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Bilingualism and brain structure: insights from healthy ageing and progressive neurodegenerative diseases

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Bilingualism and brain structure: insights from healthy ageing and progressive neurodegenerative diseases

Running head: Bilingualism and brain structure

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Abstract

The study of the effects of bilingualism on brain structure has gained significant traction in the last decade, naturally following from the pioneering work by Ellen Bialystok and others on the effects of bilingualism on cognition. However, and despite the general interest and enthusiasm about the related evidence, the field of bilingualism-induced structural brain plasticity remains young and relatively unexplored, while it has been largely limited to young and healthy populations. This chapter revisits and reviews the evidence about bilingualism-induced neuroplasticity, and the contemporary theories that provide explanations to the available evidence, with a particular focus on the ageing and patient bilingual brain. Specifically, a full account of the reported effects on healthy ageing bilinguals is provided, followed by the limited findings from diseases that cause progressive brain decline, such as mild cognitive impairment, Alzheimer's and Huntington's diseases, epilepsy and multiple sclerosis. The chapter concludes with some suggestions for future directions for the field.

1. Bilingualism and brain structure: evidence and theories

a. The influence of Ellen in the field, and a personal anecdote

This chapter focuses on evidence showing how the experience of learning and using additional languages affects the structure of the brain, in other words on bilingualism-induced structural neuroplasticity. It is only appropriate this chapter features in this book in honour of Ellen Bialystok, as she has been one of the major influences on, and driving forces of, the field. Indeed, it was only a matter of time before Ellen's empirical work and theoretical suggestions on the effects of bilingualism on cognition, especially in ageing populations, would lead to questions about exactly happens to the brain networks that underlie these abilities. Ellen was part of some of the pioneering studies looking at relevant matters in ageing, both in healthy participants (Luk et al., 2011) and in patients with Alzheimer's Disease (Schweizer et al., 2012), which largely kickstarted the field; moreover, her research group recently put forward one of the major models describing bilingualism-induced functional and structural neuroplasticity (Grundy et al., 2017), and she is still actively involved in related projects and high-quality publications (Anderson et al., 2018; DeLuca, Rothman, Bialystok, et al., 2019).

Our own acquaintance and subsequent collaboration dates back to May 2015, when Ellen gave the first Albert Wolters Public Lecture at the University of Reading, the place where I would get my first permanent academic position a few months later. I was really excited to meet Ellen in person, as my own paper on bilingualism and white matter had just come out; so excited that I inadvertently challenged some of her claims in a rather crude way in front of the audience in the Q&A session of that major talk! Thankfully, she understood that my intentions were good, which is also proven by our ongoing collaboration, which is still holding strong, and which I am grateful of, and honoured by.

b. Bilingualism and brain restructuring: what we know

The study on the effects of bilingualism on brain structure is a relatively young field, with the first study dating to 2004, around the same time as when Ellen's work on the effects of bilingualism on adult cognition came out (Bialystok et al., 2004). That was the seminal paper by Mechelli and colleagues (2004), which reported that the age of acquisition of, and proficiency level in, a second language predicted grey matter density in a region in the left inferior parietal cortex. This initial finding was followed by several cross-sectional studies comparing the brain structure of bilinguals to monolinguals, which revealed greater grey matter tissue (measured in various ways, such as volume, thickness, density, surface area extent) in a range of cortical regions, albeit with limited replicability between studies (for a comprehensive overview of the available evidence, see Pliatsikas, 2019). For example, some studies reported effects in regions related to cognitive control, such as the anterior cingulate gyrus (Felton et al., 2017), whereas others in regions related to language acquisition and processing, including frontal, temporal and parietal regions (Grogan et al., 2012; Olulade et al., 2016; Ressel et al., 2012). Perhaps even more convincing evidence for the effects of bilingualism on the structure of the brain has been provided from longitudinal studies that have shown grey matter increases over time as a result of language training in largely the same regions reported in cross-sectional studies (Hosoda et al., 2013; Mårtensson et al., 2012; Stein et al., 2012).

An interesting observation in the literature has been that, when effects in subcortical structures are reported, they are rarely accompanied by effects in the cerebral cortex. Indeed, a handful of studies have reported several subcortical structures to change in shape and/or volume as a result of being a bilingual. These have most typically included the caudate nucleus, the putamen, the globus pallidus and the thalamus (Burgaleta et al., 2016; DeLuca, Rothman, & Pliatsikas, 2019; Pliatsikas et al., 2017), regions that have all been linked to language control, including articulatory control (Abutalebi & Green, 2016). Some limited effects of bilingualism have also been reported on the structure of the cerebellum (Burgaleta et al., 2016; DeLuca,

Rothman, & Pliatsikas, 2019; Filippi et al., 2011; Pliatsikas et al., 2014), a structure also implicated in language control, but with some additional linguistic functionality related to grammatical and phonological processing (De Smet et al., 2013). A closer inspection to the literature reveals that the bilinguals tested in these studies tend to be more experienced users of both languages, e.g. simultaneous and/or lifelong bilinguals, or bilinguals with substantial immersion in a country where their second language (L2) is spoken; in contrast, cortical effects are usually reported in less experienced bilinguals, including individuals with limited immersion in a country where their L2 is spoken, or those embarking on language training studies.

Turning to white matter, although a few studies report significant effects on the microstructure of several white matter tracts, these effects also tend to be reported in more experienced bilinguals compared to monolinguals. Indeed, several white matter tracts have been shown to have higher integrity in bilinguals, measured in terms of reduced water diffusivity, which in turn is an indicator of the availability of myelin in the tract, in that the more the myelin the higher the integrity. Affected tracts include those implicated in language (syntactic, semantic, phonological) processing, such as the superior and interior longitudinal fasciculi (SLF and ILF), the inferior fronto-occipital fasciculus (IFOF), the arcuate fasciculus and the uncinate fasciculus (AF, UF), as well as tracts related to cognitive control, including the corpus callosum (CC), forceps minor and anterior thalamic radiation (ATR) (Felton et al., 2017; Hämäläinen et al., 2017; Pliatsikas et al., 2015; Rossi et al., 2017). The link between white matter microstructure and bilingual experiences is further corroborated by studies that show that measures of white matter diffusivity are directly predicted by measures such as L2 age of acquisition or immersion in L2-speaking environments (DeLuca, Rothman, Bialystok, et al., 2019; Nichols & Joanisse, 2016).

c. *Explaining bilingualism-induced neuroplasticity as an effect of experiences: theoretical proposals*

The observation that additional language learning and control restructures the brain might appear intriguing but is hardly novel if viewed via a perspective of learning and skill acquisition. Indeed, the reported findings suggest that bi-/multilingualism is on par with other types of long-term experiences that lead to significant structural adaptations during the acquisition and maintenance of a new skill, such as juggling, use of novel tools, navigation etc. (Draganski et al., 2004; Maguire et al., 2000; Quallo et al., 2009; Taubert et al., 2010). This experience-based neuroplasticity is not random but appears to specifically target brain regions and tracts related to the acquisition of the particular skill. Several interpretations have been proposed for the mechanisms which underlie the observed structural adaptations in the brain. With respect to grey matter, the Expansion- Partial renormalisation Hypothesis (EPH) (Lövdén et al., 2013) proposes that skill acquisition is marked by transient local expansion of the implicated regions, which over time return to baseline. According to the EPH, the expansion signifies an initial increase in the pool of local connections by means of development of new dendritic spines within the implicated area; this is in order for the most efficient circuitry to be identified and take over the newly learnt skill. This is followed by a slow process of pruning of older and idle spines, eventually leading to the gradual disappearance of the initial expansion, while the newly-formed networks are stabilised over time and with practice. With respect to white matter, the observed adaptations relate to changes in the amount of myelin in implicated tracts, with increases in myelin usually interpreted as optimisation of neural communication. Increases in myelin can manifest in several ways, one of the most common and important being increased axonal myelination, i.e. “reinforcement” of the myelin around the axon. Importantly, these increases can be driven by several mechanisms; while myelination is regulated by how active the axon is (Ishibashi et al., 2006), it also promotes efficient

connectivity between brain regions, and is itself regulated by experience (Zatorre et al., 2013). It appears then that acquisition of skills that require coordination of several brain regions leads to increased communication needs between these regions; these needs are addressed with increased amounts of myelin in the implicated tracts, which leads to more efficient communication, and this process might be subject to how frequently and efficiently newly learnt skill is applied.

Bilingualism is one of those experiences that fit the above description and has been shown to induce neuroplasticity. Not only bilingualism requires acquisition of an additional language system (including phonology, lexico-semantics and grammar) on top of an already known and used language, at least in cases of sequential bilingualism, it also assumes constant control between the two systems for production and comprehension, even in simultaneous acquirers of two languages. Based on these observations, bilingualism would be expected to affect the structure of regions underlying language processing and control, both cortical and subcortical, but also of the white matter tracts that connect these regions, in order to achieve efficient processing. Indeed, the reported neuroplastic effects of bilingualism are most commonly found in regions underlying these processes, as becomes apparent from the above literature review.

A detailed review of the neuroplastic effects of bilingualism on the brain, and the proposed mechanisms that underlie them, is beyond the scope of this paper (for detailed reviews, see Hayakawa & Marian, 2019; Pliatsikas, 2019). What is of particular importance are the theoretical interpretations of this bilingualism-induced neuroplasticity, the common denominator which is that these effects are a direct consequence of, and can predicted by, the experiences of the bilingual. For example, Li, Legault and Litcofsky (2014) suggested that the location and extent of neuroplastic adaptations in the bilingual brain might depend on three main factors: the *timing* of L2 learning, the *nature* (or type) of the L2 input, and the *extent* (or intensity) of the L2 input. Similar suggestions were put forward by Abutalebi and Green (2016)

who proposed that structural adaptations rely on the type of context in which the languages are spoken, with contexts with increased interactional needs heavily engaging the language control networks, and as a result leading to more widespread structural adaptations of the same networks. Neuroemergentist approaches have similarly argued that experience is central to neuroplastic adaptations in language control networks, though they also allow for an interplay between environmental and genetic predictors (Hernandez et al., 2015, 2018). More recent approaches have argued for the dynamic and transient nature of bilingualism-induced neuroplasticity, and attempted to describe the trajectory of these effects: for example, in their Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model, Grundy, Anderson and Bialystok (2017) suggested that, with increased bilingual experience, the processing weight related to language control shifts from anterior cortical structures to more posterior ones, as well as to subcortical nuclei and the cerebellum; similarly, experienced bilinguals are less likely to show evidence for structural effects in more anterior regions of the brain. Similarly, the more recent Dynamic Restructuring Model (DRM) (Pliatsikas, 2020) followed from the EPH (Lövdén et al., 2013) to argue that the effects of bilingualism on brain structure are similar to those induced by the acquisition of any other skill, including motor skills, are dynamic, and they pertain to the particular demands imposed by second language acquisition, processing and control. The DRM, which is to a great extent complimentary to the BAPSS model, argues that bilingualism-induced neuroplasticity dynamically cycles through stages, with the various available studies capturing different windows of this dynamic process. Specifically, the DRM proposes that the initial stages of L2 learning induce local grey matter increases related to lexical, phonological and grammatical acquisition; with greater experience, these initial effects gradually renormalize and are replaced by subcortical and cerebellar adaptations and white matter reinforcement as a result of progressively more efficient language control in experienced users of more than one language. This prediction has been corroborated more recently by

evidence showing experience-based modulations in metabolic processes underlying bilingualism-induced neuroplasticity in the basal ganglia (Pliatsikas et al., 2021).

2. Bilingualism and brain structure in healthy ageing

The patterns proposed by the DRM and BAPSS models would lead to well-described predictions on the brain structure of older and experienced bilinguals: indeed, it can easily be predicted that lifelong bilinguals would show enhanced white matter structure compared to age-matched monolinguals, and particularly in posterior regions of the brain. Similarly, the proposed shift from anterior to posterior and subcortical structures as an effect of bilingualism would mean that the same groups would have more tissue in their basal ganglia and the cerebellum, but limited differences (if any) in the cerebral cortex, especially the anterior parts of it, when compared to age-matched monolinguals. However, another important factor needs to be taken into account when studying older bilinguals, and this is the specific effects of *ageing* on these structures, including whether they are independent to, and interact with, any effects of bilingualism (see also Pliatsikas et al., 2021). Indeed, it has been suggested that long-term accumulation of white or grey matter tissue in regions related to language acquisition and control can lead to increased resilience of these regions to age-related decline. Perani and Abutalebi (2015) called this mechanism *neural reserve*, and argued that this is one of two mechanisms (the other one being *neural compensation*, i.e. effective use of spared tissue in the face of severe neurodegeneration), that underline and characterise the cognitive abilities of ageing bilinguals, including the proposed bilinguals advantages in cognition in healthy bilinguals (Bialystok et al., 2004) and the reported delays in the expression of dementia symptoms in bilingual patients with Alzheimer's Disease (AD) (Alladi et al., 2013; Woumans et al., 2014).

Indeed, viewing the effects of long-term bilingualism-induced neuroplasticity as contributors to neural reserves may help interpret the available structural evidence from older bilinguals, which only partially corresponds to the general predictions of the DRM and BAPSS models. With respect to white matter, Luk, Bialystok, Craik, & Grady (2011) showed greater white matter integrity in 70-year old lifelong bilinguals compared to monolinguals in several white matter tracts, including the CC, the bilateral SLF and the right IFOF; however, only some of these effects were reported in more posterior portions of these tracts. Similarly, Olsen and colleagues (2015) compared 70-year old lifelong bilinguals and monolinguals and reported greater white matter volume in the frontal lobe bilaterally, and the same effect only approached significance in the temporal lobe, but not in the parietal or occipital lobes. Moreover, Anderson and colleagues (2018) compared two carefully matched samples of 74-year old lifelong bilinguals and monolinguals and reported greater integrity for bilinguals in an anterior portion of the left SLF. However, and perhaps counter-intuitively, Gold, Johnson, & Powell (2013) reported *reduced* white matter integrity in 64-year old lifelong bilinguals compared to monolinguals in a series of tracts bilaterally, including the ILF, the IFOF, the CC and the fornix; nevertheless, the two groups did not differ in terms of their cognitive abilities, despite the more seriously declined bilingual brains.

With respect to grey matter, there is more available evidence, which again does not appear fully compatible with the predictions of the BAPSS and DRM models. Specifically, although a few studies do not show any significant differences in terms of grey matter volume between lifelong bilinguals and monolinguals (Borsa et al., 2018; Gold, Johnson, et al., 2013; Gold, Kim, et al., 2013; Olsen et al., 2015; Prehn et al., 2018), a finding that would satisfy the predictions of the DRM, at least as far as the cerebral cortex is concerned, the majority of the available studies do show effects, and they do so in a range of regions. For example, greater grey matter volume has been reported in bilinguals compared to monolinguals in their early

60s in regions such as the left inferior temporal gyrus (Abutalebi et al., 2014), the left inferior frontal gyrus (Heim et al., 2019), the left anterior cingulate cortex (Abutalebi, Guidi, et al., 2015; Del Maschio et al., 2018), the right hippocampus (Voits, Robson, et al., 2020) and the bilateral inferior parietal lobule (Abutalebi, Canini, et al., 2015; Del Maschio et al., 2018; Heim et al., 2019), as well as in the left insula and anterior temporal lobe in slightly younger bilinguals vs monolinguals (L. Li et al., 2017). Importantly, in several of the above studies the effects of ageing appeared to differ between bilinguals and monolinguals, with steeper age-related declines for monolinguals in regions such as the anterior temporal lobe, the inferior frontal gyrus, the insula, the right inferior parietal lobule and the hippocampus and amygdala (Abutalebi et al., 2014; Abutalebi, Canini, et al., 2015; Borsa et al., 2018; L. Li et al., 2017; Olsen et al., 2015).

From the available findings on healthy ageing bilinguals a main observation can be made: The affected regions and tracts in older bilinguals appear to overlap very well with those reported in younger bilinguals, and they are all closely related to language processing and control. What clearly differs between younger and older adults is the *pattern* of these effects, namely the fact that they have been reported for both cortical grey matter and white matter of older, and presumably long-term and experienced, bilinguals. It is therefore possible that a different mechanism underlies these effects in older age, and this can indeed be a neural reserve as defined by Perani and Abutalebi (2015) . In this view, the reported greater amounts of tissue in ageing bilinguals compared to monolinguals might be more appropriately viewed as *steeper age-related structural brain decline* in the monolingual group; in other words, the reported effects do not point towards *more* tissue for bilinguals, but towards *less* tissue for monolinguals (but note that this pattern may be inverted in much later life in some regions (Heim et al., 2019)). It is therefore worth examining whether and how the neural reserve that is brought

about by bilingualism affects the expression and progression of AD and its prodrome condition, mild cognitive impairment, at the level of brain structure.

3. Bilingualism and brain structure in patient populations

a. Mild cognitive impairment and Alzheimer's Disease

The effects of bilingualism on brain function and structure in patients diagnosed with dementia, and how they translate into effects on cognition, have been the subject of vivid interest in recent years (for reviews, see Gold, 2016; Kim et al., 2019). This section turns to the specific evidence on brain structure in bilinguals diagnosed with Mild Cognitive Impairment (MCI) and AD, how it differs to that of monolinguals with similar diagnosis, and whether the observed patterns point towards a neural compensation mechanism as described by Perani and Abutalebi (2015).

MCI is condition characterised by declining cognitive abilities but limited or no impairment in how the patient functions in everyday life; importantly, patients with MCI are expected to convert to Alzheimer's disease within 2-3 years post-diagnosis (which might actually vary between bilinguals and monolinguals; see Berkes et al., 2020). If that is the case, it is interesting to see whether and how the bilingual brain "utilises" the proposed accumulated neural reserve, and how these effects carry over to the AD stage. The handful of available studies have pointed towards greater preservation of the brain in bilingual patients with MCI, arguing indeed for neural reserve that has accommodated over the lifespan as a result of bilingualism. For example, Duncan and colleagues (2018) compared 74 year old multilingual and monolingual MCI patients matched on clinical severity and cognitive functioning, and reported better preserved grey matter in the right IFG, right ventromedial prefrontal cortex, right cerebellum and bilateral hippocampus. In terms of white matter, Marin-Marin and

colleagues (2020) compared active and passive bilingual MCI patients that were matched in terms of the MCI severity and their cognitive abilities. They reported higher white matter integrity in the parahipocampal cingulum and the uncinate fasciculus, and lower integrity in the fornix, tracts that are relevant to memory retrieval, for the active group versus the passive one. The authors explained this pattern as a compensatory mechanism, in that a compromised fornix is compensated by a reinforced parahippocampal cingulum, which would also explain why the two groups did not differ in terms of their performance in the cognitive tests. Similarly, the greater integrity in the UF might be explained as the outcome of long-term bilingualism, as it has been reported in healthy bilingual adults (Luk et al., 2011). More recently, Costumero and colleagues (2020) reported overall *smaller* parenchymal (i.e. combined grey and white matter) volume in bilingual MCI patients compared to monolingual patients otherwise matched in terms of their cognitive and language abilities. A subsequent region of interest analysis revealed that these effects were more prominent in the right SMG and the left lingual gyrus. The findings from the latter study were interpreted as evidence for *cognitive reserve* in the bilingual group, i.e. more efficient brain function in the face of tissue loss, further supporting the idea of a neural compensation mechanism (see also Gold, Johnson, et al., 2013, for similar suggestions in healthy bilinguals). The same patients were also tested again after seven months, and it was revealed that the loss of overall parenchymal volume was *slower* for bilinguals in this period compared to monolinguals, pointing towards a neural reserve this time. Region of interest analyses showed that this effect was particularly prominent in the right cingulate gyrus, right putamen, right caudate, right hippocampus, and left fusiform gyrus.

Similar to MCI, only a handful of studies have directly looked at the effects of bilingualism on brain structure of patients diagnosed with Alzheimer's Disease, and they both point towards neural compensation mechanisms. Specifically, in the earliest study on this subject, Schweizer and colleagues (2012) reported greater temporal lobe atrophy in a group of 77 year old bilingual

patients diagnosed with AD, compared to a group of monolingual patients that were matched on age, education and general cognitive performance. This finding was also interpreted as evidence for a cognitive reserve¸ i.e. more efficient recruitment of spared brain tissue in bilinguals, which corroborates suggestions that bilingualism might delay the expression of dementia symptoms by several years (Alladi et al., 2013). Recently, Smirnov and colleagues (2019) compared 72 year old bilingual patients with AD to age-matched bilingual healthy controls. They reported significant atrophy for the patient group in a series of temporal, parietal and frontal regions, the thickness of most of the affected regions correlating to the patients naming abilities in both their languages. Notably, the patients also showed significant atrophy only in the rostral portion of the left ACC, but not the caudal one or in the right ACC. The authors interpreted this resistance to atrophy of the greater portion of the ACC as evidence of the increased burden placed on this structure as a result of atrophy in the other cortical regions; in other words, decline of memory systems brings about a cognitive reserve in bilingualism, which is delivered by regions related to cognitive control, like the ACC, and this process leads to better preservation of such regions. A more recent study was the first to report greater subcortical volumes in bilingual compared to monolingual AD patients, specifically in the bilateral ventral diencephalon and the brainstem (Raji et al., 2020). The authors interpreted this finding as evidence for increased resistance of subcortical structures to AD pathology. In sum, the limited literature on bilinguals with MCI and AD suggests that both mechanisms of neural reserve and neural compensation appear to come to play and potentially overlap, with neural reserve becoming more prominent at earlier stages of decline (esp. in MCI) and neural compensation emerging later (esp. after conversion to AD).

b. Other diseases

The small but promising literature on the effects of bilingualism on the declining brain, including in patients with MCI and AD, has very recently led to investigations on how the proposed neural and cognitive reserves might apply to other diseases that affect brain structure and function. The relevant literature is fully reviewed in a different chapter in this book (Voits, this volume; see also Voits, Pliatsikas, et al., 2020, for a detailed review), but it is worth briefly reviewing the available evidence on brain structure here. For example, Reyes and colleagues (2018) reported *lower* integrity in the uncinate fasciculus and the cingulum, both white matter tracts implicated in executive control, in a group of 35 year old patients with temporal lobe epilepsy, compared to both monolingual patients and healthy controls. Importantly, the bilingual patient group did not differ to the other groups in terms of their performance in tasks tapping on executive control, and this finding was interpreted as evidence for a cognitive reserve in bilinguals with temporal lobe epilepsy. Similarly, Martínez-Horta and colleagues (2019) studied early stage bilingual Huntington's disease patients, and reported a positive correlation between grey matter volume in the right IFG and a bilingualism index measuring the extent to which they used their two languages for equal amounts of time, in that the more balanced the use the higher their score in this index. More recently, Ehling and colleagues (2019) looked at the effects of language learning on brain structure in multiple sclerosis. Specifically, they introduced 37year old monolingual MS patients and age- and education-matched healthy controls in an 8-session English language training programme, and they scanned them twice, before and after the programme. Ehling et al. reported that the patient group had lower grey matter volume in the insula pre-training, but this difference did not affect their success in language learning, which was comparable to that of healthy controls. Interestingly, the patient group also showed significant post-training increases in the matter volume of the right hippocampus and the right putamen, regions related to language acquisition and control (Abutalebi & Green, 2016). The literature remains extremely limited, but at the

same time constitutes a potentially valuable avenue for the study of hoe bilingualism interacts with brain degeneration.

4. Future directions

This chapter has showcased that the study of the structure of the ageing and/or declining bilingual brain is still in its infancy, and the available theories of bilingualism-induced neuroplasticity might not be adequate to describe effects in the particular populations. Nevertheless, the limited available evidence remains compelling and warrants for further and more detail investigations in the ways that the experience of bilingualism might interact with brain decline. The relative scarcity of the appropriate populations, especially the patient ones, calls for carefully designed experiments that will better describe these effects. Several suggestions have been recently made on how the field should progress in general, and these are particularly applicable to ageing and patient populations (Pliatsikas et al., 2020): For example, longitudinal designs on the trajectory of brain decline are currently lacking in the bilingual literature, despite the fact that the bilingual brain has been shown to be plastic over time even in the absence of language training (DeLuca, Rothman, & Pliatsikas, 2019); moreover, if the observed adaptations on the bilingual brain are linked to the particular bilingual experiences, then approaches that take into account these experiences, and use them as predictors for structural changes, appear to be in order for ageing and patient populations, the same way they have been recently applied to younger bilingual adults (DeLuca, Rothman, Bialystok, et al., 2019; Hervais-Adelman et al., 2018). Finally, it is becoming clear that any claims for cognitive reserves that are caused by bilingualism cannot simply be based on behavioural evidence only, but should be viewed in conjunction with brain structure (and function) (see Bialystok, 2021). Future research along these lines will not only help update and improve theoretical models on the effects of bilingualism on the healthy and diseased brain but will also add to our knowledge

of how the multifaceted and cognitively challenging experience of bilingualism might bring about beneficial effects to the brain.

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