxford Dictionaries, bilingual is defined as "speaking two languages fluently", and the Merriam-Webster Dictionary defines bilingual as "using or able to use two languages especially with equal fluency". This leads to the next question; how fluent must one be in order to be considered bilingual? As it turns out, there is currently no widely accepted definition of this concept, nor means of evaluating the degree of bilingualism.

In current research studies, researchers specify several important aspects of bilingualism in their individual participant's. One of these aspects include the age of acquisition of the second language, referring to an individual as for e.g. 'early' or 'late' bilingual. Typically, the mean age of acquisition is reported in each language. Another important aspect is the degree of proficiency, meaning the extent to which an individual masters the second language or both languages. To measure the degree of proficiency, most researchers use different forms of self-report questionnaires, interviews and/or behavioral methods such as picture naming or translation tasks. However, different research groups apply different criteria to determine if participants are considered bilingual or monolingual as well as using different measurements to determine the degree of proficiency. As a consequence, it becomes difficult to compare the results of different findings, due to the many different variations of methodological approaches used by different research groups. This has recently lead to the emergence of inconsistent results and contradictory findings in some research (Anderson, Mak, Chahi, & Bialystok, 2018b; Garbin et al., 2011).

Other important aspects to consider when studying individual participants are the preference for each language, the current and past exposure to the languages and the frequency of use. Most of the standardized tests available are in Spanish and English and the reason for this might be because of the numerous studies conducted in the United States on Spanish-English bilinguals, as well as in Barcelona where Catalan-Spanish bilingualism is common. In these cases, researchers typically capture the proficiency levels of both languages (Anderson et al., 2018b). In order to prevent confusion, it should be mentioned that second-language learners are those who are in the process of acquiring a second language in addition to their native language (Poarch & van Hell, 2012).

Clearly, defining and quantifying an individual's bilingualism are difficult challenges, considering that bilingualism is a complex and multifaceted experience shaped by many different factors such as the context, society and the individual herself (Anderson et al., 2018b).

1.3. BILINGUAL LANGUAGE CONTROL

In order to correctly understand and speak two languages fluently, the speaker must implicitly master the demands that are imposed on the language control systems, and these cognitive abilities are what define bilingual language control (BLC). Essentially, BLC includes the monitoring of potential interference from the non-target language(s) not in use, allowing the speaker to use the intended language in a given context (Calabria et al., 2018). A finding that has been widely replicated and confirmed in relation to highly proficient bilinguals who frequently use their languages, is that during reading, listening and planning speech, all of their languages are active and available in parallel (e.g. Kroll, Gullifer, & Rossi, 2013; Kroll & Bialystok, 2013). Thus, regardless of the language and its script, L1 is active when L2 is in use, and vice versa. This implies that there will be a constant implicit influence of the non-target language, which gives rise to competition of cognitive resources between the two languages during language production. As a consequence, bilinguals are required with more cognitive control to solve this internal linguistic conflict and manage language processing so that speech can be generated correctly and fluently in the target language. In other words, it requires the ability to tune out irrelevant stimuli in order to prevent cross-language interference from the language not in use (Kroll et al., 2015; Li et al., 2015).

1.4. KEY ASPECTS CAUSING CONTROVERSY

Considering that more than half of the world's population is bilingual, it is important to investigate the possible implications of this experience on brain structure and cognitive functioning (Anderson et al., 2018b). Over the past three decades, scientists have been curious to understand the nature of the bilingual mind, devoting a substantial body of research to the domain-general nonlinguistic cognitive effects and brain bases of bilingualism. Research on this topic has rapidly expanded and it is now well-established that the main cognitive effect of mastering two languages is the enhancement of certain cognitive control systems, such as goal maintenance, controlled attention, task shifting, conflict monitoring, cognitive flexibility and selective response inhibition (Baumgart, & Billick, 2018; Calabria, Costa, Green, & Abutalebi, 2018).

In addition, observations of executive control advantages in bilinguals (as compared to monolinguals) have been observed in different behavioral studies implementing conflict resolution, selective attention, cognitive flexibility and switching skill tasks. Such non-verbal tasks mainly include the Flanker task, the Simon task and the Stroop task. In other words, executive control may include the ability to change or adapt behavior according to a complex set of task demands, to switch attention to relevant information and to suppress competing information (Dong & Li, 2015). However, in some experiments such executive control advantages are not always found, concluding that bilingualism has no effect on cognitive systems (Paap & Greenberg, 2013; Paap, Johnson, & Sawi, 2015). This has sparked controversy and strong debate. Although this thesis will not go further into this particular issue, it is crucial to recognize and understand the possible explanations of the inconsistencies in the literature before examining neuroimaging studies on the topic, notably since the implicated neural regions of BLC are modulated by the same variables. As aforementioned, part of the controversy stems from the lack of clear and precise definitions and constructs, providing inconsistent results. Next, factors that might be contributing to the existing controversy will be outlined.

1.4.1. Language proficiency. Previous studies suggest that higher levels of proficiency in both languages affect executive performance positively in bilinguals. Having more exposure and activation to both languages in everyday conversations, regardless if used from birth or later in life, is an important factor that enhances inhibitory control. Most of the cognitive advantages found in bilinguals across the lifespan, such as in conflict resolution and switching tasks, are with children and older adults, whereas a clear deviation is found in young adults. This lack of an effect has been described as a matter of sensitivity, meaning that young adults are at the peak of their cognitive performance. As a result, it becomes difficult to observe a performance that goes beyond that peak (Kroll, Dussias, Bice, & Perrotti, 2015). As aforementioned, another plausible explanation for this is the different measurements used by different research groups to capture language proficiency (Anderson et al., 2018b).

1.4.2. Age of acquisition & years of language use. The age of the second language (L2) acquisition is also an important variable that if not controlled, can create misleading results from EC tasks. For example, early bilinguals commonly perform better on switching tasks than late bilinguals, not because of their age of acquisition but because of them having more practice in both languages. However, Tao and colleagues observed a reversed situation, where late bilinguals outperformed early bilinguals in a conflict resolution task due to their increased language frequently and proficiency (Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). It is therefore important not to draw any misleading conclusions by simply calculating the age of acquisition of each participant since it might be confounded with years of experience and level of language proficiency. These factors should be fully distinguished in order to prevent mixed results (Dong & Li, 2015). On the other hand, recent studies have also shown that acquiring two languages from birth does imply a bilingual advantage in brain connectivity as compared to acquiring a language later in life. In a study, resting-state functional magnetic resonance imaging (rs-fMRI) was recorded to examine functional connectivity (i.e. the temporal dependency of neural activation between anatomically separated brain areas, in the absence of task-driven performance) in two groups of French and English young bilingual adults. One group was established as the simultaneous group (i.e. acquiring both languages from birth) and the other group as the sequential group (i.e. learning the L2 after the age of 5 years). Results showed that the simultaneous group had stronger resting-state functional connectivity as compared to the sequential group in brain areas involving language control, such as the dorsolateral prefrontal cortex (DLPFC), inferior parietal lobule (IPL) and cerebellum. Within the sequential group, however, earlier age of L2 acquisition positively correlated with stronger connectivity between inferior frontal regions and right parietal regions, meaning that earlier L2 acquisition predicted stronger functional connectivity (Berken, Chai, Chen, Gracco, & Klein, 2016).

In another recent study, the researchers used rs-fMRI to examine the link between bilingualism and cognitive control. It was found that simultaneous bilinguals had stronger anti-correlations between the default mode network and the attention network, and stronger anti-correlations were positively correlated with interference suppression in a Simon task; smaller interference suppression scores predicted greater anti-correlations. The simultaneous bilingual group therefore demonstrated better performance in the Simon task (which measures cognitive control through interference suppression) by showing smaller interference suppression scores. In brief, these findings demonstrated a simultaneous bilingual advantage in brain connectivity in relation to cognitive control compared to sequential bilinguals (Kousaie, Chai, Sander, & Klein, 2017).

It should be stressed that in both of the studies outlined above, participants were considered high proficient bilingual speakers. Together, these rs-fMRI studies show that simultaneous language acquisition predicts stronger brain connectivity compared to sequential conditions. Yet again, it is important to emphasize the commonly held confusion concerning the age of acquisition of the L2 and its effects on the years of language use; earlier age of acquisition may imply that bilinguals have been actively using their languages for a longer period of time. Therefore, the years of bilingual language use may be equally important to consider like the age of L2 acquisition.

1.4.3. Frequency of use. Finally, the frequency of which both languages are used is a major contributing factor that determines the degree of cognitive control. By frequently using both languages, it enhances inhibitory control by producing less language interference, and more practice is received in monitoring processes such as word selection in each language (Dong & Li, 2015). This aspect should therefore be captured when assessing the degree of bilingualism in participants.

Despite the existing controversy regarding bilingual executive control advantages, enough evidence has been gathered to motivate researchers in the field to continue to study the functional and structural effects of using two languages. In addition to the cognitive consequences of bilingualism, it is also important to examine the biological underpinnings of BLC, that is, the neural mechanisms of these cognitive effects (Dong & Li, 2015).

1.5. AIM & STRUCTURE

In the present thesis, current research concerning the cognitive neuroscience of BLC is outlined and discussed. The consequences of lifelong BLC has proven to be beneficial for the brain in its ability to maintain cognitive functioning with age, even during cognitive decline.

Indeed, lifelong overuse of cognitive systems through language control has proven to induce neuroplastic changes, which may help to delay the onset of age related-decline and even neuropathological symptoms, such as dementia. Therefore, the aim of this thesis is not only to identify the neural correlates of BLC, but also to outline some of the key neuroplastic changes that occur as a consequence of lifelong BLC and how these effects may protect against cognitive decline.

I will mainly be covering for fMRI studies (including functional connectivity studies) as well as studies concerning the structural changes in brain areas related to the BLC network. More specifically, this investigation process will be constrained to articles involving neural correlates of BLC in *high* proficient bilinguals with preferably a *frequent use* and exposure of both languages. The reason is twofold: first, because highly proficient individuals who absorb both languages often and use their languages on a highly regular basis are those exposed to the most extreme form of bilingualism, and therefore most interesting in the context of its cognitive and neural implications. Second, this approach will narrow the breadth of this topic and therefore increase the chances of going into depth into those articles that fulfill the criteria. Similarly, although it is well-documented that bilinguals have stronger and better-maintained white matter connectivity (e.g. Anderson et al., 2018a; Calabria et al., 2018; Perani & Abutalebi, 2015), studies covering for these findings will not be brought up in this thesis. It should also be clarified that in addition to bilingual investigations, a few studies conducted on multilingual participants with high proficiency in at least two of their languages are also included in this thesis.

The structure is described as follows: first, I will describe a well-known model in the field which concerns important interactional contexts that may modulate the neural expression of BLC. Second, the key neural BLC regions will be outlined before I move on into a closely related subfield, namely the positive impacts of bilingualism on the aging brain. Lastly, there will be a discussion including a summary of the main content highlighted in this thesis, along with a section covering for limitations and problems. Together with potential future research goals in this field, the present thesis will finish with a conclusion.

1.6. METHODS

In order to collect articles relevant to this thesis, I searched through several databases including Scopus, Google Scholar and Web of Science, using keywords such as ”bilingualism”, ”neural reserve”, ”cognitive reserve” and ”bilingualism+language control”. Further, articles were selected based on the criteria highlighted above, and they were sorted into different groups and categories, for e.g. ”grey matter studies”, ”functional connectivity studies” and ”fMRI studies” to simplify the searching process and make it more organized. When assessing the articles, I carefully examined the method sections including the sample size and the way researchers define bilingualism and the bilingual experience of each individual. This included their levels of language proficiency, second language exposure, and language contexts. The citation rate was also considered when assessing the articles.

2. THE ADAPTIVE CONTROL HYPOTHESIS

The bilingual experience and its implications on cognitive systems may look very different depending on the linguistic environment in which the bilingual speaker is accustomed to. Therefore, the context of bilingualism is important to consider and may help to understand the cognitive and neural implications that occur as a consequence. The complex experience of bilingualism has recently driven researchers to attempt to identify important features to distinguish bilinguals from each other (Kroll et al., 2015). For example, Green and Abutalebi (2013) proposed the adaptive control hypothesis as an updated model of their original neurocognitive language control model (Abutalebi & Green, 2007). In their updated model, they approach this issue by suggesting that the BLC networks adapt to the demands that are placed upon them through the specific interactional context. The reason is that if the control systems do not adapt to the demands, it will not be possible to fluently speak an L2, since increased language proficiency equals increased language interference, which reduces language fluency. Three different interactional switching contexts are described; single language context, dual language context, and dense code-switching context, followed by the different demands that they place on eight different control processes involved in BLC. Below, the three interactional contexts will be described briefly along with the eight cognitive processes outlined in the adaptive control model.

The single language context is described by the usage of one language in one environment (e.g. at work) and the other language in a different environment (e.g. at home).

In the dual language context, both languages are used but with different speakers. In the dense code-switching context, switching between the two languages is very frequent, where words from one language might even be borrowed in a sentence using the other language. These three interactional contexts are each predicted to play a role in the adaptive changes in the regions related to language control, a prediction based on the different demands that they place on cognitive function. The adaptation may be observed in a variety of ways such as through grey matter density, change in the responsiveness or the tuning of neural populations and white matter connectivity. Importantly, Green and Abutalebi suggest that neural changes may differ among bilinguals who are used to different patterns of interactional circumstances. Another reason for this is due to the cognitive processes that are required to enable bilingual proficiency under a specific interactional context. Next, the eight cognitive processes will be outlined.

Goal maintenance refers to the ability to maintain the speech of one language rather than another. Goal maintenance goes hand in hand with the capacity to control interference from the language not in use. In their model, Green and Abutalebi established two top-down control processes that help to deal with this interference and sustain the current language in use; conflict monitoring and interference suppression. The precise locus of these control processes is not specified, and depends on the source of interference. Further, salient cue detection is considered a control process since it is required when the speaker is forced to switch from one language to another. Selective response inhibition is connected to salient cues, helping the speaker to disengage from the current language. Thus, fully switching from one language to another requires both task disengagement and task engagement. Green and Abutalebi distinguish task disengagement and engagement from conflict monitoring and interference suppression in a language switching context by suggesting that changing a task might involve processes such as vocabulary and syntax shift. Further, they refer to previous studies indicating that different neural regions are involved in task switching and interference control (e.g., Cools & D'Esposito, 2011). Opportunistic planning is the last cognitive process which they define as the ability for the bilingual speaker to plan their way of translating their message into speech. Together, each of these eight cognitive processes is required in a switching context to a greater or lesser extent depending on the interactional context. For example, Green and Abutalebi suggest that there is a great demand on goal maintenance, conflict monitoring and interference suppression in a dual-language context, whereas the demand is highest on opportunistic planning in a dense code-switching context (Green & Abutalebi, 2013).

Moreover, in their model, Green and Abutalebi suggest promising behavioral and neural predictions that should follow from each of the eight cognitive processes that occur as a consequence of the three interactional contexts in relation to these processes. For example, in a study conducted by Yang, Ye, Wang, Zhou, and Wu (2018), they found that inhibitory control is modulated by the specific languages used in a dual-language context by displaying different patterns of functional connectivity. However, the present thesis will not go further into these specific predictions. The reason is that although the model addresses important environmental factors that are essential for the understanding of the complex bilingual experience and its effects on neural and cognitive function, further evaluation and examination are needed to fully support this model since current support remains preliminary (Bialystok, 2017).

3. THE NEURAL CORRELATES OF BILINGUAL LANGUAGE CONTROL

Growing evidence indicates that different forms of experiences have a profound impact on the brain and cognition (Anderson et al., 2018b). This has been observed not only in the field of psycholinguistics, but in other unrelated areas of research as well. For example, a longitudinal study demonstrated that individuals undergoing an eight-week mindfulness-based stress reduction had associated gray matter density changes in the posterior cingulate cortex, the temporoparietal junction, the left hippocampus and the cerebellum. Such areas are involved in learning and memory processes (Hölzel et al., 2011). Similarly, Kühn and colleagues were able to prove significant gray matter increase in the right hippocampal formation, right dorsolateral prefrontal cortex and bilateral cerebellum elicited through a two-month video gaming intervention which involved orientation skills in a three-dimensional environment. These areas are crucial for spatial navigation, strategic planning, working memory and motor performance (Kühn, Gleich, Lorenz, Lindenberger, & Gallinat, 2014). A similar, classical finding reported enlarged regions of the hippocampus found in London taxi drivers due to their extensive habitual practice in route-finding and spatial navigation (Maguire et al., 2000).

In the same vein, experience-related structural changes in terms of increased gray and white matter densities occur in bilingual and multilingual individuals a consequence of the extra involvement of certain brain areas related to cognitive control (Calabria et al., 2018). These changes include having increased gray matter volume in regions involved in BLC, such as the dorsal anterior cingulate cortex (dACC) (Borsa et al., 2018), in parietal regions (Abutalebi et al., 2014), cerebellar regions (Grogan, Green, Ali, Crinion, & Price, 2009), and left anterior temporal pole (Abutalebi et al., 2014). Further, grey matter density grows as L2 proficiency increases. The specific functions of these brain structures (in the context of BLC) will be described more in detail later. Furthermore, it has recently been suggested that these structural effects induced by lifelong bilingualism benefits against cognitive decline and degenerative changes with aging, which is known as cognitive and neural reserve (see section 4) (Baumgart, & Billick, 2018; Calabria et al., 2018). Understanding how bilingualism gives rise to neuroplasticity is therefore highly important to investigate (Grundy, Anderson, & Bialystok, 2017).

The accumulating knowledge of the neural correlates of BLC stems from the increasing number of functional and structural neuroimaging research devoted to the investigation of the consequences of the bilingual experience on the brain (Kroll et al., 2015). Through the implementation of neuroimaging methods, the brain mechanisms responsible for the cognitive control processes can be more carefully examined, contributing to a greater understanding of their nature as well as the conditions that may bring about these cognitive effects (García-Pentón, Fernandez Garcia, Costello, Duñabeitia, & Carreiras, 2016). Functional magnetic resonance imaging (fMRI) is the most widely used research method in cognitive neuroscience, which has also been used extensively to identify brain areas and brain networks related to language control processing.

The majority of studies in this field compare monolinguals with bilingual participants in patterns of neural activity during cognitive, non-linguistic tasks that measure executive functions, combined with verbal tasks such as language switching or picture naming tasks. As mentioned, some of these studies include the implementation of tasks such as the Flanker task, Simon task and Stroop task. The Flanker task measures the ability to suppress responses that are inappropriate in a given context by displaying congruent and incongruent stimuli. In the Simon task, participants are asked to quickly respond to visual stimuli based on the rules governed by that stimulus. For example, participants are asked to press a button on the right side of the screen when an object appears (e.g. a circle) and press a button on the left side of the screen when another object appears (e.g. a square). Finally, in the Stroop task, participants must name a color of a word but avoid to name the word. Thus if the word “red” appears in yellow, the correct answer would be yellow (Dong & Li, 2015). The following section will present central current functional neuroimaging studies describing the key neural regions of the BLC network.

3.1. THE ACC AND CONFLICT MONITORING

An effective way to measure different language control mechanisms, such as the inhibition of language interference and conflict monitoring, is by studying language switching. Switching from one language to another requires the ability to select the right words from the target language but at the same time inhibit language interference from the language not in use (Hosoda, Hanakawa, Nariai, Ohno, & Honda, 2012). Studies adopting this approach have consistently revealed an association between conflict monitoring and activation in the dACC (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999) in high proficient bilinguals during language switching tasks (e.g. Abutalebi, et al., 2012; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2015; Garbin et al., 2011). Below, the key studies demonstrating these findings will be outlined.

In an event-related fMRI and structural neuroimaging study conducted by Abutalebi and colleagues, the activation of the dACC and the pre-supplementary Motor Area (SMA) was found to be present in monolinguals and high proficient bilinguals (assessing their proficiency using a translation task) both during a nonverbal conflict task (i.e. the Flanker task) and a language control task (i.e. a language switching task where participants are asked to name pictures in both languages, respectively). The idea was to investigate if the BLC network shares common brain structures with more general cognitive control processes, measured through the Flanker task. During the second and last session of the Flanker task, bilingual subjects revealed having significantly reduced activation in the dACC area compared with the monolingual group, as well as a significant decrease in conflict effects (i.e. faster responses to incongruent trials).

The results suggest a quick adaptive change in bilinguals during conflicting situations elicited through the Flanker task, better adjusting to conflict than monolinguals. The findings also reveal a bilingual advantage in using less neural resources to resolve cognitive conflicts (Abutalebi, et al., 2012; Rodríguez-Pujadas et al., 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013). The same effect has been detected in highly proficient multilinguals, where less language interference occurs in comparison to low proficient multilinguals, who need to actively suppress L1 when speaking an L2 to a much greater extent (Costa, Branzi, & Avila, 2016). Abutalebi and colleagues further observed a positive correlation between bilingual brain activity in the dACC and local grey matter volume in this area. Taken together, they suggest that the lifelong practice of resolving language conflicts has a strong impact on brain plasticity and leads to a more tuned ACC for conflict monitoring in bilinguals as compared to monolinguals (Abutalebi, et al., 2012).

Similarly, Garbin and colleagues investigated the neural basis of language switching in early, high proficient bilinguals. It is important to stress that bilingual participants in their study not only acquired two languages simultaneously from birth, but due to their sociolinguistic environment, they were used to switch between their two languages on a highly regular basis. This unique form of lifelong bilingual experience could be described as the peek of language control. In their study, individual proficiency was assessed through a self-report questionnaire. Although the participants rated their proficiency on the highest score, they still had preferences for one of their two languages. One language was therefore considered the dominant language (L1), and the second language the non-dominant language (L2). They found that when switching between L1 and L2, significantly greater activation was found in the left caudate and the pre-(SMA) complex/ACC in comparison to the non-switching condition. However, the activation of these brain areas was sensitive to the direction of language switching and language proficiency, where forward switching (from L1 to L2) induced activity in left caudate and backward switching (L2 to L1) induced activity only in pre-SMA complex/ACC areas. The researchers suggest that controlling two languages involves different brain areas even in early and high proficient bilinguals. Consistent with previous research, they also suggest that in high proficient bilinguals, the left caudate is involved in language selection and control during language switching, production and comprehension, and that the pre-SMA/ACC has an important role in response inhibition, (i.e.

monitoring conflict between the two languages by suppressing unwanted action and detecting errors) (Garbin et al., 2011; Abutalebi et al., 2012).

In contrast, Abutalebi and colleagues found that when multilingual individuals switched from their most proficient language (L1) to the least proficient language (L3), it significantly increased responses of the left caudate, while the pre-SMA/ACC region was not as sensitive in its response to the level of proficiency. Regardless of language proficiency, language switching recruited activation in the pre-SMA/ACC area. An increase in left caudate activation was also observed when switching from L1 to L2 as compared to switching from L2 to L1 (Abutalebi et al., 2013). This was observed although the L2 was established as a highly proficient language. Overall, there was a higher demand on left caudate activation when switching from a more proficient language to a less proficient language, which is consistent with the idea that there is a greater need to control language interference from L1 during low proficient language use.

It can be concluded that both the ACC and left caudate is actively involved in conflict resolution, language control and selection during language switching in high proficient bilinguals and multilinguals. Regarding language proficiency as an influence for ACC activity, studies show that lower language proficiency requires increased monitoring for conflict (i.e. more ACC activation) from the dominant language, whereas highly proficient bilinguals express a reduction in ACC involvement due to the extensive practice of frequent language switching (i.e. involvement of conflict monitoring). Moreover, one study concludes that the ACC remains stable in its activation and is affected by neither low nor high language proficiency.

It should also be stressed that the observed ACC/pre-SMA activation is not exclusive to BLC but also seen in monolingual conflict monitoring when switching between nouns and verbs. The left caudate on the other hand has been shown to be actively engaged by bilinguals and multilinguals while deactivated for monolinguals. In addition, studies are consistent with the idea that the involvement of the left caudate is highly dependent on language preference and proficiency during language switching since lower language proficiency demands more activation of the left caudate (Abutalebi et al., 2013; Calabria et al., 2018). Finally, the reason bilinguals have increased grey matter density in dACC as previously mentioned is because of their frequent exposure to language conflict (Abutalebi & Green, 2016).

3.2. THE PREFRONTAL CORTEX & SUBCORTICAL STRUCTURES

Another brain structure proven to be a key player in BLC is the prefrontal cortex (PFC), which consists of many different areas such as the superior, middle, and inferior frontal gyri and the orbitofrontal cortex. A large body of research indicates that the left middle and inferior frontal gyrus (LIFG) are important structures for the BLC network, overriding automatic responses and controlling for interference. Much of these findings come from simple language production tasks as well as language switching studies (Abutalebi & Green, 2016). For example, the very first fMRI study on language switching was conducted by Hernandez and colleagues, who used a picture-naming paradigm where the participants had to either switch between Spanish and English or maintain one of their languages. Results revealed an increase in dorsolateral prefrontal cortex (DLPFC) activation during switching, due to the competition of the selection between the two languages (Hernandez, Martinez, & Kohnert, 2000). Since then, studies have been consistent with the claim that the DLPFC has a key role in BLC (Seo, Stocco, & Prat, 2018).

Further, it has been suggested that language proficiency and the degree of L2 exposure modulates the activity in the PFC; less exposure and low proficiency leads to greater activation, while high proficiency and high exposure predicts less activation (Abutalebi & Green, 2016; Calabria et al., 2018; Perani, et al., 2003). According to this perspective, a greater cognitive effort is demanded from the PFC when the weaker language is processed. However, this conclusion may be too simplistic. For example, Videsott and colleagues investigated the neural correlates of language proficiency using a picture naming task in multilinguals who were highly proficient in two of their languages: Ladin (L1) and Italian (L2). In the picture naming task, 144 common object pictures were presented in different colors representing each language. The fMRI data revealed that for the least fluent language, English (L3), the left prefrontal cortex (LIFG) and the cerebellum were more activated than during the L1 and L2. For the most proficient languages (L1 and L2) the right prefrontal areas were recruited significantly more than during L3. The researchers suggest that the right prefrontal areas are key areas in high language proficiency since the magnetic resonance signal in this region correlated positively with naming accuracy in the picture naming task (Videsott et al., 2010). Hence, this study disproves the idea that less exposure and proficiency leads to greater activation in the PFC and that high proficiency and exposure predicts less activation in the PFC. Instead, this study shows that some parts of the prefrontal cortex (i.e. LIFG) are sensitive to lower language proficiency and exposure, while other parts of the prefrontal cortex (i.e. right prefrontal areas) have proven sensitive to high proficient language and exposure.

Furthermore, Grundy and colleagues suggest that enhanced brain efficiency in areas related to cognitive control in bilinguals is not restricted to the ACC solely, as discussed earlier (Abutalebi, et al., 2012). In fact, the DLPFC, which is suggested to deal with conflict resolution (Calabria et al., 2018), has also been shown to be less activated during non-verbal executive tasks in bilinguals relative to monolinguals. In contrast, subcortical regions (mainly the basal ganglia [BG] including the left caudate) are used more extensively in bilinguals than in monolinguals, in the absence of a behavioral confound (Grundy et al., 2017). The BG consist of a set of subcortical nuclei including the striatum, which makes up of the caudate nucleus and putamen. The striatum is the largest nuclei in the BG and acts as an information source to receive input from all cortical areas in the brain. The putamen has been shown to be involved during language production and is also proposed to be involved in articulatory processes (Abutalebi et al., 2013b). Further, structural plasticity in the form of increased grey matter in the bilateral thalamus and putamen, right caudate nucleus and left globus pallidus has been detected in simultaneous bilinguals compared to monolinguals (Burgaleta, Sanjuán, Ventura-Campos, Sebastian-Galles, & Ávila, 2016) In addition, previous research reveals that the striate nuclei gates access and direct signals to frontal regions (including PFC and ACC) during executive control tasks (Stocco, Yamasaki, Natalenko, & Prat, 2014).

In a study conducted by Stocco & Prat, BG involvement was detected. In their study, the rapid instructed task learning (RITL) was implemented, a task in which participants were given new instructions at the beginning of each trial to investigate in the response to changing demands. They found that on a behavioral level, bilinguals outperformed monolinguals in their ability to quickly reconfigure their behavior based on the novel task that was presented. The neuroimaging results were consistent with the behavioral finding, indicating stronger adaptability in the striate nuclei during the task execution, with a more effective modulation of this area in response to the demands of the changing task. Modulatory activity was assessed through the comparison between how the execution of novel and practiced instructions differed between monolinguals and bilinguals. Based on the present findings and previous research, Stocco & Prat concluded that the BG are important loci for BLC which helps to more quickly select and combine rules during the task. They also claim that there may be a possibility that the need to engage prefrontal resources is smaller in bilinguals, but this conclusion could not be drawn due to limited power in their study (Stocco & Prat, 2014).

Again, according to Grundy and colleagues, the involvement of the BG together with less recruitment of DLPFC and ACC in bilinguals as compared to monolinguals, is interpreted as a reflection of greater brain efficiency. Most studies show no behavioral differences between bilinguals and monolingual groups, or they show matched behavior, which creates no behavioral confounds in the observation of brain activity. Further support for efficient brain recruitment comes from studies examining the correlation between behavior and activation, where bilinguals tend to express reduced performance when recruiting frontal regions (Grundy et al., 2017). However, whether or not this interpretation is correct remains for future research to fully confirm.

In another study conducted by Rodríguez-Pujadas and colleagues, a non-linguistic switching task was used to investigate differences in brain activity related to language control between thirty-six early, highly proficient bilinguals and monolinguals. The bilingual participants were used to switch between their languages on a daily basis. Results showed no significant behavioral differences in the performance of the task between the two conditions, yet fMRI data revealed larger recruitment in the left caudate nucleus and left inferior and middle frontal gyri in bilinguals as compared to monolinguals. This finding provides evidence that brain areas associated with language control are more engaged in bilinguals when performing domain-general executive control tasks where language is not involved. Further, the researchers suggest greater efficiency in monolingual control processing during the task than bilinguals, due to the recruitment of less neural activation to obtain the same behavioral performance (Rodríguez-Pujadas et al., 2013).

Up until now, it is clear that the ACC, PFC and BG (i.e. mainly the left caudate) are all core brain regions important for BLC. In a more recent study conducted by Seo and colleagues, the researchers conclude that these three brain areas engage in distinct neurocognitive processes. In their fMRI experiment, 23 Spanish-English bilinguals participated in a RITL paradigm, which was employed to measure three task phases of language control; Prepare Target Language phase, Rule Selection phase and Execution phase.

The Prepare Target Language phase started with a cue indicating the language (Spanish or English) of the next trial. This phase was used to prepare the subject to speak the target language. Next, the Rule selection phase consisted of a code used to indicate which morpho-syntactic rule(s) the subject was going to select in the paradigm. Finally, the Execution phase presented either a word or a pair of words in the language that had been cued in phase one, for the participant to perform the rule instructed in phase two. For example, the participant may be asked to pluralize the word “dog” in English (Seo et al., 2018).

The researchers in the present experiment chose to investigate nine regions of interest (ROI). The ROIs were selected based on a meta-analysis conducted by Luk, Green, Abutalebi, & Grady (2012), which reflects the key neural regions supporting BLC at large. Neuroimaging results revealed significant effects of the task phases in five of the nine regions: the ACC, DLPFC, left lateral orbitofrontal cortex, left inferior frontal gyrus, and the pre-supplementary motor area (pre-SMA). Data results also revealed that different patterns of activation took place during the three phases. The ACC was significantly more active during the Prepare Target Language phase than during the remaining two phases, while the Execution phase activated the left frontal regions (left DLPFC, left orbitofrontal, left inferior frontal) and pre-SMA significantly more than the Prepare Target Language phase. The Rule Selection phase kept the activation in between that of the prepare target language and execution phase. The remaining four ROIs (left middle temporal lobe, right precentral cortical regions and BG, i.e. right caudate and left caudate) remained constant across phases and were not affected by the task phase (Seo et al., 2018).

Overall, the results suggest that each of the three phases display different patterns of brain activity. The researchers propose a preparatory activation (greatest during the preparation of the target language), execution activation (increasing across the task but greatest activation during task execution) and stable activation (consistent activation across all phases), depicting the results of activation in the study. To summarize, the study clarifies the role of the DLPFC, BG and ACC in BLC by observing their distributed activity during the three different phases. More specifically, the researchers suggest that the consistent activation in bilateral striatum is involved in “keeping track” of the target language, that the DLPFC region (including the left lateral prefrontal cortex and pre-SMA) increases across tasks and are most active during bilingual task execution. Finally, the ACC activity in the study was proven not to be restricted to language switching and conflict monitoring. Instead, results suggested that the ACC also has an early role in monitoring the target language during language conflict, and is important for top-down language preparation (Seo et al., 2018).

Taken together, all of the studies mentioned above identify the involvement of ACC, PFC and BG in BLC, despite the fact that three different tasks were applied (i.e. language switching, picture naming task and RITL). However, their functions are explained differently by different researches. For example, the pre-SMA, which is commonly considered to work in parallel with the ACC for conflict monitoring (Abutalebi & Green, 2016; Green & Abutalebi, 2013), was instead involved in bilingual task execution together with the DLPFC in the study conducted by Seo and colleagues.

3.3. THE CEREBELLUM

Although it is well established that the cerebellum is primarily concerned with motor control and coordination, researchers have more recently recognized its involvement in language processing and motoric aspects of speech such as verbal fluency, articular processes and speech planning (Abutalebi & Green, 2016; Tyson, Lantrip, & Roth, 2014). Furthermore, evidence from neuroanatomical studies reveals that the cerebellum communicates with regions of the PFC and parietal cortex through the thalamus. Studies have also found that the cerebellum and the BG are interconnected (Bostan, Dum, & Strick, 2013). Thus, the cerebellum is a critical structure because it is linked to central regions of the BLC network (Calabria et al., 2018).

In an fMRI study, low proficient Chinese-English bilinguals participated in a picture naming task. Results revealed that when participants named pictures in L2 (English) greater activity was observed in the left inferior parietal lobule (IPL) and left cerebellum compared to naming pictures in L1. Thus, more neural resources in these areas were involved in order to maintain and produce the less dominant L2. Also, enhanced recruitment may be explained by less verbal fluency and articulatory processing when producing L2 (Fu, et al., 2017). Although these results do not tell anything about high proficient bilinguals, it proves that the cerebellum is an important component for language production in BLC.

In another study, the researchers emphasize the important role of the cerebellum in the establishment and use of grammatical processing in L2. They found that speaking a second language leads to increased grey matter volume in the cerebellum. More specifically, they found that high proficient L2 learners (as compared to monolinguals) expressed a positive correlation between cerebellar grey matter volume and the processing speed of morphologically (i.e, word and grammatical processing). According to the researchers, the increased grey matter volume is interpreted as a reflection of their morphological processing in L2 observed through a masked priming task. No behavioral differences were found between the monolingual and bilingual participants. However, a negative correlation was found between grey matter volume and the reaction times in the highly proficient bilinguals, indicating that the larger the cerebellar grey matter volume, the quicker and more efficient is the rule application in the task, i.e. less reaction time (Pliatsikas, Johnstone, & Marinis, 2014). Together, these findings provide evidence that bilingualism can lead to grey matter volume in cerebellar regions, and that the cerebellum is not exclusively involved in motor function but also in non-motor functions such as grammatical processing and language production, communicating with important regions responsible for BLC.

4. BILINGUALISM & THE MAINTENANCE OF COGNITIVE FUNCTIONING

4.1. INTRODUCING THE CONCEPTS

4.1.1. Cognitive reserve. Among certain activities such as cognitive and physical exercise, educational attainment and engagement in leisure and social activities (Barulli & Stern, 2013), current research widely confirms that the lifelong experience of mastering multiple languages improves general mental health (e.g through general intelligence, reading scores and verbal fluency) in healthy aging populations (Grant, Dennis, & Li, 2014). Moreover, bilingualism has proven to create resilience to degenerative changes in the brain, protecting against age-related cognitive decline. This effect is known as cognitive reserve and refers to the brain’s resilience to neuropathology. Individual differences in cognitive functioning (i.e neural networks that give rise to cognitive performance) allow some people to cope better than others with existing pathology or brain damage (Stern, 2009). In other words, individuals with higher levels of cognitive reserve are more resistant to loss of brain tissue, may tolerate a larger lesion before the onset of clinical impairment appears, and may therefore also show reduced risks of clinical symptoms as compared to individuals with lower levels of cognitive reserve (Abutalebi et al., 2015; Stern, 2009). Cognitive reserve is particularly crucial within the context of age-related decline and dementia but can be applied into all forms of brain damage (Barulli & Stern, 2013).

It should be clarified that cognitive decline slowly and progressively damages memory and cognitive functioning that occurs from pathological conditions in the elderly (Abutalebi et al., 2015) and can range from dementia to mild cognitive impairment, to age-related decline (Daviglus, et al., 2010). While most seniors have preserved cognitive health with perhaps a mild decline in short-term memory and processing speed, others are exposed to more serious conditions that may develop into mild cognitive impairment or into various forms of dementia. Mild cognitive impairment is recognized through problems with important cognitive functions such as memory or language and can therefore be identified on cognitive tests, but does not, however, interfere with daily life. Dementia, on the other hand, is a more serious, progressive condition where global cognitive functions are affected, such as memory, learning, judgment and orientation, interfering with daily life (Daviglus, et al., 2010). Dementia has a significant social and economic burden of medical and social costs (World Health Organization, 2017). Saving time from Alzheimer's disease and other forms of dementia would therefore not only ease the economic burden in society at large but more importantly, prevent families and carers affected from experiencing psychological stress and emotional pressure. Currently, there are no treatments for Alzheimer's disease. However, different lifestyle modifications, such as diets and exercise, can help with the delay of the onset of Alzheimer's disease (Schelke et al., 2016). As described, lifelong bilingualism has also been shown to be one such plausible lifestyle-related variable.

4.1.2. Neural reserve. Neural reserve can be explained as the neural basis of cognitive reserve and serves as a protective source against clinical manifestations such as Alzheimer's disease (Abutalebi et al., 2015). While cognitive reserve is typically measured through reaction times in inhibition tasks, memory tasks and controlled attention, neural reserve can be studied through levels of brain activity as well as structural changes in the brain, i.e. the development of grey or white matter volumes in those brain areas related to executive functions and language learning (Borsa et al., 2018; Perani et al., 2017). Magnetic Resonance imaging (MRI) is an effective tool used to measure these structural changes. Thus, neural reserve allows brain networks to be more efficient with stronger capacity and therefore less susceptible to degenerative changes and pathological disruptions (Stern, 2006).

4.1.3. Neural compensation. In addition to structural changes, bilingualism has repeatedly proven to induce functional changes in form of brain connectivity. This effect is referred to as neural compensation (Calabria et al., 2018; Stern, 2006), and manages the loss of brain structure (e.g. brain atrophy and neurodegeneration) by compensating with stronger functional connectivity induced by the lifelong bilingualism due to the extensive use of language control. In other words, stronger functional connectivity between brain networks (see section 4.4) may help the brain to cope with neurodegeneration and loss of neurons, responsible for the onset of mental diseases such as Alzheimer's or other forms of dementia (Perani et al., 2017).

Although some researchers argue against bilingualism as an effective tool against dementia (Mukadam, Sommerlad, & Livingston, 2017; Zahodne, Schofield, Farrell, Stern, & Manly, 2014), a substantial body of research has provided evidence that there are in fact neurocognitive benefits of managing multiple languages on a regular basis in the elderly. Multiple studies suggest that bilingualism delays the onset of dementia by approximately 4.5 years (e.g. Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007). This evidence stems from studies conducted all over the world in different populations and linguistic environments (Borsa et al., 2018). Moreover, bilinguals have shown to cognitively recover better from stroke than monolinguals (Alladi et al., 2016). Thus, bilingualism may be considered a relevant variable for a delaying effect of cognitive decline in the elderly. As described, bilinguals generally outperform monolinguals on tasks that demand executive control and selective attention, which suggests that bilingualism as an experiential factor, has a strong impact on cognitive functioning with aging. Logically, cognitive advantages are more apparent in the elderly as compared to younger individual participants. Investigating older bilingual participants allows researchers to take on the unique possibility to explore the effects of this environmental factor and lifelong experience on the human brain (Perani & Abutalebi, 2015).

In this section, central studies concerning cognitive reserve, neural reserve and neural compensation will be outlined. This area of research is arguably of much importance for public health and has become an area of great interest within this field. Understanding the nature of cognitive reserve, which may regulate and even determine the clinical expression of dementia including Alzheimer's disease, is crucial in order to develop approaches that may prevent such outcomes (Perani & Abutalebi, 2015).

4.2. GREY MATTER ALTERATIONS

Studies have consistently revealed an increase in grey (and white) matter density in bilinguals as compared to monolinguals, in areas related to executive control such as the ACC (Abutalebi et al., 2015; Abutalebi, et al., 2012), PFC (Stein et al., 2012), left inferior parietal lobe (LIPL) (Della Rosa et al., 2013), left caudate (Zou, Ding, Abutalebi, Shu, & Peng, 2012) and putamen (Abutalebi et al., 2013b; Abutalebi et al., 2014). The IPLs are part of the BLC network important for both executive functions and language processing (Grogan et al., 2012). The posterior supramarginal gyrus, which is part of the parietal region and related to lexical knowledge, is specifically reported to have increased grey matter in bilinguals as compared to monolinguals. Further, higher L2 proficiency positively correlates with grey matter density in this region, which may be interpreted as having stronger vocabulary knowledge (Calabria et al., 2018). Again, these structural changes are strongly suggested to be the answer to why bilinguals, as opposed to monolinguals, have proven to have enhanced brain endurance against degenerative changes that comes with aging, providing neural reserve (Perani & Abutalebi, 2015). Further, brain regions affected by bilingualism partially overlap with regions responsible for age-related cognitive decline. For example, as described earlier, the PFC is a central brain region of the BLC network which also reduces in volume with age (Olsen et al., 2015). Yet, only a few studies have identified the nature of neural reserve induced by bilingualism by linking behavioral performance on cognitive tasks and increased grey matter density in those areas related to cognitive decline, vulnerable for the loss of grey matter volume with age (Abutalebi et al., 2014).

In a study conducted by Abutalebi and colleagues, the effects of neural reserve were investigated in a group of bilingual seniors as compared to a senior monolingual control group. Participants performed the Flanker task and their results were correlated with grey matter volume to explore whether cognitive performance could induce grey matter volume in areas affected by aging. Results displayed an overall association with increased grey matter volume in the ACC for bilinguals only. Further, monolingual task performance was correlated with decreased grey matter density in the DLPFC. Although bilinguals performed better on the Flanker task than monolinguals, no associations between cognitive performance of the Flanker task and grey matter volume in the ACC was found. Thus, the results of the cognitive performance may be fully independent of the increase in grey matter volume. Overall, the researchers are in favor of neural reserve as an explanation of the results and describe their study as supportive of such findings, but also conclude that more functional studies confirming a relationship between ACC activity and behavioral performance on the Flanker task are needed for both bilinguals and monolinguals before there can be any conclusions drawn that cognitive reserve results from greater grey matter volume in the ACC (Abutalebi et al., 2015).

In another study, the protective effects of bilingualism were examined by looking at the differences in grey matter volume in monolingual and bilingual participants in the left anterior temporal pole. This structure is a common locus for bilingualism and cognitive reserve since it is associated with strong age-related decline as well as with concepts, semantics and lexical storage and retrieval of proper names (Ross, McCoy, Wolk, Coslett, & Olson, 2010). Proficiency was assessed through a picture naming task in both L1 and L2. While controlling for confounding variables such as education and socioeconomic status, the researchers found significantly increased grey matter volume in the bilateral temporal poles and the orbitofrontal cortex for bilingual participants only, while overall stronger age-related grey matter decrease was found in monolingual participants. Further, high language proficiency in L2 picture naming positively correlated with grey matter volumes in the left anterior temporal pole. The researchers propose an explanation for this observation, suggesting that higher levels of fluency or semantic processing of their second language predict neuroprotective structural plasticity (i.e. neural reserve) in the left temporal pole, a structure sensitive to age-related grey matter decline. Taken together, results show that bilingualism may provide protective effects by inducing more grey matter density in an area sensitive to age-related decline. Lifelong bilingualism may therefore be considered a preventative factor against cognitive decline (Abutalebi et al., 2014).

Furthermore, Olsen and colleagues investigated the structural effects of lifelong bilingualism in older bilingual adults (n = 14, mean age = 70.4) compared to a group of monolinguals (n = 14, mean age= 70.6). In their study, they employed two different approaches: first, they examined the global structural differences in grey and white matter volumes and second, they examined the difference in cortical thickness of specific ROIs. These included the temporal pole (previously found to differ in grey matter among bilinguals and monolinguals), the entorhinal cortex and hippocampus, regions in the temporal lobe that typically decreases in volume with age and dementia. They also implemented the Stroop task to investigate the involvement of white matter in the frontal lobe to resolve interference. Results showed a positive correlation between interference performance in the Stroop task and frontal lobe white matter in both groups, which describes the important relationship between white matter and the ability to maintain executive function skills in aging. Results also showed overall greater frontal lobe white matter in bilinguals compared with monolinguals. No mean differences in volume were found between the two groups in the hippocampus, entorhinal cortex or temporal pole. However, a negative correlation between age and cortical thickness in the temporal pole was found solely in the monolingual group, meaning that as age increased, cortical thickness decreased for monolinguals. Together, this study supports previous findings indicating that bilingualism helps to preserve frontal and temporal pole function with aging (Olsen et al., 2015).

Overall, enough evidence has been gathered to confirm that speaking two (or more) languages induce neuroplastic changes in areas related to BLC and that these adaptive changes may eventually work as a protective effect against cognitive decline.

4.3. FUNCTIONAL CONNECTIVITY

Similar to rs-fMRI, functional connectivity alone is an fMRI method that measures correlated activity between brain networks during some sort of task-driven performance. It may be that the distinct brain networks are being driven by the same external task or that one influences the other. Intrinsic connectivity is another closely related fMRI method, which identifies sets of large-scale functionally connected brain networks through either task-based or resting state neuroimaging data (Laird et al., 2011). As aforementioned, bilingualism has been associated with stronger functional connectivity between BLC networks, which has been suggested to provide neural compensation (Perani & Abutalebi, 2015; Grundy et al., 2017).

During task-driven brain activity, bilinguals have also expressed to be better at modulating functional connectivity than monolinguals, meaning that they adapt to task demands more efficiently by recruiting different networks (Grundy et al., 2017).

In their study, Grady and colleagues measured resting state data of intrinsic functional connectivity in the frontoparietal control network (FPC) and the salience network (SLN), two networks that are closely related to executive control functions (e.g, attention, shifting and error detection). Additionally, the default mode network (DMN) was examined since previous research has shown that stronger functional connectivity in the DMN during executive control tasks is related to better performance in older adults. The FPC includes the dorsolateral and inferior frontal regions, as well as the inferior parietal lobes, while the SLN involves the anterior insula, dACC and supramarginal gyri. DMN on the other hand, involves the posterior cingulate cortex, ventromedial prefrontal cortex, angular gyri and parahippocampal gyri. Stronger intrinsic connectivity was found in the FPC and DMN among older bilingual adults as compared to older monolingual adults. These results map out the functional properties underlying executive control functions in bilinguals and as the researchers argue, this cognitive control advantage may provide benefits in the elderly through cognitive reserve (Grady, Luk, Craik, & Bialystok, 2015).

Although previous research has concluded that bilingualism delays the onset of Alzheimer's disease in the elderly, the exact neural mechanisms providing these protective effects are poorly understood with no direct evidence explaining these findings. In order to get to the roots of this issue, Perani and colleagues combined rs-metabolic activity (using positron emission tomography, [PET]) with functional connectivity in both bilinguals and monolinguals with Alzheimer's disease. Data revealed that although bilinguals had more severe brain hypometabolism than monolinguals (bilinguals were on average 5 years older than monolinguals), they outperformed monolinguals on verbal memory tasks in addition to having stronger metabolic connectivity in the DMN, the executive control network and anterior-posterior regions. Further, the relative use and exposure of L2 was negatively correlated with more severe hypometabolism in posterior regions and in turn, positively correlated with increased metabolism in control regions (i.e. the orbitofrontal, inferior frontal, and cingulate cortex). According to the researchers, the increased metabolism may reflect a neural compensation for the degenerative changes in bilingual individuals with Alzheimer's disease (Perani et al., 2017).

Moreover, compared with monolinguals, bilinguals have shown to have stronger functional connectivity in the frontoparietal network (FPN) and the SLN during a go/no-go task, predicting better performance and reaction times (Costumero, Rodríguez-Pujadas, Fuentes-Claramonte, & Ávila, 2015). Bilinguals have also expressed stronger functional connectivity at rest in the FPN and DMN compared to monolinguals (Grady at al., 2015).

Previous studies of healthy cognitive aging have consistently revealed a reduction in occipital activity linked with increased frontal activity (especially in the DLPFC). This effect is known as the posterior–anterior shift and is generally recognized as a form of neural compensation that comes with aging, allowing older adults to preserve their cognitive performance (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2007; Grant et al., 2014). As seen, Perani and colleagues observed stronger metabolic connectivity in the anterior-posterior regions, which may indicate that cognitive reserve in bilinguals results as a consequence of the increased connectivity (i.e. neural compensation) between these two brain regions (Calabria et al., 2018; Grundy et al., 2017).

Further support for this proposal comes from a study conducted by Luk and colleagues, where the authors found that monolinguals exhibited stronger short-range rs-connectivity within the frontal cortex, while bilinguals exhibited greater long-range frontal-to-posterior connections, including the occipital and parietal cortex (i.e the middle temporal and occipital gyri, precuneus, the right inferior parietal lobe and the caudate) (Luk, Bialystok, Craik, & Grady, 2011). Thus, while monolinguals rely mainly on frontal activity to compensate for the reduced posterior activity with aging, the lifelong bilingual experience may provide cognitive reserve by preserving frontal-posterior connectivity (Grant et al., 2014).

In conclusion, the lifelong demand of language control in bilingual speakers has proven to induce plastic changes in the brain in form of grey and white matter as well as alterations in functional connectivity, allowing the rise of cognitive reserve which over time may create resistance against brain aging effects (Perani et al., 2017). It has even been proposed that learning foreign languages may serve as a potential preventative treatment (i.e. cognitive reserve) in the elderly (e.g., Antoniou, Gunasekera, & Wong, 2013). Moreover, stronger functional connectivity, as seen in bilinguals, may provide a more distributed BLC network, whereas monolinguals are forced to rely more heavily on frontal regions during cognitive tasks that are non-verbal. Thus, this may be a plausible, contributing factor to an alleged increased brain efficiency in bilinguals (Grundy et al., 2017).

5. DISCUSSION

The purpose of this thesis is to explore and identify the neural correlates of BLC in high proficient bilinguals with frequent use in both languages. The aim is also to provide current knowledge on some of the neuroplastic changes that occur as a consequence of the lifelong experience of juggling two languages and its effects on cognitive functioning in the aging brain. Throughout this thesis, I have somewhat discussed and brought up various explanatory suggestions in relation to the findings. Next, there will be a critical reflection summarizing the main content, before limitations and problems in relation to the findings as well as to this thesis will be elucidated. This will be followed by a section on potential future directions of research in this field. Finally, a conclusion of the central findings and reflections brought up in this thesis will be provided.

A major finding in the field of cognitive neuroscience is the effect of various forms of lifelong experience or practice on the expression of structural changes in the brain, including that of speaking two or more languages. BLC occurs as a consequence of two languages being active in parallel and allows bilinguals to use their intended language while monitoring for interference from the unintended language (Calabria et al., 2018). Thus, in order to resolve this constant internal linguistic conflict, it requires a set of cognitive abilities such as language selection, language interference, inhibition, speech monitoring, language engagement and disengagement (Green & Abutalebi, 2013). For this reason, cognitive systems in bilinguals evolve differently from those of monolinguals. Considering the many years of practice in both languages, leading to the extra demand imposed on the control systems, bilinguals develop neuroplastic changes in a network of cortical and subcortical brain areas, closely related to those areas responsible for executive control and language (Branzi et al., 2015).

These brain areas include the dACC/pre-SMA complex, responsible for error detection and conflict monitoring during non-verbal interference tasks as well as during language switching (Abutalebi et al., 2012). Further is the left PFC (especially the DLPFC), a critical area for language selection and conflict resolution during task execution. This area is also sensitive to language proficiency and the degree of exposure of L2 (Calabria et al., 2018; Seo et al., 2018). The IPLs are also part of the BLC network important for both executive functions and lexical knowledge. Grey matter density in this area correlates with increased L2 proficiency (Grogan et al., 2012). The role of the BG as a subcortical structure is central to the BLC network, with the left caudate being a key player in language selection and control for verbal interference during language switching (Branzi et al., 2015). This particular structure has also been proven to be highly sensitive to the degree of language proficiency, with lower language proficiency demanding more left caudate activation due to the increased interference from the more dominant language during the production of the less dominant language (Abutalebi et al., 2013). Finally, the cerebellum has been shown to be linked to several structures in the BLC network such as BG and PFC through the thalamus. Grey matter increase in this structure has been observed, with researchers suggesting its role in grammatical processing and speech production.

In terms of bilingualism as a protective variable against age-related decline and dementia, a great body of evidence is currently pointing towards a beneficial outcome of the long-lasting bilingual language learning process, delaying the onset of cognitive decline including Alzheimer's disease. Neural reserve is proposed to be the reason behind these neuroprotective effects, induced through grey matter density in brain areas vulnerable to neurodegenerative changes that come with aging (Perani & Abutalebi, 2015). Indeed, some parts of the bilingual neural network have shown to partially overlap with structures that decline with aging, such as the PFC and the temporal pole. Furthermore, bilinguals have shown to recruit language control areas (e.g. left caudate nucleus and left inferior middle frontal gyri) during non-verbal executive control tasks more extensively than their monolingual peers (see section 3.2.), which means that these over recruited brain areas may over time develop grey matter density, mitigating the effects of cognitive decline as a result. In addition to neural reserve, bilingualism also induces neural compensation through stronger functional connectivity between certain brain areas. This way, the brain may cope better with the loss of brain structure such as brain atrophy and neurodegeneration. Taken together, the lifelong bilingual experience has extensive consequences on the brain's cognitive and functional processing, as well as anatomical structure, serving as a protection against age-related cognitive decline (Grant, et al., 2014). As such, it is important for laypeople to learn and become aware of the long-term positive impacts of bilingualism on the aging brain. Further, teaching an L2 from a young age should be a priority in educational systems.

As aforementioned (see section 4.3.), some researchers argue that learning a foreign language in older age can induce cognitive and neural reserve and thus protect against age-related cognitive decline. According to the literature reviewed in this thesis, cognitive reserve is developed after a lifetime of overusing cognitive systems through language control, meaning it requires high levels of language proficiency and frequent use of both languages. For a senior to become highly proficient in an L2 is not only difficult but requires a long period of time, which arguably, makes this proposal problematic since it is not consistent with current research.

Furthermore, as mentioned in section 3.1. and 3.2. and 4.3., some researchers argue for more efficient brain recruitment in bilinguals, adapting to task demands by recruiting some brain areas more than others as well as relying less on frontal regions than monolinguals. Instead, bilinguals have shown to rely more on posterior and subcortical regions which is the opposite effect of the normal posterior-anterior shift that occurs with aging. In addition, bilinguals are reported to have stronger frontal to posterior connectivity. Thus, bilinguals seem to preserve posterior regions of the cortex and their connections with the PFC more than their monolingual peers. The posterior-anterior shift may therefore not occur as extensively in bilingual individuals, due to the fact that posterior regions are less declined. The preservation not only comes from neural compensation (i.e through stronger functional connectivity between posterior and anterior regions) but also due to neural reserve, with increased grey matter in posterior regions such as the temporal pole and parietal regions (Grant et al., 2014). Thus, when first learning a new language, frontal resources as well as regions controlling for conflict monitoring are used more extensively which over time creates enlarged grey matter density. With time and practice however, these structures are remodeled in an efficient way by showing volume reductions and instead, bilinguals rely less on anterior regions and change from demanding top-down processing to more automatic processing in subcortical regions (see reductions of ACC and PFC in section 3.2. & 3.3.) (Grundy et al., 2017).

However, as seen in their study, Rodríguez-Pujadas interpreted their results as monolinguals exerting more efficient brain control than bilinguals, since both conditions performed similarly in the task. In their study, significantly more frontal activity coupled with more left caudate activity was detected in bilingual participants. These results are highly inconsistent with the notion that bilinguals posit stronger efficiency in PFC and ACC areas. However, their sample was relatively small and the results should therefore be interpreted with caution.

5.1. LIMITATIONS & PROBLEMS

In this section, limitations and problems in relation to the methods and restrictions made in this thesis as well as to the findings outlined will be highlighted. First and foremost, it is important to stress that the findings brought up in this thesis do not entirely cover the breadth of this topic. As described in section 1.4., I have selected the most central research but also left out several studies including for example electroencephalography (EEG) studies and studies examining white matter connectivity in the context of bilingualism. Thus, the content and final conclusions of this thesis come from a restricted amount of studies. However, the reason for this form of selectivity is because most of the research in this area is concentrated on fMRI studies. Further, it has helped to narrow the breadth of this topic, since this area of research is quite large. As a result, it has enabled me to provide a complete view of the most essential parts of the field.

As described previously (see section 1.4), various factors have been proven to be responsible for the inconsistent results in previous studies regarding a bilingual advantage in executive control. These factors include the lack of clear definitions and constructs as well as not providing enough information on language exposure, age of acquisition, years of language use and frequency of use. Naturally, if some research groups assess these variables while others do not, it becomes difficult to compare the results. Moreover, confounds can easily come about when leaving this important information out, decreasing the internal validity of the studies. It also becomes difficult to generalize, meaning that external validity is threatened. Further, language proficiency in L2 is another important variable that as seen in the literature, modulates neural activity in multiple brain regions, where high proficiency induces less neural activity and low proficiency induces more neural activity. Language proficiency is an adequate example of a variable that is constantly measured differently by different research groups, which again, makes it difficult to compare results from different studies. While some research groups use picture naming task or translating tasks to assess language proficiency, the choice of self-report questionnaires is very frequent, which also can become problematic since it may be self-biased or modulated by social desirability bias, a confounding that drives participants to behave what they believe is expected from them. For example, participants might indicate that their language skill is much higher than what it would be if assessed through a translation task.

A further critical limitation deserving attention is that although many studies assess the frequency of use of each language (e.g. Abutalebi et al., 2014; Rodríguez-Pujadas et al., 2013) others do not (e.g. Abutalebi et al., 2012; Abutalebi et al., 2013; Abutalebi et al., 2013b; Olsen et al., 2015). As mentioned previously (see section 3.), a high frequency of use in each language activates both languages in parallel more easily, which requires more inhibition of the non-target language to avoid language interference. This way, inhibitory control increases, and more demands are imposed on the control systems which as described, affects the neural activation and structure of the brain. Thus, leaving out this information becomes highly problematic, since the neural correlates in those studies may not reflect a complete view of the actual cognitive control. The fact that the frequency of use of both languages is a crucial factor influencing brain activity means that the influence of bilingualism on neural reserve is modulated by the same variable. This also includes language proficiency, discussed above. Therefore, it is equally important that research groups examining neural reserve in the context of bilingualism assess these variables in their studies.

A further aspect which has not been brought up in this thesis is whether L1 and L2 belong to the same language family or not and whether it affects the difficulty of language control. In other words, switching between two languages from different language families may have different neural effects than languages within the same family (e.g. switching between English and German which are Germanic languages and Italian which is a Romance language). It would also be interesting for future research to examine the neural correlates of even more extreme cases such as switching from non-European languages to European languages.

5.2. FUTURE RESEARCH DIRECTIONS & CONCLUSIONS

Despite the progress that has been made over the past two decades in understanding the nature of the bilingual brain, there are improvements to be done, especially regarding methodological approaches. Research groups in this field need to agree on and apply common methods when assessing bilingualism, that is, the degree of language proficiency, exposure and daily language use. This way, differences among bilinguals will become more distinguishable and results will become more accurate. After all, bilingualism is a complex and unique experience modulated by many different factors, such as context, society and lifestyle. Defining bilingualism is therefore essential before neuroimaging methods can be applied in research studies where bilingual participants are included. Likewise, researchers need to continue to include subjects that match in social background, education and socioeconomic background with similar profiles of bilingual language experience.

Further, integrating and combining structural MRI, fMRI, functional connectivity, EEG, diffusion tensor imaging (DTI), magnetoencephalography (MEG) and other innovative methods would contribute to a broader understanding of the BLC workings, provide a more coherent view and give a fuller understanding of the effects of the lifelong bilingual experience (Olsen et al., 2015). Moreover, regarding the three interactional contexts described in section 2, not many studies have examined the neural effects of the interactional context (i.e. single - or dual- language context or code-switching) to which participants are accustomed to in their every day lives. As described, language switching, which is especially common in a code-switching context, is a key task used to identify brain activity related to language control. Thus, studies investigating the effects of an individual's language circumstance on the structure and function of the brain should be a priority. This way, researchers may also be able to determine how the BLC network adapts to the demands imposed on the control systems from the different interactional contexts (Calabria et al., 2018). Furthermore, in order to determine causal relationships between the lifelong bilingual experience and differences in age-related changes of brain structure, follow-up longitudinal studies using a combination of behavioral assessments of cognitive function with neuroimaging methods are needed (Olsen et al., 2015).

Taken together, most of the literature reviewed in this thesis indicate that when comparing monolingual with bilingual participants in verbal and non-verbal conflict tasks, bilinguals consistently show an increased brain activity of cortical and subcortical areas related to executive/cognitive control and language processing. These brain areas mainly include the dACC, PFC, IPLs, BG and the cerebellum. Some studies, however, reveal a decrease in activation in the PFC and dACC coupled with increased activity of subcortical areas in bilinguals, which has been suggested to reflect more efficient brain recruitment. Moreover, the existing evidence suggests that lifelong BLC contributes to cognitive reserve. Cognitive reserve delays the onset of age-related decline including Alzheimer's disease, due to the increase of grey matter volume, white matter volume and stronger functional connectivity in areas sensitive to degenerative changes. Delaying the onset of dementia not only has beneficial implications for the economic costs in society but also for the well-being of the families and people affected. Thus, it demonstrates the importance of the continuance of research investigating the long-term effects of bilingualism on the human brain.

6. REFERENCES

Abutalebi, J., Canini, M., Della Rosa, P. A., Sheung, L. P., Green, D. W., & Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiology of aging*, *35*(9), 2126-2133. doi: 10.1016/j.neurobiolaging.2014.03.010

Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex*, *49*(3), 905-911. doi: 10.1016/j.cortex.2012.08.018

Abutalebi, J., Della Rosa, P. A., Gonzaga, A. K. C., Keim, R., Costa, A., & Perani, D. (2013b). The role of the left putamen in multilingual language production. *Brain and language*, *125*(3), 307-315. doi: 10.1016/j.bandl.2012.03.009

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., ... & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral cortex*, *22*(9), 2076-2086. doi:10.1093/cercor/bhr287

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of neurolinguistics*, *20*(3), 242-275. doi: 10.1016/j.jneuroling.2006.10.003

Abutalebi, J., & Green, D. W. (2016). Neuroimaging of language control in bilinguals: neural adaptation and reserve. *Bilingualism: Language and cognition*, *19*(4), 689-698. doi: 10.1017/S1366728916000225

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B. S. (2015). Bilingualism provides a neural reserve for aging populations. Neuropsychologia, 69, 201-210. doi: 10.1016/j.neuropsychologia.2015.01.040

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K., ... & Kaul, S. (2013). Bilingualism delays age at onset of dementia, independent of education and immigration status. Neurology, 81(22), 1938-1944. doi: 10.1212/01.wnl.0000436620.33155.a4

Alladi, S., Bak, T. H., Mekala, S., Rajan, A., Chaudhuri, J. R., Mioshi, E., ... & Kaul, S. (2016). Impact of bilingualism on cognitive outcome after stroke. *Stroke*, *47*(1), 258-261. doi: 10.1161/STROKEAHA.115.010418

Anderson, J. A., Grundy, J. G., De Frutos, J., Barker, R. M., Grady, C., & Bialystok, E. (2018a). Effects of bilingualism on white matter integrity in older adults. *NeuroImage*, *167*, 143-150. doi: 10.1016/j.neuroimage.2017.11.038

Anderson, J. A., Mak, L., Chahi, A. K., & Bialystok, E. (2018b). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behavior research methods*, *50*(1), 250-263. doi: 10.3758/s13428-017-0867-9

Antoniou, M., Gunasekera, G. M., & Wong, P. C. M. (2013). Foreign language training as cognitive therapy for age-related cognitive decline: a hypothesis for future research. *Neurosci. Biobehav. Rev.* 37(10 Pt 2), 2689–2698. doi: 10.1016/ j.neubiorev. 2013.09.004

Barulli, D., & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. *Trends in cognitive sciences*, *17*(10), 502-509. doi: 10.1016/j.tics.2013.08.012

Baumgart, C. Q., & Billick, S. B. (2018). Positive cognitive effects of bilingualism and multilingualism on cerebral function: A review. *Psychiatric Quarterly*, *89*(2), 273-283.

Berken, J. A., Chai, X., Chen, J. K., Gracco, V. L., & Klein, D. (2016). Effects of early and late bilingualism on resting-state functional connectivity. *Journal of Neuroscience*, *36*(4), 1165-1172. doi: 10.1523/JNEUROSCI.1960-15.2016

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological bulletin*, *143*(3), 233. doi: 10.1037/bul0000099

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, *45*(2), 459-464. doi: 10.1016/ j.neuropsychologia.2006.10.009

Borsa, V. M., Perani, D., Della Rosa, P. A., Videsott, G., Guidi, L., Weekes, B. S., ... & Abutalebi, J. (2018). Bilingualism and healthy aging: Aging effects and neural maintenance. Neuropsychologia, 111, 51-61. doi: 10.1016/j.neuropsychologia. 2018.01.012

Bostan, A. C., Dum, R. P., & Strick, P. L. (2013). Cerebellar networks with the cerebral cortex and basal ganglia. *Trends in cognitive sciences*, *17*(5), 241-254. doi: 10.1016/j.tics 2013.03.003

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, *402*(6758), 179. doi: 10.1038/46035.

Branzi, F. M., Della Rosa, P. A., Canini, M., Costa, A., & Abutalebi, J. (2015). Language control in bilinguals: monitoring and response selection. Cerebral Cortex, 26(6), 2367-2380. doi: 10.1093/cercor/bhv052

Burgaleta, M., Sanjuán, A., Ventura-Campos, N., Sebastian-Galles, N., & Ávila, C. (2016). Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *NeuroImage*, *125*, 437-445. doi: 10.1016/j.neuroimage.2015.09.073

Calabria, M., Costa, A., Green, D. W., & Abutalebi, J. (2018). Neural basis of bilingual language control. *Annals of the New York Academy of Sciences*. doi: 10.1111/nyas.13879

Cools, R., & D'Esposito, M. (2011). Inverted-U–shaped dopamine actions on human working memory and cognitive control. Biological psychiatry, 69(12), e113-e125. doi: 10.1016/j.biopsych.2011.03.028

Costa, A., Branzi, F. M., & Avila, C. (2016). Bilingualism: switching. In: *Neurobiology of Language (ed. G. Hickok and S. Small), 419–430. Cambridge, MA: Academic Press.* doi: 10.1016/B978-0-12-407794-2.00035-3

Costumero, V., Rodríguez−Pujadas, A., Fuentes−Claramonte, P., & Ávila, C. (2015). How bilingualism shapes the functional architecture of the brain: A study on executive control in early bilinguals and monolinguals. *Human brain mapping*, *36*(12), 5101-5112. doi: 10.1002/hbm.22996

Daviglus, M. L., Bell, C. C., Berrettini, W., Bowen, P. E., Connolly, E. S., Cox, N. J., ... & Patel, D. (2010). National Institutes of Health State-of-the-Science Conference statement: preventing Alzheimer disease and cognitive decline. Annals of internal medicine, 153(3), 176-181.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2007). Que PASA? The posterior–anterior shift in aging. *Cerebral cortex*, *18*(5), 1201-1209. doi: 10.1093/cercor/bhm155

Della Rosa, P. A., Videsott, G., Borsa, V. M., Canini, M., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2013). A neural interactive location for multilingual talent. *Cortex*, *49*(2), 605-608.

Dong, Y., & Li, P. (2015). The cognitive science of bilingualism. *Language and Linguistics Compass, 9*(1), 1–13. doi: 10.1111/lnc3.12099

Fu, Y., Lu, D., Kang, C., Wu, J., Ma, F., Ding, G., & Guo, T. (2017). Neural correlates for naming disadvantage of the dominant language in bilingual word production. *Brain and language*, *175*, 123-129. doi: 10.1016/j.bandl.2017.10.005

Garbin, G., Costa, A., Sanjuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N. E. E. A., ... & Avila, C. (2011). Neural bases of language switching in high and early proficient bilinguals. *Brain and Language*, *119*(3), 129-135. doi: 10.1016/j.bandl.2011.03.011

García-Pentón, L., Fernandez Garcia, Y., Costello, B., Duñabeitia, J. A., & Carreiras, M. (2016). The neuroanatomy of bilingualism: how to turn a hazy view into the full picture. *Language, Cognition and Neuroscience*, *31*(3), 303-327. doi: 10.1080/23273798.2015.1068944

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *Journal of Neuroscience*, *33*(2), 387-396. doi: 10.1523/JNEUROSCI.3837-12.2013

Grady, C. L., Luk, G., Craik, F. I., & Bialystok, E. (2015). Brain network activity in monolingual and bilingual older adults. *Neuropsychologia*, *66*, 170-181. doi: 10.1016/j.neuropsychologia.2014.10.042

Grant, A., Dennis, N. A., & Li, P. (2014). Cognitive control, cognitive reserve, and memory in the aging bilingual brain. *Frontiers in psychology*, *5*, 1401. doi: 10.3389/fpsyg.2014.01401

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*(5), 515-530. doi: 10.1080/20445911.2013.796377

Grogan, A., Green, D. W., Ali, N., Crinion, J. T., & Price, C. J. (2009). Structural correlates of semantic and phonemic fluency ability in first and second languages. *Cerebral Cortex*, *19*(11), 2690-2698. doi: 10.1093/cercor/bhp023

Grogan, A., Jones, Ō. P., Ali, N., Crinion, J., Orabona, S., Mechias, M. L., ... & Price, C. J. (2012). Structural correlates for lexical efficiency and number of languages in non-native speakers of English. *Neuropsychologia*, *50*(7), 1347-1352. doi: 10.1016/j.neuropsychologia.2012.02.019

Grosjean, F. (1982). Life with two languages: An introduction to bilingualism. Harvard University Press.

Grosjean, F. (2013). Bilingualism: A short introduction. In F. Grosjean & P. Li (Eds.), *The psycholinguistics of bilingualism* (pp. 5–25). Malden, MA: Wiley-Blackwell.

Grundy, J. G., Anderson, J. A., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, *1396*(1), 183-201. doi: 10.1111/nyas.13333

Hernandez, A. E., Martinez, A., & Kohnert, K. (2000). In search of the language switch: An fMRI study of picture naming in Spanish–English bilinguals. *Brain and language*, *73*(3), 421-431. doi: 10.1006/brln.1999.2278

Hosoda, C., Hanakawa, T., Nariai, T., Ohno, K., & Honda, M. (2012). Neural mechanisms of language switch. *Journal of Neurolinguistics*, *25*(1), 44-61. doi: 10.1016/j.jneuroling.2011.08.007

Hölzel, B. K., Carmody, J., Vangel, M., Congleton, C., Yerramsetti, S. M., Gard, T., & Lazar, S. W. (2011). Mindfulness practice leads to increases in regional brain gray matter density. *Psychiatry Research: Neuroimaging*, *191*(1), 36-43. doi: 10.1016/j.pscychresns.2010.08.006

Kousaie, S., Chai, X. J., Sander, K. M., & Klein, D. (2017). Simultaneous learning of two languages from birth positively impacts intrinsic functional connectivity and cognitive control. *Brain and cognition*, *117*, 49-56. doi: 10.1016/j.bandc.2017.06.003

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of cognitive psychology*, *25*(5), 497-514. doi: 10.1080/20445911.2013.799170

Kroll, J. F., Dussias, P. E., Bice, K., & Perrotti, L. (2015). Bilingualism, mind, and brain. *Annu. Rev. Linguist., 1*(1), 377-394. doi: 10.1146/annurev-linguist-030514-124937

Kroll, J. F., Gullifer, J. W., & Rossi, E. (2013). The multilingual lexicon: The cognitive and neural basis of lexical comprehension and production in two or more languages. *Annual review of applied linguistics*, *33*, 102-127. doi: 10.1017/S0267190513000111

Kühn, S., Gleich, T., Lorenz, R. C., Lindenberger, U., & Gallinat, J. (2014). Playing Super Mario induces structural brain plasticity: gray matter changes resulting from training with a commercial video game. *Molecular psychiatry*, *19*(2), 265. doi: 10.1038/mp.2013.120

Laird, A. R., Fox, P. M., Eickhoff, S. B., Turner, J. A., Ray, K. L., McKay, D. R., ... & Fox, P. T. (2011). Behavioral interpretations of intrinsic connectivity networks. Journal of cognitive neuroscience, 23(12), 4022-4037. doi: 10.1162/jocn_a_00077

Li, L., Abutalebi, J., Zou, L., Yan, X., Liu, L., Feng, X., ... & Ding, G. (2015). Bilingualism alters brain functional connectivity between “control” regions and “language” regions: Evidence from bimodal bilinguals. *Neuropsychologia*, *71*, 236-247. doi: 10.1016/j.neuropsychologia.2015.04.007

Luk, G., Bialystok, E., Craik, F. I. M., & Grady, C. L. (2011). Lifelong bilingualism maintains white matter integrity in older adults. *J. Neurosci.* 31, 16808–16813. doi: 10.1523/JNEUROSCI.4563-11.2011

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and cognitive processes*, *27*(10), 1479-1488. doi: 10.1080/01690965.2011.613209

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., & Frith, C. D. (2000). Navigation-related structural changes in the hippocampi of taxi drivers. *Proceedings of the National Academy of America*, 97, 4398–4403. doi: 10.1073/pnas.070039597

Mukadam, N., Sommerlad, A., & Livingston, G. (2017). The relationship of bilingualism compared to monolingualism to the risk of cognitive decline or dementia: a systematic review and meta-analysis. *Journal of Alzheimer's Disease, 58*(1), 45-54. doi: 10.3233/JAD-170131

Olsen, R. K., Pangelinan, M. M., Bogulski, C., Chakravarty, M. M., Luk, G., Grady, C. L., & Bialystok, E. (2015). The effect of lifelong bilingualism on regional grey and white matter volume. *Brain research*, *1612*, 128-139. doi: 10.1016/j.brainres. 2015.02.034

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive psychology*, *66*(2), 232-258. doi: 10.1016/j.cogpsych.2012.12.002

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, *69*, 265-278. doi: 10.1016/j.cortex.2015.04.014

Perani, D., & Abutalebi, J. (2015). Bilingualism, dementia, cognitive and neural reserve. *Current opinion in neurology*, *28*(6), 618-625. doi: 10.1097/WCO.0000000000000267

Perani, D., Abutalebi, J., Paulesu, E., Brambati, S., Scifo, P., Cappa, S. F., & Fazio, F. (2003). The role of age of acquisition and language usage in early, high−proficient bilinguals: An fMRI study during verbal fluency. *Human brain mapping*, *19*(3), 170-182. doi: 10.1002/hbm.10110

Perani, D., Farsad, M., Ballarini, T., Lubian, F., Malpetti, M., Fracchetti, A., ... & Abutalebi, J. (2017). The impact of bilingualism on brain reserve and metabolic connectivity in Alzheimer's dementia. *Proceedings of the National Academy of Sciences*, *114*(7), 1690-1695. doi: 10.1073/pnas.1610909114

Pliatsikas, C., Johnstone, T., & Marinis, T. (2014). Grey matter volume in the cerebellum is related to the processing of grammatical rules in a second language: a structural voxel-based morphometry study. *The Cerebellum*, *13*(1), 55-63.

Poarch, G. J., & van Hell, J. G. (2012). Executive functions and inhibitory control in multilingual children: Evidence from second-language learners, bilinguals, and trilinguals. *Journal of experimental child psychology*, *113*(4), 535-551. doi: 10.1016/j.jecp.2012.06.013

Rodríguez-Pujadas, A., Sanjuán, A., Fuentes, P., Ventura-Campos, N., Barrós-Loscertales, A., & Ávila, C. (2014). Differential neural control in early bilinguals and monolinguals during response inhibition. *Brain and language*, *132*, 43-51. doi: 10.1016/j.bandl.2014.03.003

Rodríguez-Pujadas, A., Sanjuán, A., Ventura-Campos, N., Román, P., Martin, C., Barceló, F., ... & Ávila, C. (2013). Bilinguals use language-control brain areas more than monolinguals to perform non-linguistic switching tasks. *PLoS One*, *8*(9), e73028. doi: 10.1371/journal.pone.0073028

Ross, L. A., McCoy, D., Wolk, D. A., Coslett, H. B., & Olson, I. R. (2010). Improved proper name recall by electrical stimulation of the anterior temporal lobes. Neuropsychologia, 48(12), 3671-3674. doi: 10.1016/j.neuropsychologia.2010.07.024

Schelke, M. W., Hackett, K., Chen, J. L., Shih, C., Shum, J., Montgomery, M. E., ... & Isaacson, R. S. (2016). Nutritional interventions for Alzheimer's prevention: a clinical precision medicine approach. *Annals of the New York Academy of Sciences*, *1367*(1), 50-56. doi: 10.1111/nyas.13070

Seo, R., Stocco, A., & Prat, C. S. (2018). The bilingual language network: Differential involvement of anterior cingulate, basal ganglia and prefrontal cortex in preparation, monitoring, and execution. *NeuroImage*, *174*, 44-56. doi: 10.1016/j.neuroimage.2018.02.010

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., ... & Dierks, T. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex*, *48*(4), 458-465. doi: 10.1016/j.cortex.2010.10.007

Stern, Y. (2006). Cognitive reserve and Alzheimer disease. *Alzheimer Disease & Associated Disorders*, *20*, S69-S74.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015-2028. doi: 10.1016/j.neuropsychologia.2009.03.004

Stocco, A., & Prat, C. S. (2014). Bilingualism trains specific brain circuits involved in flexible rule selection and application. *Brain and language*, *137*, 50-61. doi: 10.1016/j.bandl.2014.07.005

Stocco, A., Yamasaki, B., Natalenko, R., & Prat, C. S. (2014). Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function. *International Journal of Bilingualism*, *18*(1), 67-92. doi: 10.1177/1367006912456617

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in psychology*, *2*, 123. doi: 10.3389/fpsyg.2011.00123

Tyson, B., Lantrip, C., & Roth, R. M. (2014). Cerebellar contributions to implicit learning and executive functions. *Cognitive Sciences*, *9*(2), 179.

Videsott, G., Herrnberger, B., Hoenig, K., Schilly, E., Grothe, J., Wiater, W., … & Kiefer, M. (2010). Speaking in multiple languages: Neural correlates of language proficiency in multilingual word production. *Brain and language*, *113*(3), 103-112. doi: 10.1016/j.bandl.2010.01.006

Zahodne, L. B., Schofield, P. W., Farrell, M. T., Stern, Y., & Manly, J. J. (2014). Bilingualism does not alter cognitive decline or dementia risk among Spanish-speaking immigrants. *Neuropsychology*, *28*(2), 238. doi: 10.1037/neu0000014

Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *Cortex*, *48*(9), 1197-1206. doi: 10.1016/j.cortex.2011.05.022

Yang, J., Ye, J., Wang, R., Zhou, K., & Wu, Y. J. (2018). Bilingual contexts modulate the inhibitory control network. *Frontiers in psychology*, 9, 395. doi: 10.3389/fpsyg.2018.00395

World Health Organization (2017) retrieved 190401 from https://www.who.int/en/news-room/fact-sheets/detail/dementia