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Chapter 23

Title: The effects of multilingualism on brain structure, language control and language processing: insights from MRI

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1.0 INTRODUCTION

The use of more than one language has broad implications on various aspects of cognition, ranging from linguistic domains such as acquisition and attrition to cognition such as executive functions (see for example Chapter 20). Notably, the underlying neural mechanisms in terms of structure and functional activity are also subject to bilingualism and multilingualism effects, and these effects will be explored in this chapter. Indeed, a growing body of research shows that the brain adapts to the learning and acquisition of a second language (Hayakawa & Marian, 2019; Pliatsikas, 2019). However, less is known regarding whether or how this process differs when we learn a third language or even a fourth. Does the brain continue to change in terms of its structural architecture, connectivity networks and function, and if so, how? Are any changes modulated by the number of spoken languages, as well as by factors such as proficiency in, and relative use of, each language? The literature examining neuroplasticity stemming from the use of more than two languages; multilingualism, remains small but growing. This chapter will review the available evidence with the aim to address the above questions and to determine the extent to which multilingualism differs from bilingualism. We begin with a brief introduction on what has been reported about the effects of bilingualism on brain structure and function before transiting into how it can be similarly or differentially applied to the field of multilingualism. The studies reviewed hence not only provide a glimpse of the effects of multilingualism on 1) cortical and subcortical grey matter volume and 2) integrity of connecting white matter tracts, but also unveil 3) the functional activation related to the various processes that occur during language processing and language control, and 4) the functional connectivity of resting-state networks. With the exception of structural imaging methods, all the other techniques in the reviewed studies were executed in tandem with behavioural tasks assessing language processing, language switching and cognitive control.

Additionally, modulating factors of multilingual neuroplasticity such as the age of acquisition (AoA), proficiency, and level of expertise will be discussed. The chapter will then discuss conflicting and agreeing evidence in the literature and attempt to consolidate the findings with suggestions based on contemporary frameworks such as the Dynamic Restructuring Model (Pliatsikas, 2020). Finally, in closing, it will highlight gaps and pose suggestions for future research directions.

2.0 BRAIN ANATOMY

Before revealing the evidence for neuroplasticity through multilingualism, it is compelling to first understand the make-up of our brains. Neurons are nerve cells that communicate through electrical and chemical signals across junctions called synapses. Neurons are made up of a cell body, dendrites, and a tail-like axon. Refer to Figure 1 for an illustration of a typical neuron. The cell bodies of neurons make up the grey matter (GM), which is largely where processing occurs and is mainly lined up on the outer region of the brain. Conversely, the axons of neurons are what embodies the white matter (WM), which is where the coordination of communication occurs and is found in deeper layers of the brain. Figure 2 depicts a typical high-definition MRI scan showing the contrast between GM and WM, and is labelled with GM regions that will be discussed in this chapter. Surrounding the axons of neurons is a layer of cholesterol or fatty insulation called myelin which aids in the transmission of electrical impulses down the neuron and on to the next, and is crucial for the maintaining the axon and enabling more efficient functioning (Aggarwal, Yurlova, & Simons, 2011). When damage to the myelin sheath occurs, as found in various diseases like Multiple Sclerosis, it often results in disrupted communication in brain signals and manifests as cognitive impairments (Vasquez & Zakzanis, 2015).

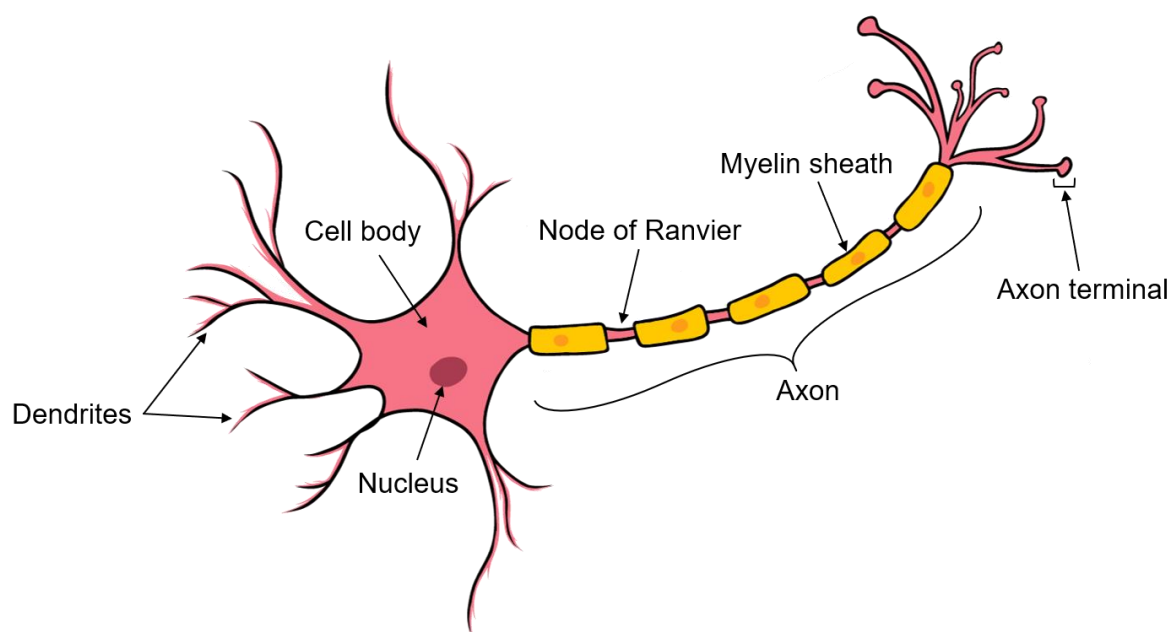


Fig. 1. Parts of a typical neuron

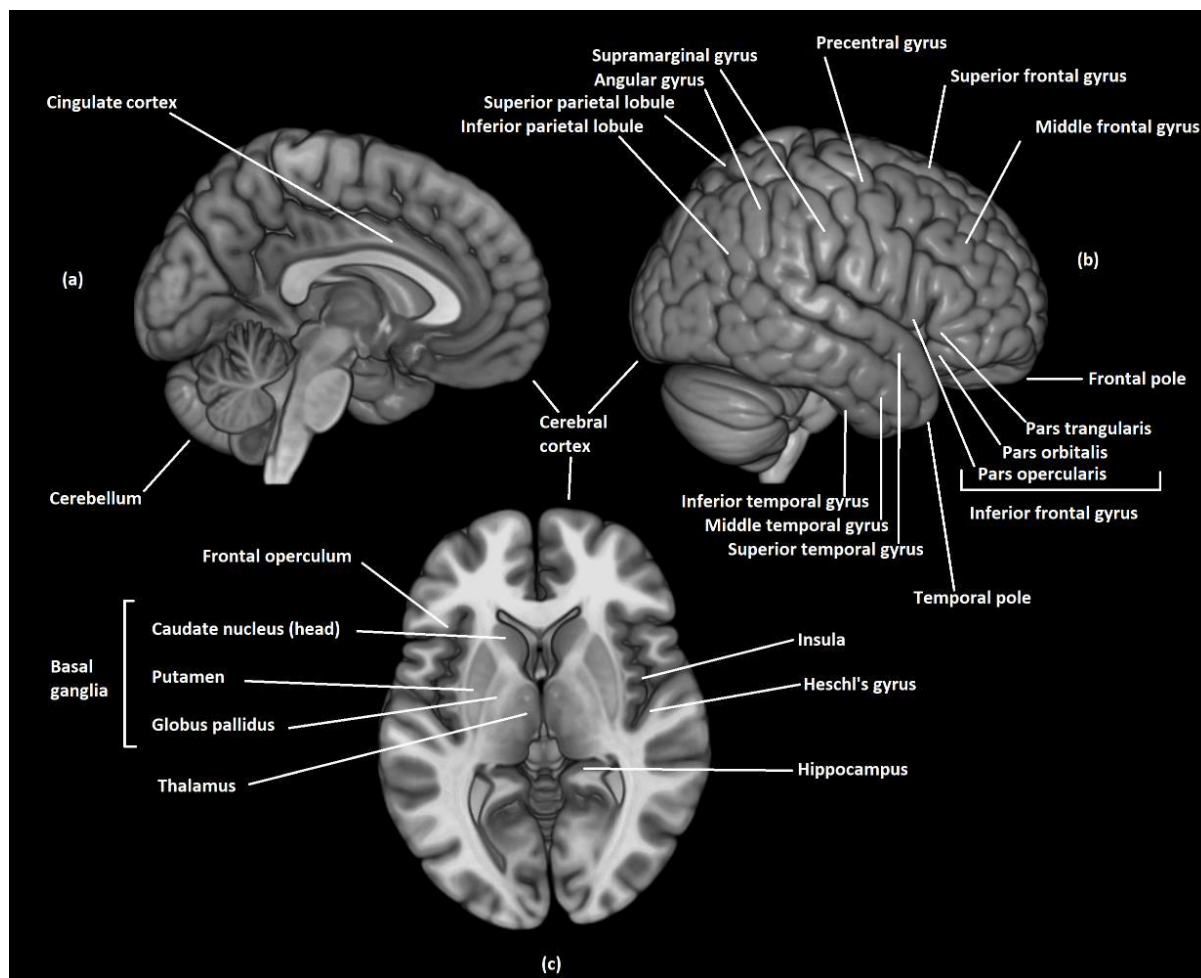


Fig. 2. A mid-sagittal (a), lateral (b) and mid-axial (c) view of a template brain, indicating the main GM regions that will be discussed in this chapter. WM, and how it differentiates from cortical and subcortical GM, is visible in (c). Reprinted from *Handbook of the Neuroscience of Multilingualism* (p 230-251), by C. Pliatsikas, 2019. Wiley-Blackwell. Copyright 2019 by John Wiley & Sons.

Neuroplasticity is evident not merely from the natural neural maturation processes in early development or neurodegenerative processes that occur through old age and disease, but also from day-to-day immersive experiences and skill acquisition (Spear, 2013; Richardson & Price, 2009). Evidence of brain restructuring through skill acquisition include music and navigational training among others where adaptations in WM tracts and GM regions directly involved in these tasks has been documented (Fauvel et al., 2014; Bengtsson et al., 2005; Ozturk et al., 2002; Maguire et al., 2000). These structural adaptations reflect the remarkable ability of the brain to seek and maintain neural efficiency. For the purposes of this chapter, WM microstructure is examined using quantitative diffusion tensor imaging (DTI) which quantifies the direction and degree of diffusivity within the axonal bundles forming the WM tracts. Low diffusivity, which can be contributed by increased myelination (or axonal density)

is reflective of more efficient signal transmission and better structural connectivity of WM tracts. This can be inferred from decreases in axial diffusivity (AD) and radial diffusivity (RD), and increases in fractional anisotropy (FA) and mean diffusivity (MD) (Dubois et al., 2014; Ben-Shachar et al., 2007; Geng et al., 2012).

3.0 STRUCTURAL AND FUNCTIONAL ADAPTATIONS FROM BILINGUALISM

It would be helpful to first briefly review the bilingualism literature before delving into the structural adaptations from the acquisition, processing, and control of a third or subsequent language. The neurocognitive adaptations associated with bi/multilingualism are on the notion of adaptation to the cognitive demands associated with controlling and processing an additional language. The languages one speaks are thought to be jointly and constantly 'active' in the brain, creating a state of competition in language comprehension and production (see e.g., Marian & Spivey, 2003; Green, 1998). To facilitate successful communication, this competition needs to be resolved (Bialystok et al., 2012; Kroll et al., 2012), and the brain is thought to adapt both structurally and functionally in order to facilitate this more effectively (Pliatsikas, 2019; Li, Legault, & Litcofsky, 2014).

When compared to monolinguals, bilinguals acquiring a non-native language have greater volume in several cortical regions involved in language learning and control, but not in subcortical structures (Della Rosa et al., 2013; Mårtensson et al., 2012; Mechelli et al., 2004). These areas consist of the inferior frontal gyrus (IFG), which forms part of the articulatory network (Price, 2010), the middle frontal gyrus (MFG), which is implicated in language switching (Sierpowska et al., 2018), the anterior cingulate cortex (ACC), which is part of the language control network (Green & Abutalebi, 2013), the supramarginal gyrus (SMG) of the left inferior parietal lobule (IPL), both said to be involved in novel word learning (Lee et al., 2007; Mechelli et al., 2004), Heschl's gyrus which is involved in processing foreign sounds (Golestani et al., 2011; Warrier et al., 2009), the superior temporal gyrus (STG) which is involved in recognising spoken words (Yi, Leonard & Chang, 2019), and the superior parietal lobule (SPL) which is implicated in language control (Hernandez, 2009; Wang et al., 2009). WM effects from the sequential learning of a second language (L2) are mixed; with some studies reporting increased diffusivity while others showing decreased diffusivity of various tracts such as the IFOF (Rossi et al., 2017; Mamiya et al., 2016; Cummine & Boliek, 2013). Traditional factors such as the AoA and proficiency also play a role in predicting the effects on structural adaptations. For instance, Stein et al. (2012) demonstrated that the more proficient an individual is in their newly-acquired L2, the greater the density of the left anterior temporal lobe and left IFG. Interestingly, some longitudinal studies with L2 learners reported the decline or disappearance of the volumetric increase initially identified several months after the end of the language training despite the skill having survived (Mamiya et al., 2016; Hosoda et al., 2013).

Contrastingly, there was a lack of GM effects for more immersed or experienced bilinguals when they were compared to monolinguals (Olsen et al., 2015). Bilinguals who have had more opportunities to switch between their languages because of greater immersion exhibited relatively consistent WM effects in the form of reduced diffusivity in tracts such as the inferior fronto-occipital fasciculus (IFOF), superior and inferior longitudinal fasciculi, uncinata fasciculus and corpus callosum (Singh et al., 2018; Pliatsikas, Moschopoulou, & Saddy, 2015; Luk et al. 2011). Greater structural connectivity in various regions in the frontal, temporal and parietal regions of the left hemisphere were also found (García-Pentón et al., 2014). In a study on child bilinguals, an increase in WM integrity was observed only for simultaneous bilinguals and a similar increase for sequential bilingual children only occurred after three years of continuous use (Mohades et al., 2015). This highlights the impact of immersive language experiences on structural adaptations in the brain. These WM adaptations reflect greater integrity and better communication amongst various regions of the brain implicated in language processing. Additionally, volumetric increases in several subcortical structures such as the caudate nucleus, putamen, thalamus and globus pallidus, which have been proposed to be part of Green and Abutalebi's (2013) language control network have also been identified in individuals who acquired both their languages concurrently (Pliatsikas et al., 2017; Berken et al., 2016; Burgaleta et al., 2016).

Structural adaptations underlying language control are expected to correspond with functional adaptations. When engaged in executive control tasks, bilinguals exhibited common and distinct functional activity in comparison to monolinguals (Olulade et al., 2015). Most crucially, the regions with increased activity for bilinguals often overlap with areas implicated in language control (Green & Abutalebi, 2013; Gold et al., 2013). These regions include the dorsolateral prefrontal cortex (dlPFC), ventrolateral PFC, ACC, caudate nucleus, left IFG, and left PCG (Coderre et al., 2016; Mohades et al., 2014; Luk et al., 2011; Garbin et al., 2010; Bialystok et al., 2009). When examining resting-state networks in bilinguals and monolinguals, Luk et al. (2011) identified in bilinguals more distributed functional connectivity with bilateral temporal, parietal, and occipital regions and the left caudate, while monolinguals portrayed greater connectivity with other frontal regions. The bilingual experience was also found to increase functional connectivity in the default mode network (DMN) and frontoparietal control network (Grady et al., 2015). Furthermore, it appears that bilinguals tend to recruit more posterior and subcortical regions than monolinguals (Rodriguez-Pujadas et al. 2013; Luk et al., 2012; Waldie et al., 2009).

3.1 THEORETICAL PROPOSALS

It is clear from the evidence reviewed here, that structural adaptations are dynamic in nature and depend on factors beyond the number of languages per se (monolingualism versus bilingualism), but also in the qualitative ways in which bilinguals use their languages. The three-stage Dynamic Restructuring Model (DRM; Pliatsikas, 2020) provides an interpretation

of the observations by accounting for the fact that every bilingual/multilingual's linguistic repertoire is unique; they vary in the AoA, level of immersion and the contexts in which they use their languages. These experience-based factors can modulate an array of systematic structural and cognitive adaptations (Sulpizio et al., 2020; Beatty-Martínez et al., 2019; DeLuca et al., 2019; Gullifer et al., 2018; Kuhl et al., 2016). The first stage of the DRM is marked by the *Initial exposure* to an additional language, which gives rise to cortical GM changes particularly in regions that underlie linguistic functions and in areas involved in executive control. Brain tissue may grow in response to the acquisition of the skills to (a) rapidly expand vocabulary, and (b) control between lexical alternatives. The second stage, *Consolidation*, occurs after extended language immersion/experience where the initial GM adaptations in stage one revert towards baseline, while subcortical and WM adaptations begin to emerge. The GM reductions is posited to be driven by cortical pruning and follows up on the expansion-partial renormalisation hypothesis which suggests that upon successful acquisition of a skill, the dendritic spines that were spawned at the beginning strips itself of underutilised connections, preserving only the most efficient ones (Lövdén et al., 2013; Johnson, 2011; Giorgio et al., 2010). Subcortical adaptations are suggested to support the control between the available semantic, phonological, and grammatical alternatives in a setting that demands the continuous inhibition of the non-target language. Decreased diffusivity of WM tracts also contributes towards the greater efficiency that characterises this stage by facilitating communication amongst regions crucial for semantic, syntactic, and phonological processing. In stage three, *Peak efficiency*, it is predicted that bi-/multilinguals with even greater language experiences might demonstrate a further posterior shift that is characterised by greater WM diffusivity in anterior regions and lower diffusivity in posterior regions, maximal volumetric increase of the cerebellum, full renormalisation of the caudate nucleus and a generally consistent volume of the putamen and globus pallidus. With regards to the trends observed for functional adaptations, they align with the Bilingual Anterior-to-Posterior and Subcortical Shift model (BAPSS; Grundy, Anderson, & Bialystok, 2017) which posits that with increased language experience, the brain becomes more efficient in its recruitment of resources. Specifically, frontal regions which are known to underlie more effortful and controlled processing are less engaged while the reliance on subcortical and posterior areas increases, indicating more a more automated approach to cognitive control.

4.0 CORTICAL GREY MATTER ADAPTATIONS FROM MULTILINGUALISM

The literature on structural adaptations stemming from a third or subsequent language use is still relatively limited (with only six studies highlighted in this section of the chapter at the time of writing). The acquisition and mastery of three or more languages would mean having additional language systems to process, toggle and control: to monitor, inhibit and select. Although the control demands of multilingualism are less well understood presently, it is argued that they would diverge from those of bilingualism (see for review Rothman et al.,

2019). In what follows, we review the available evidence on neural adaptations to multilingual experience.

Parallel with Mechelli et al. (2004)'s finding of greater density in the posterior SMG (pSMG) in bilinguals as compared to monolinguals, multilinguals of at least three languages exhibited even greater density in this region than bilinguals (Grogan et al., 2012). These multilinguals speak a variety of European and non-European languages but converge on English as one of their languages. The results indicate an additive effect of language acquisition in areas typically affected by subsequent language learning. The density of the pSMG was previously associated with the acquired lexicon size (Richardson et al., 2010). This led the researchers to implicate this region's function with the number of words acquired through explicit teaching by associating phonology with semantics.

Variation in GM volume of language-related areas was also examined using voxel-based morphometry (VBM), a whole-brain unbiased objective analysis technique, in a study of 44 trilinguals split into two groups; a group that learned two languages simultaneously followed by the third one later in life, and another that learned two languages consecutively later in life (Kaiser et al., 2015). Consecutive but not simultaneous bilinguals had substantially bigger volume in frontal, temporal and parietal regions related to language processing despite being equally proficient in all three languages. Similar to bilinguals, the age of learning a subsequent language is related to the volume of regions involved in language processing. The authors conclude that early and simultaneous exposure to two languages make structural adaptations less responsive to the learning of a third subsequent language. The effects of early exposure and development are sustained and have bearings on neuroplasticity stemming from experiences beyond childhood, just as was found for bilinguals (Pliatsikas et al., 2020). Kaiser and colleagues suggest that the brain is able to assimilate additional language experiences into the existing neural architecture with greater efficiency the sooner one gains language exposure.

A special case of multilingualism – translators and interpreters – have remarkable multilingual abilities that enable them to switch between languages more frequently and at higher intensities than the average multilingual. Elmer, Hänggi & Jäncke (2014) examined the effects of expert multilingual skills in a group of 12 simultaneous interpreters and 12 multilingual control subjects who are fluent in at least three languages. The researchers investigated if simultaneous interpretation, an extremely cognitively demanding task with its intense activation of linguistic, articulatory, and executive processes, would facilitate structural GM adaptations. Using region of interest analysis of areas known to be involved in language control and processing, they reported significantly smaller GM volumes in the left middle-anterior cingulate gyrus, bilateral pars triangularis, left pars opercularis, bilateral middle part of the insula, and left SMG in simultaneous interpreters but not in the translator controls. Furthermore, the volume of the inferior frontal left pars triangularis, right pars opercularis,

middle-anterior cingulate gyrus (ACG), and bilateral caudate nucleus correlated negatively with the number of hours spent interpreting. To explain the grey matter volume reduction, Elmer and colleagues speculate that the intense language control training involved in simultaneous interpreting may encourage greater cortical pruning where inefficient connections are removed to enable efficiency and functional specialisation. Structural changes in the middle-ACG were similarly found in the bilingualism literature, suggesting its function in conflict monitoring that is involved in interpretation. The pars triangularis, which is related to sentence comprehension and syntactic processing (Friederici & Gierhan, 2013; Martin, 2003; Grodzinsky, 2000) has also been said to facilitate general cognitive abilities. Thus, its structural change could be an adaptation from handling vigorous demands on executive functions and linguistic processing involved in interpretation. Finally, the SMG, a structure in the IPL, is said to be related to the IPL's function in attention, working memory and phonological processing (Deschamps, Baum, & Gracco, 2014; Buchsbaum & D'Esposito, 2009; Rushworth, Krams, & Passingham, 2001).

Similarly, Becker et al. (2016) found a structural effect of simultaneous interpreting on the left frontal pole. The GM volume analysis of 45 multilinguals who speak four languages revealed that practising simultaneous interpreters have a larger left frontal pole (BA 10) as compared to translators. It might come as no surprise that this region was also found to be a crucial node that is functionally more interlinked with other nodes in the connectivity network for simultaneous interpreters as compared to translator controls. The left frontal pole also exhibited a negative partial correlation with mixing costs for the simultaneous interpreters (the more efficient they were during mixed-task trials, the higher the activity of the left frontal pole), further implicating its role in multitasking, monitoring and attention as previously identified (Arredondo et al., 2017; Gilbert et al., 2006; Crosson et al., 2002).

From these two studies on simultaneous interpreters, the findings appear to be rather different. However, it must be considered that the type of control groups used by each study are different. In Becker et al. (2016)'s study, all participants were recruited from the Federal Association of Interpreters and Translators. Thus, the professional simultaneous interpreters were compared with professional translators who had comparable amounts of formal training and work experience in translation. While translation does not require the same level of language switching and control, its demands are much greater than what is required of an average non-professional multilingual. Contrastingly, in Elmer et al.'s (2014) study, professional simultaneous interpreters who exercise incredible language and attentional control for a living, were compared with multilingual controls. This forms a much wider expertise gap between the two groups. Hence, it would be logical to expect much smaller volumetric differences between simultaneous interpreters and controls in Becker et al.'s study, and more regions with reduced volumes in Elmer et al.'s study.

Some subcortical effects have also been identified in the multilingualism literature. The putamen, a structure suggested to underlie articulatory processes (Abutalebi & Green, 2016), was found to adapt structurally and functionally. For instance, in a VBM study of 14 German-Italian-English trilinguals and Italian monolinguals, left putaminal GM density of the trilinguals was also greater than that of the monolinguals (Abutalebi et al., 2013). Furthermore, fMRI results from a picture naming task revealed additional activation in this structure for a non-native and low proficiency language. The authors interpreted these observations as a function of managing additional articulatory processes with the acquisition of a further language.

With the aim to account for not only the number of languages but also the language experience, a recent study assessed the influence of AoA and level of proficiency on the structural adaptations of four subcortical areas (caudate nucleus, putamen, pallidum, and thalamus). In this volumetric study with 75 multilinguals proficient in three or more languages, the researchers found evidence for the reshaping of the caudate nucleus, a structure linked to handling lexico-semantic systems (Hervais-Adelman, Egorova, & Golestani, 2018). It appears that the earlier the AoA and the higher the language proficiency, the larger the volume of the caudate nuclei. More specifically, proficiency played a stronger role than AoA in relation to the restructuring of the caudate nucleus. This highlights the continuous adaptation of the caudate nucleus with linguistic expertise and reflects a similar trend to Pliatsikas et al.'s (2017) immersed sequential bilinguals where reshaping of the caudate nucleus occurred for proficient bilinguals despite not using their languages continuously. The left caudate has also previously been identified as having connectivity with brain regions essential for executive functioning, highlighting its involvement in language monitoring and control (Zou et al., 2012; Brovelli et al., 2011; Abutalebi et al., 2008). However, interestingly and unlike Abutalebi and colleagues (2013), Hervais-Adelman et al. did not find putaminal restructuring. The authors suggest that because the role of the putamen may relate with in-the-moment inhibition to allow the selection of the target language, it is possible that increasing the number of languages would not significantly alter the demands of this role.

4.1 WHITE MATTER ADAPTATIONS FROM MULTILINGUALISM

The literature on the relationship between WM integrity and multilingualism remains small, and there are no clear comparisons between bilinguals and multilinguals. Nevertheless, the following studies make valuable contribution by revealing WM restructuring amongst multilinguals who speak at least three languages.

Hämäläinen and colleagues (2017) examined structural WM microstructure of 30 multilinguals, with a focus on the impact of the age of L2 acquisition on language-related tracts. All participants received formal education in Finnish, Swedish and English, and took on approximately 2-3 additional foreign languages. Early L2 exposure was found to lead to higher FA in the portion of the left arcuate fasciculus (AF) that supports phonological functions, and

lower MD in the posterior portion of the AF, suggesting increased density along this tract. However, the early L2 group had higher MD/decreased density in the IFOF, a tract important for semantic processing. Being exposed to an L2 sequentially, after the age of eight was related with significantly greater axonal density along the IFOF of both hemispheres as compared to early simultaneous L2 multilinguals. It was suggested that if one acquires an additional language after having attained proficiency in the L1, the IFOF could be an indication of restructuring stemming from bilingualism. In line with this, learning an additional language consecutively has structural implications on the brain, while simultaneous bilingualism does not have such additive effects (Kaiser et al., 2015). In terms of structural laterality, acquiring two languages early in life led to a more bilateral structural configuration of the AF, while acquiring the L2 later in life was associated with a more left-lateralised configuration of the AF. The authors conclude that L2 AoA could give rise to qualitatively distinct adaptations in these language-related WM tracts. Furthermore, the results support the notion that the multifaceted processing of additional languages have small but unique structural markers on the brain. However, apart from L2 AoA, the results do not elucidate if the number and properties of the subjects' additional languages contribute towards the structural WM adaptations as well.

The one other study that examined WM restructuring involved expert multilinguals of at least three languages who were students training to become simultaneous interpreters and translators (Van de Putte et al., 2018). They were recruited for a longitudinal study where the researchers examined structural adaptations at two time points – before and after nine months of training. These two groups of participants differed in language and attentional control needs - simultaneous interpreters are required to understand the message in the source language and reword it into the target language while concurrently producing the last interpreted message (Prior and MacWhinney, 2010). On the other hand, translators would only do so when the speaker has stopped talking, making it relatively less challenging. A substantial decrease in WM diffusivity in the frontal-basal ganglia subnetwork and another network consisting of the cerebellum and the SMA was found for the interpreters but not the translators. The basal ganglia subnetwork consists of five regions and four connections connecting the frontal regions of the brain with the basal ganglia, with the right pallidum functioning as the central node in the network. The other subnetwork consists of eight regions and seven connections (left SMA, right PCG, right superior frontal gyrus, right middle temporal pole, right amygdala, vermis 3 of the cerebellum, left inferior parietal gyrus and superior parietal gyrus). The basal ganglia subnetwork was previously found to have a role in verbal and non-verbal inhibitory control (Guo et al., 2018; Seo, Stocco, & Prat, 2018) and was suggested to modulate the frontal cortices by enabling suitable responses and inhibiting conflicting responses which are being considered by the frontal cortices. The second subnetwork includes the cerebellum, the SMA and the parietal lobes which are regions proposed in the language control network (Abutalebi & Green, 2016). These neuroanatomical restructuring in cognitive control networks underscores the tremendous amounts of language

control involved in simultaneous interpreting and highlights the shared mechanisms between language and cognitive control.

These observations of both GM and WM restructuring found in multilinguals of at least three languages and professional multilingual experts can be explained by the DRM. More specifically, with increased language experience, these multilinguals can be said to be at the stages of *Consolidation* or of *Peak efficiency*. The increased language experience from intensely toggling between multiple languages is reflected through reductions in GM volume, which appear to be a return to baseline volumes in areas that expanded in the first stage of *Initial exposure*. The documented cortical effects could indicate the successful optimisation of the neural networks that drive lexical acquisition and control. At the *Consolidation* stage, effects in subcortical regions like the thalamus, caudate nucleus, putamen, basal ganglia and globus pallidus that begin to emerge may reflect the increased demands to select amongst even more sets of semantic, phonological, and grammatical options that compete for the multilingual's attention. Moreover, the increased language control and switching opportunities in multilinguals appear to also induce lower diffusivity of WM tracts which indicates re-adaptations of the language network to accommodate for the further language experiences. *Consolidation*, as we recall, additionally entails WM adaptations to facilitate more efficient communication amongst various GM regions implicated in language control, which was previously only documented in simultaneous or immersed bilinguals (Singh et al. 2018; García-Penton et al., 2014). It is possible that the simultaneous interpreters in Van de Putte et al.'s (2018) study are at the stage of *Peak efficiency*. As representatives of multilinguals most adept at language switching, they exhibited lower WM diffusivity in posterior regions involving subcortical structures, demonstrating further posterior and subcortical adaptations which live out what would be expected in the last stage of the DRM. However, we acknowledge that with the limited amount of evidence at hand, it is difficult to definitively conclude so.

5.0 FUNCTIONAL ADAPTATIONS FROM MULTILINGUALISM

Structural adaptations are expected to occur along with functional adaptations (Zou et al., 2012; Abutalebi et al., 2012; Green & Abutalebi, 2013; Martínez-Horta et al., 2019), which should in turn underlie any behavioural differences. The studies to be reviewed revolve around functional activation and connectivity relating to language control and cognitive control.

5.1 FUNCTIONAL CHANGES RELATING TO LANGUAGE CONTROL

Like bilinguals, all the languages of a multilingual are activated concurrently and contend for selection (Aparicio & Lavour, 2014; Lemhöfer, Dijkstra, & Michel, 2004). Therefore, it is logical

to think that the command of more than two languages entails greater levels of language control to monitor, inhibit and select the appropriate language.

To understand the patterns of neural activity underlying language switching, de Bruin and colleagues (2014) recruited Dutch-English-German trilinguals to perform a picture naming task in an MRI scanner. The right IFG and the pre-SMA are areas known to be linked with domain-general inhibitory control, and they exhibited higher levels of activity when the multilinguals switched to their second and third languages. However, this pattern of activity was not found when they switched to their first language, which according to the Inhibitory Control Model (Green, 1998), requires additional inhibition. Therefore, this was interpreted as language switching and domain-general inhibition sharing neural mechanisms, and multilinguals recruiting inhibition to toggle between different languages. This pattern of findings is not different from that of bilinguals (Abutalebi & Green, 2007).

In another study which similarly examined the neural mechanisms underlying language control, Abutalebi and colleagues (2013) recruited monolinguals as well as trilinguals who exhibited within-subject variability in language proficiencies to avoid between-subject confounds. The multilingual participants performed an overt picture naming task in different languages while the monolinguals performed a within-language version of the overt picture naming task. Switching within a language increased activity in the pre-SMA and the anterior cingulate cortex (ACC), but decreased activity in the left caudate nucleus. Language switching also increased activity in both the pre-SMA and ACC no matter the difference in proficiency. However, interestingly, the left caudate nucleus increased in activity only when language switching occurred from the most proficient to least proficient language. These were interpreted as the pre-SMA and ACC being involved in conflict monitoring and the left caudate being implicated in language selection of the less proficient one. More crucially, this pattern of activity in trilinguals mirror what has been found in bilinguals and is coherent with the BAPSS (Grundy et al., 2017). The increased language experience gives way to greater reliance on subcortical structures, which is potentially indicative of increased automaticity and neural efficiency.

5.1.1 EXTREME LANGUAGE CONTROL

In what follows, we discuss four fMRI studies examining multilingualism, particularly special cases requiring higher demands on language control. These studies involve simultaneous interpreters, a unique group of multilinguals who are able to switch between languages accurately and more rapidly than the average multilingual. This is a cognitively demanding feat that entails intensive control of linguistic, articulatory, and executive processes. Firstly, Hervais-Adelman et al. (2015a) recruited 50 multilinguals who speak at least three languages and compared the neural activity during simultaneous interpretation with the activity during simultaneous repetition where participants simply repeated the sentences they hear

immediately after the sentence onset. Simultaneous interpretation engaged not only all the areas involved in simultaneous repetition, but also further activated the left pre-SMA, anterior insula, right cerebellum, caudate nuclei and the left IFG. These additional activations thus reflect the demands of simultaneous interpreting which necessitates extreme language control. The duration spent simultaneously interpreting correlated significantly with putaminal activity. The authors suggest that when engaged in simultaneous interpretation, the caudate nucleus is recruited for planning; the monitoring, control, and selection of the right language while the putamen is suggested to be involved in the execution of language output; inhibiting irrelevant languages. These two dorsal striatal structures have also been previously implicated in non-linguistic executive control. They thus conclude that subcortical structures play important roles in multilingual language control, and that the shared network for language control and general cognitive control underlines the positive effects gained from juggling multiple languages.

Hervais-Adelman, Moser-Mercer, & Golestani (2015b) conducted a longitudinal study with students training to be simultaneous interpreters and used fMRI to compare functional activity during simultaneous interpretation and simultaneous repetition. This was done at the start and at the end of an intensive 15-month simultaneous interpreting training. Functional activity changes occurred between the two scans in widespread regions that were unique enough to differentiate between the simultaneous interpreting trainees from the control group. These regions include the cerebellum, subcortical structures such as the thalamus and the caudate nuclei, and classic areas implicated in speech comprehension and production. Similar to Hervais-Adelman et al. (2015a), a significant effect of simultaneous interpreting training on the right caudate nucleus was found. The caudate nucleus, which is implicated in language control (Green & Abutalebi, 2013), exhibited decreased activity after 15 months of training for the trained simultaneous interpreters as compared to controls matched in proficiency, age, and sex. The researchers posit that this experience-dependent change is in line with the notion that as the task becomes more reflexive due to practice, its demands on language control naturally decreases. Supported by other studies which have also identified adaptations of this structure in experts of various skills (Duan et al., 2012; Wan et al., 2011), these results reinforce the crucial role of the caudate nucleus in networks associated with expert behaviours (Wan et al., 2012).

Making sense of these two functional studies, it is plausible that as a multilingual increases in skill level, there is a decreased reliance on the caudate nucleus, which underscores its role in expertise-related behaviour. However, as the multilingual reaches a certain level of expertise in language control (as did the simultaneous interpreters in Hervais-Adelman et al.'s (2015a) study), the efficiency at task performance would be reflected in the caudate's increased activity. It thus appears to be the case that these highly skilled multilinguals are able to do more with less. Congruent with the BAPSS model, the consistent mentioning of additional

subcortical recruitment in multilinguals echoes what has been identified in bilinguals when compared with monolinguals.

5.2 FUNCTIONAL CHANGES RELATING TO NON-LINGUISTIC COGNITIVE CONTROL

Apart from language control, the literature on bilingualism has provided evidence of cognitive advantages in non-linguistic domains such as inhibitory control and working memory. Both types of control have been found to share similar functional networks (De Baene et al., 2015). The highly demanding process of simultaneous interpreting has been found to confer positive effects on domain-general cognitive functions. Becker et al. (2016) recruited 50 multilinguals of whom 27 are simultaneous interpreters and 23 are matched translator controls. The participants took part in a colour-shape switching task and a dual-task paradigm consisting of reaction time tasks, while undergoing fMRI scans. Behaviourally, the simultaneous interpreters did not differ on the switching task, but were generally quicker in responding to the two choice reaction time tasks, thus highlighting that the complexities involved in simultaneous interpreting confers cognitive advantages. Functionally, resting-state fMRI analysis showed significantly greater functional connectivity between BA 10 and the left inferior frontal pars opercularis and pars triangularis. Stronger connectivity between BA 10 and the left middle temporal gyrus was also observed for simultaneous interpreters but not for the controls. Such functional connectivity changes highlight the importance of the left frontal pole in cognitive control, and may reflect more efficient brain recruitment.

In a longitudinal study investigating the effects of simultaneous interpreting on executive functions, Van de Putte and colleagues (2018) recruited simultaneous interpreting students to perform non-verbal cognitive control tasks before and after their interpreting training. The researchers compared their results with that of a group of translators who do not go through such intensive degrees of language switching. The simultaneous interpreting students displayed greater activity in the left STG during the Simon task and the right angular gyrus during the colour-shape shift task as compared to the translators after nine months of training. These were interpreted as the development of a greater capacity for cognitive control functions (Rubia et al., 2006).

6.0 MULTILINGUAL BRAIN FUNCTION IN LANGUAGE PROCESSING

The functional adaptations we have seen so far inform us of the inner workings of multilingual language and cognitive control. In the final section of this chapter, we will examine if language processing itself would be any different in the multilingual brain. Even though the past literature on language representation has been inconsistent, it has largely shown that L1 and L2 have overlapping representations in the bilingual brain, and any differences identified tend to be modulated by language experiences like AoA and proficiency (Wang et al., 2020; Abutalebi, 2008; Hernandez et al., 2007; Jeong et al., 2007; Perani & Abutalebi, 2005;

Rüschemeyer et al., 2005; Wartenburger et al., 2003; Luke et al., 2002). We will now review the available studies conducted with multilinguals and examine whether a similar pattern emerges when an L3 is included in the mix.

6.1 LANGUAGE PROCESSING MODULATED BY AoA

The AoA is an influential variable in the study of multilingualism. Apart from its impact on structural adaptations (Wei et al., 2015), it also has consequences on functional activations during language processing. Vingerhoets et al. (2003) examined the neural representation of different languages in a group of Dutch-English-French multilinguals. The 12 participants were recruited to engage in several linguistic tasks (word fluency task, picture naming, comprehension reading) in all three of their languages as they underwent an fMRI scan. All of them were native speakers of Dutch, with English and French as their foreign languages which were taught formally in school after the age of 10. While all tasks in all three languages exhibited mostly a shared network, performing in their foreign languages appears to further engage areas already activated in native language processing and elicit activity in more regions. For instance, generating words in the non-native languages revealed activity in the inferior frontal cortices of both hemispheres, which was not observed for the native Dutch. Picture naming in the foreign languages saw the activation of additional left-dominant inferior-lateral and medial frontal areas, while doing so in the native language saw more activation in the posterior regions in the right hemisphere. When covertly reading, native languages elicited greater activity in medial posterior areas. The authors suggest that different languages mostly share the same neural mechanisms, but languages that are acquired later necessitate additional resources to execute the task with similar competence.

With a group of multilinguals varying in age of L2 acquisition, Bloch and colleagues (2009) compared the neural activity of 44 multilinguals as they engaged in a silent free narration task. The multilinguals either acquired L2 simultaneously with L1, sequentially between the ages 1 to 5 or acquired L2 late after the age of 9. They were all proficient in an L3. Regardless of the age of L2 acquisition, all the multilinguals exhibited activity in Broca's area, Wernicke's area, left PFC, premotor cortex, supplementary motor cortex, occipital regions, and ACC. The researchers found that multilinguals who acquired L2 early on in life exhibited similar neural activity across all three languages, sharing a largely overlapping network for language. The degree of variability was on par with that of simultaneous bilingualism. Conversely, multilinguals who acquired L2 late (after the age of nine) demonstrated more varied patterns of activation in different languages, suggesting an autonomous access to their various languages. The late multilinguals also displayed greater activity for the later learned languages, including more right hemispheric activity in the basal ganglia, Broca's and Wernicke's area. The authors conclude that variability in language representation in the brain increases with the age of L2 exposure, highlighting a diminishing access to a shared network for processing language.

Using fMRI and a sentence production task, Wattendorf et al. (2012) similarly examined the effect of age of L2 acquisition on the organisation of the language network. While all the participants acquired an L3 after the age of nine, they differed on the age of L2 acquisition. Early multilinguals learned their L2 before the age of three and late multilinguals acquired their L2 after the age of nine. They performed a silent sentence production task in all three languages separately while undergoing an fMRI scan. Early multilinguals had greater activity in the frontal cortices and subcortical areas (fronto-striatal) of mainly the left hemisphere, for both early and later-acquired languages. For early multilinguals, the left dIPFC and left fusiform gyrus were activated to a greater extent when reading in L1 and L2, while the left orbitofrontal BA 47 only exhibited greater activity when reading in L1. As compared to early multilinguals, late multilinguals exhibited greater activity in the left posterior STG for all three languages. Additionally, activation patterns for later-acquired languages were similar to that of early acquired languages. This suggests that in terms of functional activity, language experiences early on in life can exert a persistent influence beyond childhood, where the processing of subsequent languages depends on networks that were formed for the first language.

The general consensus of these three studies show that the multilingual's languages are processed via highly similar brain regions and networks, with the later-learned languages appearing to recruit additional regions. This view coincides with what has previously been discovered in bilinguals where late L2 learners activate a wider set of regions for their non-native language (Roberts et al., 2018; Hernandez et al., 2007).

6.2 LANGUAGE PROCESSING MODULATED BY PROFICIENCY

Apart from AoA, proficiency has also been a notable factor in language processing, exerting its effects on the way languages are organised in the brain. One of the earliest studies that sought to examine the neural activity elicited by the various languages that a multilingual speaks included both AoA and proficiency as potential modulators (Briellman et al., 2004). Six quadrilinguals of English, German, French, Italian, and Spanish took part in a noun-verb generation task in their four languages while being scanned and completed three measures of language proficiency (COWAT). Through regions of interest analysis, the task was shown to activate classic language-related brain regions across the different languages such as the IFG, anterior cingulate STG and angular gyrus. Four of the participants who had two languages with "good" proficiency and two others with "poor" proficiency had higher activation volumes for languages they are less proficient in and lower activity for languages they are more proficient in. The other two participants who had three "good" proficiency languages and one "poor" had similar neural activity for their different languages. The authors did not find significant relationships between AoA and activity levels, but found that the lower the proficiency, the greater the activation. Languages with the lowest proficiency level were

correlated with the amount of cortical activation, highlighting an explicit impact of language proficiency. Briellman and colleagues did not identify any influence of the age of language acquisition on functional activation. This coincides with the hypothesis of neural efficiency where expertise correlates negatively with the amount of functional activation as the task becomes more automatized (Bernardi et al., 2013; Gobel, Parrish, & Reber, 2011; Milton et al., 2007).

While picture naming elicits activity in regions of the brain involved in perception, semantics, and language, performing this task in different language proficiencies seem to activate different areas. For instance, picture naming in a language that a multilingual is highly proficient in is related to greater activity in the right PFC (Videsott et al., 2010). More specifically, the right anterior and dorsolateral prefrontal regions exhibited greater activation in a group of native Ladin-Italian-English speakers when they used fluent Ladin and Italian as compared to less fluent English. On the other hand, the language that they are least proficient in (English) activated the left IFG and the cerebellum more than did Ladin. English also activated the cerebellum more than did Italian. The variability of IFG activation was previously found to correspond with proficiency levels and the age of language acquisition instead of the variability between one's languages. The stronger influence of proficiency and AoA on IFG activation stems from its proposed function in managing conflicts, behaviour control and executive function (Abutalebi and Green, 2007). Furthermore, with naming accuracy as a proxy for proficiency, increasing activity in the right PFC correlated with naming accuracy in English and Italian, but not in Ladin. These results highlight the role that the right PFC plays in the mechanisms associated with proficiency, regardless of the number and type of languages. The researchers argue that because the functional differences found go beyond the typical language-related regions, and into regions implicated in domain-general cognitive control, using different languages do not just have different language representations but also different processing demands.

The influence of proficiency was also identified in a longitudinal study of five multilinguals acquiring Russian as a second or third language (Andrews et al., 2013). These participants were scanned during auditory comprehension and reading at three time points across a year. As their proficiency in Russian increased, as measured through standardised language proficiency exams, the average activation level across 12 regions of interest that are typically involved in sentence comprehension tasks also exhibited significant changes. On the other hand, such changes were not observed for English, which was a language that they have already acquired. This pattern of increased activity with increasing L2/L3 proficiency appears to be incongruent with the existing literature on bilinguals. However, this might be because these multilinguals are at the early stages of language acquisition in adulthood, where they may not have achieved automated processing (Van Hell & Tanner, 2012; Tzelgov & Kadosh, 2009; Segalowitz & Hulstijn, 2005).

6.3 POLYGLOTTAL NATIVE LANGUAGE PROCESSING

This review on multilingualism will not be complete without a glimpse of a subset of multilinguals known as polyglots who not only acquired multiple languages beyond childhood but are competent in them. To our knowledge, there has only been one study on language processing in the polyglottal brain. This unique study consists of 17 polyglots who speak at least five languages with advanced proficiency in at least two languages. Jouravlev and colleagues (2019) compared native language processing between polyglots and monolingual controls using fMRI. Polyglots appear to recruit fewer resources when engaged in sentence reading, exhibiting reduced activity within the language network of the left fronto-temporal lobule. As compared to monolinguals, polyglots also showed decreased left-lateralisation for language due to reduced activation in the left hemisphere. The researchers interpreted this as an indication of a small but more efficient organisation and management of language as a result of their extensive acquisition and use of languages. While there was a group difference in language processing patterns, they did not differ in high-level control networks like the multiple demand network and the DMN. This was interpreted as a limited effect of polyglotism beyond language networks in the brain. It is intriguing to notice how this set of findings do not match up with previous resting-state fMRI studies involving bilinguals and simultaneous interpreters, which have generally reported more distributed functional connectivity (Becker et al., 2016; Grady et al., 2015; Luk et al., 2011). Perhaps if we consider polyglots as having even more extensive language experiences than bilinguals and multilinguals who rely on extreme language control for a living, their streamlined functional activity may give us a hint of the nature of adaptations that may emerge with the further mastery of more languages.

7.0 CONCLUSION AND FUTURE DIRECTIONS

In conclusion, by toggling amongst three or more languages, multilinguals have increased opportunities for language switching, and correspondingly face greater demands on cognitive control as compared to bilinguals. This has translated into both structural and functional adaptations associated with controlling and processing an additional language. While the literature at the stage is new and small, making it a challenge to form conclusive interpretations, it does reveal some interesting trends that seem congruent with the bilingualism literature. Language processing appears to require highly overlapping regions, irrespective of the number of languages acquired. Like bilinguals, language and domain-general cognitive control in multilinguals share certain mechanisms, and factors that contributed towards the bilingualism effect (i.e., AoA, proficiency) appear to also impact on adaptations arising from multilingualism. Furthermore, although we cannot concretely describe how multilingualism diverges from bilingualism as hardly any of the studies have directly compared between these two populations, many of the additional adaptations that were identified (i.e., subcortical changes) can be accounted for by frameworks such as the

DRM and BAPSS model which were formulated based on the evidence from bilingualism research. Overall, the pattern of changes that emerged from these seem to reflect the remarkable neuroplasticity of the multilingual brain that allows it to continually reorganise to achieve and maintain efficiency.

Future research could further test hypotheses and models that were created for bilingualism research on multilingual populations. Examples of potential next steps include recruiting multilinguals who are clearly defined with regards to the number of languages they use (i.e., monolinguals vs. bilinguals vs. trilinguals), and conducting longitudinal studies which examine the structural adaptations of cortical and subcortical GM, WM connectivity and functional activation patterns while obtaining behavioural task measures. It would also be important to tease apart experience-based factors such as the AoA, proficiency, linguistic properties, context, and duration of language use to circumvent the issue of confounds. As the literature grows to incorporate more facets of multilingualism, different indices need to be considered in tandem so as to obtain a clearer image of how they all interact with and inform one another.

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