Northumbria Research Link

Cognitive and Brain Reserve in Bilinguals: Field Overview and Explanatory Mechanisms

Federico Gallo[a,b]*, Andriy Myachikov*[a,c]*, Yury Shtyrov*[a,d]*, Jubin Abutalebi*[b, e]

[a]*Centre for Cognition and Decision making, Institute for Cognitive Neuroscience, National Research University Higher School of Economics, Krivokolenniy Pereulok 3, Entrance 2,* ***101000,*** *Moscow, Russian Federation*

[b]*Centre for Neurolinguistics and Psycholinguistics (CNPL), Vita-Salute San Raffaele University, Via Olgettina 58, 20132, Milan, Italy*

[c]*Department of Psychology, Northumbria University, Northumberland Building, Newcastle upon Tyne, NE1 8ST, United Kingdom*

[d]*Center of Functionally Integrative Neuroscience (CFIN) Institute for Clinical Medicine Aarhus University / Aarhus University Hospital, Nørrebrogade 44, bldg 1A 8000, Aarhus, Denmark*

[e] *AcqVA Aurora Centre, The Arctic University of Norway, Tromsø, Norway*

Aknowledgements

The present study has been supported by Russian Science Foundation Grant (project №19-18-00550) to the National Research University Higher School of Economics.

Address correspondence to:

Dr. Jubin Abutalebi

Centre for Neurolinguistics and Psycholinguistics

Vita-Salute San Raffaele University

Via Olgettina 58, 20132 Milan, Italy

Email: abutalebi.jubin@hsr.it

Abstract

There is an ongoing debate on potential neuroprotective effects of bilingualism against cognitive decline during healthy aging. In this paper, we consider the neural and cognitive mechanisms through which these protective effects may operate. We review the evidence suggesting that bilingualism can act as a booster of neuroplasticity and/or as a brain protection mechanism providing effective compensation. Our main aim is to better define the linkage between reserve and lifetime bilingual experience and their effects of on the mind and brain.

We first illustrate the concept of reserve and contextualize existing results of bilingualism research within the reserve framework. Then, we discuss how bilingualism-induced enhancements of certain cognitive functions may constitute the basis for the neural underpinnings of reserve, i.e., brain reserve (BR) and cognitive reserve (CR). Finally, we discuss how the interplay between BR and CR fostered by multiple language use can provide protection to the aging brain.

Keywords: bilingualism; cognitive reserve; brain reserve; neuroplasticity

INTRODUCTION

Human life expectancy has been growing steadily in recent decades and this increase is likely to continue in the forthcoming years (Raftery et al., 2013; Kontis et al., 2017). This is resulting not only into obvious benefits of an extended life span but also in some adverse consequences including the increased risk of suffering from cognitive impairment and dementia, which presently constitute two of the major causes of decreased quality of life in the elderly (for a review, see Shearer et al., 2012). Along with a significant decrease in individuals' quality of life (patients' and caregivers'), increasing rates of dementia will result in healthcare resource demands that are projected to increasingly burden the governments of industrialized countries (Prince et al., 2016; Winblad et al., 2016; Livingston et al., 2017; Wimo et al., 2017). Concerning the purely economic consequences, recent studies show that senior citizens (aged 65 or above) in the United States constitute about 15% of the total population but that they also account for 34% of total health spending (Mitchell, 2016). A similar proportion of senior citizens in Canada account for an even larger healthcare spending share of 45% (Canadian Institute for Health Information, 2014). A study supported by the American National Institute of Health (Hurd et al., 2013) estimated a $215 billion expenditure only for dementia for 2010 alone just in the US, highlighting the enormous care and treatment needs imposed by the aging population.

In such a dramatic scenario and considering the non-existence of any effective pharmacological treatment, a search for factors that may act as a buffer against neurocognitive decline constitutes one of the central issues for the community today. Ideally, one should aim at identifying "ecological" interventions in order to prevent diseases related to aging. The meaning here attributed to the term "ecological" is two-folded: on the one hand, governments should be able to implement such interventions through lower-cost policies compared to current healthcare expenses; on the other hand, such interventions should be introduced gradually but precociously in

individuals' everyday life in order to build a lifelong "armour" against age-related decline in later life stages.

Several of these protective lifestyle factors have been characterized in the recent years, ranging from higher educational and occupational levels to mentally and physically stimulating leisure activities (Clare et al., 2017; Rouillard et al., 2017; Wang et al., 2017; for a review, see Cheng, 2016). A recently coined concept of *cognitive reserve* (see e.g. Stern, 2009) groups together all the aforementioned lifestyles and activities, which account for the interindividual differences observed in rates of cognitive decline. Cognitive Reserve has been defined as the discrepancy between the severity of brain damage or age-related deterioration and the resulting level of cognitive impairment (Stern, 2009). It may act as a mechanism of protection and compensation against cognitive decline, allowing individuals to better cope with age-related cognitive impairments (Stern, 2009; Bartrés-Faz et al., 2011; Steffener et al., 2011). Hence, the protective factors mentioned above would support "successful aging" by fostering an individual's cognitive reserve. For a comprehensive overview on cognitive reserve generally, we refer the reader to Stern's work (e.g. Stern 2009; 2013). The present work will discuss *bilingualism* as a factor that may promote cognitive reserve and hence lead to healthy aging.

Bilingualism and cognitive efficiency during healthy aging

As mentioned above, widespread evidence suggest that second language use promotes the maintenance of cognitive and neural efficiency during aging (*e.g.* Bialystok et al., 2004; Gold et al., 2013b; Abutalebi et al., 2015b; Bialystok et al., 2016; Del Maschio et al., 2018). An initial indication supporting the role of bilingualism as a booster of cognitive reserve stems from studies associating multiple language use to enhancements in executive control (EC) across the lifespan , despite an ongoing debate questioning such benefits (Antón et al., 2014; Duñabeitia et al., 2014; Gathercole et al., 2014; Paap et al., 2015). In general, the effects of bilingualism upon executive functioning have

been investigated by utilizing various cognitive control tasks and analyzing differences between bilingual and monolingual individuals in resulting processing indices such as response accuracy and reaction time (RT). Early evidence indicated that bilinguals across different age groups outperform monolinguals in such tasks (see Bialystok, 2017). However, many recent studies failed to replicate bilingual effects in similar tasks (for a review, see Paap et al., 2015).

These conflicting findings may be explained if one clearly identifies the individual cognitive components that make up 'cognitive control' or 'executive functions' (Costa et al., 2009). For instance, Costa and colleagues (2009) reported the presence or absence of bilingual effects depending on the precise percentage of congruent versus incongruent trials in a given experimental task. The authors found that bilingual effects were present when the experiment involved highly demanding trials with mixed congruency (e.g., 50% congruent and 50% incongruent trials), but when the experiment had only or mostly (e.g., >90%) trials of one type, bilingual advantages would disappear. This seminal work pointed to the significance of understanding cognitive control from the perspective of task demands linking the specific effects to cognitive 'monitoring'. An alternative account suggests that younger generations in the present digital era are exposed to a multitude of cognitively challenging activities inevitably boosting their executive functions. Hence, potential bilingual effects in younger participants may be largely masked by their generally stronger executive functioning. Older individuals, particularly those in retirement, are not exposed to so many cognitively challenging activities anymore; therefore, the effects of bilingualism upon their cognitive performance may be stronger (Valian, 2015). Importantly, the latter is only true if the speaker is still exposed to her second language and actively uses it (Abutalebi et al., 2015a).

Overall, while there is no agreement on the effects of bilingualism on boosting executive functions in younger subjects, the picture is much more conclusive when it comes to senior citizens. Indeed, there is now plenty of evidence reporting that older bilinguals do maintain better cognitive

efficiency, outperforming their monolingual peers on a number of different cognitive measures not strictly limited to EC tasks (Bialystok et al., 2004; Bialystok et al., 2008; Gold et al., 2013b; Bialystok et al., 2014; Abutalebi et al., 2015b; Estanga et al., 2017; Del Maschio et al., 2018, Incera & McLennan, 2018; Rosselli et al., 2019; Zunini et al., 2019), but extending to executive-related memory recall tasks (Wodniecka et al., 2010; Ljundberg et al., 2013; Rosselli et al., 2019), semantic memory (Arce Rentería et al., 2019) and general intelligence (Bak et al., 2014). This evidence is usually put forward to explain why bilingualism could act as a cognitive reserve (Perani & Abutalebi, 2015; Bialystok et al., 2016).

Neuroprotection during pathological aging

If bilingualism indeed fosters reserve in healthy aging individuals, then its effects should be arguably strongest when these individuals have to face the burdens of cognitive decline more acutely, for instance, in dementia. Many cross-sectional studies compare clinical differences between bilingual and monolingual seniors retrospectively. The landmark work by Bialystok and coworkers (2007) showed a striking 4-years of delay in the onset of dementia for bilinguals as compared to monolingual peers matched for gender, years of education, and socioeconomic status – all factors known to have an impact on the development of cognitive reserve. While these results were replicated in a separate study (Craik et al., 2010), findings from two subsequent investigations raised a concern that the bilingualism-induced protective effects may be limited to low-education bilinguals (Gollan et al., 2011) or to immigrant groups (Chertkow et al., 2010). It is in principle possible that the real key to the development of cognitive reserve in bilinguals would be the extra cognitive challenges linked to immigration, such as learning a second language (L2) later in life, living in an L2-dominant environment, as well as facing a multitude of other cognitive, cultural and economic adjustments. Moreover, immigration status could constitute a confounding factor *per se*, as differences in lifestyle, diet, ethnic background, education, and attitude to health may implicitly

differ between non-immigrant monolingual and immigrant bilingual populations. In such cases, differences in dementia's age of onset attributed to bilingualism may actually arise from differences in these and other confounding variables. A critical contribution to this debate came from a study by Alladi et al. (2013) conducted in India on a large sample of 648 individuals. The authors reported, in striking resemblance with Bialystok's group, a 4-5 years delay of dementia symptoms in native bilinguals compared to native monolinguals. The issue of education level was also addressed by conducting a separate analysis on illiterate participants showing an even larger delay of dementia onset for bilinguals (i.e., 6-years), confirming the assumption that the beneficial effects are stronger in low-educated individuals.

A study conducted in Belgium provided further corroborating evidence (Woumans et al., 2015) by comparing bilingual and monolingual Alzheimer's dementia (AD) patients matched for gender, education, occupational complexity, and cognitive impairment severity. Consistently with previous literature, clinical manifestation of AD appeared to be delayed by 4.6 years in bilingual patients. More recent studies confirmed the bilingualism effect on the delay of AD onset: Zheng et al. (2018) reported a 7-year delay in Cantonese/Mandarin bilinguals as compared to both Cantonese and Mandarin monolinguals, while Mendez et al. (2020) reported a 4-year delay in a sample of bilinguals with different L1s and English as an L2. Moreover, Perquin et al. (2013) examined 232 senior multilinguals in Luxembourg who were either classified as healthy or affected by mild cognitive impairment (MCI). The retrospective analysis showed that MCI incidence was inversely correlated to the number of languages spoken. These results were replicated in a follow-up study by Wilson et al (2014) who followed a cohort of 964 individuals over a 6-years period, observing the incidence of MCI with time. Bilinguals developed MCI to a significantly lesser extent than monolinguals. In a retrospective study conducted in India on a cohort of 115 MCI individuals, bilingualism has also been shown to delay the onset of MCI by 7.4 years (Ramakrishnan et al.,

2017). Finally, bilinguals have been reported to develop Parkinson's Desease-related cognitive decline 3 years later than their monolingual peers (Saidi, 2019).

Even in the face of increasing evidence that bilingualism may act as a booster of cogntive reserve during healthy and pathological aging, the exact cognitive and neural mechanisms behind the phenomenon remain uncertain. In the next section we will review some evidence on the neural basis of cognitive reserve in bilinguals and an attempt will be made to understand the potential neural mechanisms that may boost cognitive reserve in speakers of multiple languages.

BUILDING UP THE RESERVE: EFFECTS OF BILINGUALISM ON MIND AND BRAIN

Based on the evidence above, one may argue that speaking multiple languages leads to the development of cognitive reserve. At the same time, we know relatively little about how cognitive reserve is built up and what its underlying cognitive and neural mechanisms look like. It has been postulated (see Abutalebi & Green, 2016) that one of the key mechanisms is to be found in the increased cognitive challenge that bilinguals have to face on a daily basis. This challenge is linked to the fact that bilinguals, differently from their monolingual peers, have to control their two languages in order to avoid unwanted interferences (Green, 1998). In order to achieve this, the bilingual person uses a cognitive device labelled as "language control" that inhibits the language not in use and activates the one to be used. This language control system is neurally tightly linked to the more domain-general EC network (Abutalebi & Green, 2007). This control process comes inevitably with a cost; for this reason, bilingual subjects are typically slower in picture naming and various other *language related* tasks (e.g., Ivanova & Costa, 2008). Following this logic, by using the control device regularly, bilinguals develop the neural structures underlying domain-general EC in terms of either increasing grey and/or white matter related to the executive network or setting up more efficient brain connections. This, in turn, could eventually compensate for the loss of brain structure

and function seen in neurodegenerative disorders as we will also illustrate below. As to its neural underpinnings, bilingual language control is governed by a network comprising cortical and subcortical brain regions overlapping with the general-domain cognitive control network including the anterior cingulate cortex (ACC), the left and right prefrontal cortex (PFC), the left and right caudate nucleus, the inferior parietal lobule (IPL) bilaterally and the cerebellum (Green & Abutalebi, 2013), each with a peculiar role in controlling multiple language usage (see Calabria et al., 2018 for details).

Alternatively, and not strictly related to the EC network, one has also to consider that bilinguals, unlike monolinguals, have two lexicons linked to a somewhat common semantic system (Kroll & Stewart, 1994). Thus, another source of enhancement in bilinguals' reserve may reside in L2 learning *per se*. Bilingual users learn new L2 words by forming new connections with the existing L1 vocabulary and general semantic knowledge (Kroll & Stewart, 1994) and this learning process could potentially drive neuroplastic changes in the bilingual brain, as observed in imaging studies (*e.g.* Mechelli et al., 2004; Grogan et al., 2012; Abutalebi et al., 2014; Olsen et al., 2015). At the same time, areas responsible for the storage of lexical and semantic conceptual knowledge (such as the temporal lobes) are heavily affected in both healthy and pathological aging, showing marked signs of neurodegeneration (Fjell et al, 2009). Thanks to the enhanced neuroplastic changes induced by the formation and strengthening of lexico-semantic connections needed to encode items in multiple lexicons, these areas could potentially resist neural decline more efficiently. An example (see below for a more detailed discussion) is the temporal pole, a region suggested to store modality-nonspecific conceptual properties of objects (Lambon Ralph et al., 2008). This area is known to be strongly affected by neurodegeneration in Alzheimer's disease, AD (Fjell et al., 2009) and fronto-temporal dementia (FTD, also known as semantic dementia, SD; Mummery et al., 2000). Reduced brain atrophy in this region has been demonstrated in bilingual seniors (Abutalebi et al.,

2014) who appeared to maintain higher gray matter volumes (GMV) in the left temporal pole than their monolingual peers. Further confirming a role of new vocabulary learning in fostering neuroplastic changes in the bilingual brain, GMV levels were found to be positively associated with L2 naming scores (Abutalebi et al., 2014).

Brain reserve, neural reserve and neural compensation

If we take for granted that bilingualism can provide protection against age-related cognitive impairment by means of increased reserve, it should also be possible to identify its direct effects on neural structure and functioning. In general, two mechanisms have been advocated to describe the structural and functional underpinnings of the reserve phenomenon: *brain reserve* (BR) and *cognitive reserve* (CR; see Figure 1).

BR has been defined as an individual's capacity for resilience to deterioration of cerebral tissue associated with healthy or pathological brain aging. It may result from the interplay between different factors, some biological (e.g., brain size or neuronal and synaptic counts), others environmental (e.g., neuroplastic structural changes promoted by life experiences). Thus, BR could act as a *passive* buffer against cognitive decline, and is thus often included in what is labelled as "passive reserve models" (Katzman, 1993; Stern, 2009).

CR, instead, may be seen as an *active* mechanism of compensation against healthy and pathological age-related decline. In particular, it would allow individuals to better cope with age-related cognitive impairment in two separate, yet interrelated ways (see Figure 1). On the one hand, the key to neuroprotection would then be *neural reserve* (NR), defined as the variable degree of flexibility, capacity, and efficiency of an individual's brain networks (Stern, 2009; Bartrés-Faz et al., 2011; Steffener et al., 2011). Individuals with more efficient brain networks would need less effort to cope with increases in task demands: in the face of the same increment in task difficulty,

they would face the need to deploy their neural resources to a lesser extent to achieve optimal results (Steffener et al., 2011). Thus, in case of further rises in task-related cognitive load, they would maintain a "fuller warehouse" to draw from, and might therefore resist brain pathology or age-related decline to a greater extent. On the other hand, the protective effect would arise from an individual's level of *neural compensation* (NC), the ability to develop new approaches to address a task in the face of neural substrate deterioration, by deploying neural resources or cognitive strategiesalternative to those usually utilized by healthy individuals (Stern, 2009; Steffener et al., 2011).

<Figure 1 here>

Brain reserve in bilinguals

As mentioned above, the development of BR, fostered by lifelong experiential factors, begins well before senescence. Evidence supporting the role of bilingualism in fostering BR has indeed been reported both for young and for older adults. Several studies highlighted differences between bilinguals and monolinguals in gray and white matter density in areas involved in language/executive control and lexico-semantic processing (see Perani & Abutalebi, 2015; Bialystok et al., 2016), consistent with the aforementioned mechanisms underlying bilingual language processing, i.e., that language processing in bilinguals (unlike monolinguals) depends to a certain degree also on cognitive control processes and engages more the lexico-semantic pathways.

Regarding gray matter investigations in young individuals, Mechelli et al.'s (2004) pioneering study revealed significantly increased GMV in bilinguals' left inferior parietal lobule (IPL). Moreover, the amount of increase was positively correlated with L2 vocabulary knowledge and inversely correlated with age of L2 acquisition. Follow-up studies replicated findings regarding the IPL (Della Rosa et al., 2013; Olulade et al., 2015 Del Maschio et al., 2018; Heim et al, 2019) and

also revealed increased GMV in the brains of young bilingual adults in a number of other regions including the anterior cingulate cortex (ACC; Abutalebi et al., 2012; Del Maschio et al., 2018), cerebellum (Filippi et al., 2011; Pliatsikas et al., 2014), dorsolateral PFC (Stein et al., 2012; Olulade et al., 2015; Del Maschio et al., 2018), and Heschl's gyri (Ressel et al., 2012). Beside cortical areas, bilingualism has also been shown to affect the structure of the subcortical areas that are part of the executive and language control network. For instance, increased GMV was found in the left (Abutalebi et al., 2013; Pliatsikas et al., 2017) and right (Pliatsikas et al., 2017) putamen, the left caudate nucleus (Zou et al., 2012), the right thalamus (Pliatsikas et al., 2017), as well as bilaterally in the globus pallidus (Pliatsikas et al., 2017).

Results reporting increased GMV in adult bilinguals have been subsequently replicated in different samples of aging individuals, with senior bilinguals showing volumetric enhancements in the IPL (Abutalebi et al., 2015a; Del Maschio et al., 2018), bilateral ACC (Abutalebi et al., 2015b; Del Maschio et al., 2018), PFC (Del Maschio et al., 2018), temporal pole (Abutalebi et al., 2014, Olsen et al., 2015), and orbitofrontal cortex (Abutalebi et al., 2014). An interesting example is Abutalebi et al.'s 2014 study, in which senior bilinguals showed increased gray matter compared to age-matched monolinguals bilaterally in the temporal poles and the orbitofrontal cortex. Moreover, bilinguals were reported to suffer from overall brain aging effects to a lesser extent than monolingual counterparts. Noteworthy is also the finding that GMV of the temporal poles – areas related to lexical retrieval and semantics – were positively associated with increasing levels of L2 proficiency. In other words, bilinguals who mastered their second language best appeared to develop the greatest BR. Olsen et al. (2015) reported similar results in a cortical thickness study: confirming the finding that the process of learning an L2 *per se* induces neuroplastic changes in the bilingual brain, these authors found greater cortical thickness in the temporal pole of bilingual seniors, as compared to monolingual peers. Of note, the temporal poles, alongside the orbitofrontal cortex, are

well-known to be among the first cortical areas to suffer from brain atrophy during non-pathological aging (Kalpouzos et al., 2009). The neuroplastic changes induced by bilingualism in this area suggest how multiple language usage may delay the onset of cognitive decline. Moreover, another recent study (Del Maschio et al. 2018), conducted GMV comparisons on several language control network's areas, between both young and senior bilingual and monolingual groups. This investigation revealed increased GMV in the ACC, PFC, and IPL, bilaterally, in bilinguals. Such findings suggest that bilingualism would help to develop BR in the EC network throughout the lifespan, beginning from early life stages. Yet, neuroprotective effects of bilingualism-induced BR do not seem to be confined to healthy aging but may also be extended to brain pathologies. Indeed, GMV loss in IPL is known to be linked to mild cognitive impairment (MCI; Saykin et al., 2006; Apostolova et al., 2007) and early stages of dementia (McDonald et al., 2009). In this light, the findings of a lifelong build-up of enhanced BR in the IPL that span from bilingual children (Della Rosa et al., 2013) to young adults (Mechelli et al., 2004; Del Maschio et al., 2018) to seniors (Abutalebi et al., 2015a; Del Maschio et al., 2018) acquire even greater relevance.

The beneficial contribution of bilingualism to BR in senescence extends also to white matter tracts. In a study employing diffusion tensor imaging (DTI), Luk et al. (2011) analyzed fractional anisotropy (FA) values in senior bilingual and monolingual subjects to investigate white matter differences. The results showed higher levels of white matter preservation for the bilingual group in parts of the corpus callosum extending bilaterally into superior longitudinal fasciculus and to the right inferior fronto-occipital and uncinate fasciculi. As before, bilingualism appears to provide protection in brain areas that typically suffer from age-related deterioration (Pfefferbaum et al., 2005; Gunning-Dixon et al., 2009). Moreover, Olsen et al. (2015) reported higher frontal lobe white matter volumes in senior bilinguals as compared to age-matched monolinguals. Finally, Anderson et al. (2018) showed that senior bilinguals maintain higher structural integrity in the left superior

longitudinal fasciculus.

Put together, these findings suggest the route via which bilingualism may contribute to preventing healthy and pathological age-related decline, fostering the development of BR. As pointed out above, beside the *passive* protection provided by BR, the notion of CR comprises the beneficial effects that may be achieved through two different, yet interlinked, *active* neural mechanisms, NR and NC. Below, we review evidence suggesting that bilingualism may foster the development of CR in both ways.

Efficiency and flexibility: neural reserve in bilinguals

Similar to BR, NR also develops along the entire lifespan with evidence suggesting a role of bilingualism in fostering NR coming from different age groups, spanning from youth to senescence. Luk et al. (2010) administered a modified version of the Flanker task to young bilinguals and monolinguals. A NoGo trial condition, to which participants were instructed not to respond, was added to congruent and incongruent trials. These trials were introduced in order to distinguish between the suppression of interfering responses (as in standard Flanker's incongruent trials) and the general inhibition of any behavioral response. Both for the incongruent (interference suppression) and for the NoGo trials (response inhibition), bilinguals activated a diffuse network including bilateral regions of the inferior frontal and temporal cortices and subcortical regions. Monolinguals, instead, activated the network for NoGo trials only, activating a more circumscribed network when facing incongruent trials. The authors made two important conclusions based on these findings. First, they concluded that bilingualism leads to differential patterns of neural activation when encountering conflicting information. Second, they interpreted the recruitment of a common network for response inhibition and interference suppression as a sign of enhanced efficiency of bilinguals' EC function. At first glance, the activation of a more widespread network to support a cognitive function may appear as indicating lower, rather than higher, neural efficiency.

Nonetheless, one has to consider the bigger picture: while monolinguals showed the necessity to activate a second, differential network for the more demanding interference suppression, bilinguals, due to extensive training in such ability, seemed to recruit regions in the general attention control network, being able to process both kind of trials through a common network.

In another study using the Flanker task with young adults, Abutalebi et al. (2012) reported that bilinguals activated the ACC to a lesser extent than monolinguals, while outperforming them on the task thus showing a more efficient use of this structure to optimize behavioral performance. This result suggests that bilinguals' experience in resolving conflict can better "tune" their ACC for conflict monitoring. The study, which employed two runs of the Flanker task, provided further evidence confirming an enhanced flexibility of bilinguals' ACC: while behavioral conflict effect was significantly smaller in the second run for bilinguals, this was not the case for monolinguals. This pattern was also observable in fMRI data: besides activating the ACC to a lesser extent already in the first run, bilinguals showed a dramatic decrease in the signal in the ACC in the second run, while monolinguals did not. Similarly, Rodriguez-Pujadas et al. (2014) reported a more efficient use of the ACC by bilinguals, as compared to monolinguals, during a stop-signal task.

Before discussing the bilingualism-induced effects on NR in seniors, it is useful to briefly report the findings of a study carried out in children. In an event-related design study deploying a Stroop and a Simon task, Mohades et al. (2014) compared activation between simultaneous bilingual, successive early bilingual, and monolingual children. Increased activation in the ACC was found for both bilingual groups in the Stroop task in incongruent (i.e. those tapping on conflict resolution) versus congruent trials. In a similar fashion, in the incongruent versus congruent trials of the Simon task, bilingual children showed increased activation, compared to the monolinguals, in the left superior temporal gyrus, bilateral posterior cingulate gyrus, right middle frontal gyrus, and right caudate nucleus. Nonetheless, a more recent study utilizing the same Simon paradigm with

senior individuals (Ansaldo et al., 2015) reported that, during incongruent trials, bilinguals recruited the left inferior parietal lobule (IPL) while monolinguals preferentially recruited the right middle frontal gyrus. Whereas monolinguals relied on a standard inhibitory control region of the frontal lobe, known to be particularly vulnerable to age-related impairment, bilingual seniors activated brain regions not typically related to inhibitory control, possibly indicating enhanced resilience. Such pattern was indeed interpreted by the authors as a sign of enhanced NR, reflecting the highly efficient EC developed by lifelong bilinguals, whose experience allowed for optimal conflict resolution without the activation of the widespread network described for relatively inexpert bilingual children in Mohades et al. (2014). This interpretation is corroborated by the finding that senior monolinguals who lack such lifelong experience in resolving conflict activated instead parts of the same network that Mohades et al. (2014) found in children. Again, in a study deploying a nonverbal switching task, Gold et al., (2013b) reported reduced switch costs (brain activation for switch compared to non-switch trials) for senior bilinguals, as compared to monolingual peers, in the left DLPFC, VLPFC and ACC. Moreover, this activation pattern did not differ, for senior bilinguals, from that of young bilinguals and monolinguals. Finally, bilingualism has been shown to affect the functional connectivity of seniors' neural networks: for instance, a resting-state functional connectivity study by Grady et al. (2015) revealed that bilingual seniors, as compared to age-matched monolinguals, maintained stronger functional connectivity in the Default Mode- and Prefrontal Executive Control networks. A more recent study by De Frutos-Lucas et al. (2020) deploying magnetoencephalography (MEG) reported for bilingual seniors higher resting-state functional connectivity than age-matched monolinguals in 5 occipito-parietal clusters, whose functional connectivity is known to be particularly disrupted in AD (e.g. Nakamura et al., 2017; Yu, et al., 2017).

Taken together, the findings reviewed above indicate that extensive training may foster NR

in bilinguals, through enhancements of EC network's *efficiency* and *flexibility*. Such enhancements would, in turn, result in neuroprotection from age-related cognitive decline for bilingual users by allowing them to compensate for eventual decreases in their cognitive functioning during healthy or pathological aging.

Facing pathological aging: neural compensation in bilinguals

As follows from the definition of *neural compensation*, an individual with high levels of NC would still be able to maintain nearly normal cognitive functioning even in the face of brain atrophy and neurodegeneration. Existing literature offers examples of studies that deployed neuroimaging to investigate differences in NC between bilinguals and monolinguals, by comparing neural substrate integrity in groups matched for cognitive functioning, dementia severity or duration. The first such investigation was Schweizer et al.'s (2012) study, which utilized computer tomography to assess differences in brain atrophy between bilingual and monolingual AD patients, matched for education and disease severity. At comparable levels of cognitive impairment, bilinguals appeared to have significantly greater brain atrophy in areas typically affected by AD-related disruption, namely the temporal horn ratio (Zhang et al., 2008), third ventricle ratio and the radial width of the temporal horn (Frisoni et al., 2002a; Frisoni et al., 2002b). Given that the level of cognitive impairment was matched between the two linguistic groups, such results suggest that bilingual individuals had higher NC, allowing to compensate for the cerebral damage to a greater extent than monolinguals.

Similarly, Gold et al. (2013a), compared white matter integrity between senior bilinguals and monolinguals matched for performance levels on a range of cognitive tests, as well as for potentially confounding CR factors including education, socio-economic status (SES), and intelligence. Bilinguals showed lower white matter integrity in the corpus callosum, inferior longitudinal fasciculus, inferior fronto-occipital fasciculus, and the fornix. These white matter tracts are part of the brain's memory circuitry and are typically disrupted in AD and MCI (Stebbins & Murphy, 2009).

Given that the cognitive status was comparable between the two groups, the authors interpreted their findings as supporting the view that bilingualism promotes the development of cognitive reserve. Indeed, senior bilinguals were able to perform at a level comparable to that of monolinguals in spite of lower resources available, suggesting higher neural efficiency. This result may, at first glance, seem to contradict the abovementioned studies (i.e. Luk et al., 2011; Olsen et al., 2015; Anderson et al., 2018) showing better maintenance of white matter integrity in senior bilinguals as compared to monolinguals. However, we must consider that the samples of the abovementioned studies included healthy aging individuals, while Gold and colleagues' participants may have had a higher incidence of preclinical AD, as suggested by the specific white matter tracts showing reduced integrity in the bilingual sample. This may explain why, in this particular study, bilinguals showed reduced white matter integrity when compared to healthy monolinguals.

Similar results were reported in a recent study by Perani et al. (2017) utilizing fluorodeoxyglucose PET to investigate brain metabolism and neural connectivity in bilinguals and monolinguals with AD matched for disease duration and general cognitive functioning. The study revealed that cerebral hypometabolism was more severe in bilingual subjects suggesting higher levels of NC than monolinguals. Moreover, increased connectivity was found in the EC and default mode networks in bilinguals compared to monolinguals; these functional changes were positively correlated with the degree of lifelong bilingualism. Another study utilizing FDG PET (Kowoll et al., 2016) produced similar results: bilingual seniors diagnosed with MCI and probable AD showed significantly higher levels of glucose hypometabolism in frontotemporal and parietal regions and in the left cerebellum, compared to monolingual peers matched for age, gender and disease severity. Similar differences, denoting enhanced NC in bilingual individuals, were also found in the temporal and parietal cortices, structures typically involved in AD pathology. Finally, a recent study deploying a combination of cross-sectional and a longitudinal designs (Costumero et al., 2020) compared the

total amount of brain parenchyma (i.e. white matter + gray matter) in samples of MCI bilinguals and monolinguals matched for cognitive status. Bilinguals showed significantly lower parenchymal volumes, suggesting that they were able to successfully compensate for brain atrophy in order to reach levels of cognitive performance comparable with monolinguals. Additionally, the longitudinal analysis revealed that monolinguals lost more parenchyma and suffered more cognitive decline than bilinguals in a mean follow-up period of 7 months.

The studies reviewed above support the role of bilingualism in fostering CR development, in the form of enhanced NC, as bilinguals appear to be able to maintain levels of cognitive functioning comparable to monolinguals', even in the face of far more severe brain deterioration.

POSSIBLE MECHANISMS UNDERLYING BILINGUALISM-INDUCED RESERVE

One of the least studied aspects in this areas is how the bilingualism-induced BR and CR interplay throughout the lifespan to provide neuroprotection in later life stages. Del Maschio et al.'s (2018) study is particularly useful to shed light on this point. The authors deployed a Flanker task to assess EC in young and senior bilinguals, compared to young and senior monolingual controls. They also performed voxel-based morphometry (VBM) analysis in EC network's areas and conducted a joint behavioral-neuroimaging analysis to investigate how BR and CR interact to affect behavioral EC performance during aging. Their initial finding, consistent with previous literature (e.g., Bialystok et al., 2004; Gold et al., 2013b; Bialystok et al., 2014) revealed a behavioral EC advantage for bilingual seniors, but not for young adults, over their monolingual counterparts (see Valian, 2015, for a review on the issue). Furthermore, as already discussed, bilinguals in both age groups showed greater GMV in multiple EC brain areas, namely the ACC, PFC, and IPL bilaterally, thus showing that bilingualism fosters the development of BR from early life stages. Nonetheless, the most interesting results came from the conjunct behavioral-VBM analysis. In a pattern consistent across all the aforementioned regions, in which bilinguals showed enhanced BR compared to

monolinguals, bilingual seniors appeared not to rely on their neural EC substrate to optimize behavioral EC performance and outperform monolingual counterparts. In other words, senior bilinguals' performance was independent of the GMV decline and remained at optimal level even in the face of GMV reductions in the EC network areas, while senior monolinguals' performance dropped drastically with brain atrophy in such regions. The authors suggested that this result may reflect premorbid differences in cognitive strategies and brain networks recruited to perform EC tasks. Even if the scope of the VBM analysis did not allow an "online" investigation of the mechanisms underlying such phenomenon, the ensuing hypothesis was that lifelong bilingualism would help to develop BR by extensive training of EC network, which would in turn lead to enhancements in CR through increased network's efficiency and flexibility (i.e. NR) and thus to the development of different strategies to cope with age-related brain deterioration (i.e. NC). Similarly, a recent longitudinal investigation with senior bilinguals and monolinguals reported that bilingualism mitigated the semantic memory loss linked with enthorinal cortex thinning (Arce Rentería et al., 2019).

Some attempts have also been made at modeling the mechanisms through which the neuroprotective effect could develop and act. For instance, Grant et al. (2014) suggested that the mechanisms behind the beneficial effect may be understood in terms of the *posterior-to-anterior shift in aging* (PASA) model (Davis et al., 2007; Dennis & Cabeza, 2008). PASA argues that, in the face of age-related decrease in neural activity in posterior brain areas, older adults would increasingly rely on frontal regions in order to maintain optimal levels of behavioral performance. In the case of bilingualism, such goal would instead be achieved through the preservation of posterior areas and their connections with the frontal cortex. Bilinguals, due to their less expressed posterior deterioration, would experience less of the typical PASA shifting. This account is based on the results of studies above (see *"Brain reserve in bilinguals"* section) reporting increased GMV in

posterior regions such as the temporal pole and IPL (Abutalebi et al., 2014; 2015a) and enhanced frontal to posterior connectivity in bilingual seniors (Luk et al., 2011).

In similar fashion, Grundy et al. (2017) developed a model named *bilingual anterior to posterior and subcortical shift* (BAPSS), arguing that expert bilinguals would rely less on the recruitment of frontal and executive regions and more on the recruitment of posterior/subcortical regions to perform EC tasks, compared to monolinguals. The model follows five different types of findings emerging from bilingual research: (1) bilinguals show increased GMV in posterior and subcortical regions of the brain, compared to monolinguals (e.g. Abutalebi et al., 2013; Pliatsikas et al., 2014; Abutalebi et al., 2015a; Wei et al., 2015; Burgaleta et al., 2016; Pliatsikas et al., 2017); (2) bilinguals show greater white matter integrity than monolinguals (e.g. Coggins et al., 2004; Luk et al., 2011; Gold et al., 2013a; Felton et al., 2017); (3) bilinguals show less frontal activation than monolinguals with better or equivalent performance on EC tasks (e.g. Waldie et al., 2009; Abutalebi et al., 2012; Rodríguez-Pujadas et al., 2014), and (4) bilinguals show stronger functional connectivity between brain regions during EC task performance. Thus, bilinguals may be able to better distribute the effort, without tapping excessively into their frontal resources (Luk et al., 2010; Grady et al., 2015; Li et al., 2015; Costumero et al., 2015). Finally, (5) EEG studies show that bilinguals rely on earlier processing stages than monolinguals to achieve comparable levels of EC performance (Fernandez et al., 2013; Fernandez et al., 2014; Moreno et al., 2014; Sullivan et al., 2014; Barac et al., 2016). Following these findings, Grundy and colleagues argue that senior bilinguals are better able to shift from more demanding, late, top-down processing, to more automatic early processing during EC performance due to their lifelong experience in controlling two languages simultaneously. This framework may provide an explanation of the mechanisms underlying bilingualism's neuroprotective effect in aging: a lesser reliance on frontal regions and a stronger one on subcortical/posterior regions would allow bilinguals to maintain optimal cognitive

performance by experiencing less of the typical PASA shifting and maintaining more resources that can be deployed with increasing task requirements.

To conclude this section, it is worth to briefly discuss an explanation provided by Guzmán-Velez & Tranel (2015) that has, up to now, received relatively little attention. The noradrenergic theory of CR (Robertson, 2013) argues that factors known as enhancers of BR and CR would upregulate the noradrenergic system, in turn resulting in compensatory mechanisms (e.g., enhanced neurogenesis and synaptogenesis, increases in the production of brain-derived neurotrophic factor (BDNF), increased GMV and connectivity) and disease-modification mechanisms (e.g., reduced amyloid burden, plaque size and aggregation, anti-inflammatory processes, and rescue of cholinergic and dopaminergic cells). Bilingualism, among other factors promoting BR and CR, would constitute no exception, contributing to develop a bigger, more efficient and better-wired brain, capable of reorganizing itself to cope with age-related deterioration.

Future directions: resistance and resilience

A recently proposed account (Arenaza-Urquijo & Vemuri, 2018) attempts to reorganize the terminology in the field of cognitive aging by grouping the various sub-concepts of reserve and the concept of brain maintenance under a common umbrella (see Nyberg et al., 2012). This account proposes a single general distinction between the concepts of *resistance* and *resilience* to dementia. The concept of *resilience* (approximately overlapping with that of reserve) refers to an individual's ability to sustain a better-than-expected cognitive performance in relation to their degree of brain pathology. The concept of *resistance* (approximately overlapping with that of brain maintenance) refers to avoiding the appearance of brain pathology. *Resistance* is usually assessed by investigating the level of dementia biomarkers in an individual brain such as beta amyloid or tau protein, while *resilience* is assessed by investigating levels of cognitive performance associated with brain pathology or

levels of functional and structural neurodegeneration. As aforementioned, many studies seem to support the role of bilingualism in promoting *resilience* via better maintenance of gray and white matter structures, higher neural efficiency or flexibility, or better maintenance of cognitive ability in the face of neural deterioration. However , there is little research investigating the effects of bilingualism on *resistance* to age-related impairment. Nonetheless, one may argue that an indication of bilingualism's role in enhancing *resistance* may be the delay of AD onset observed in many studies as reported above. Moreover, a study directly investigating the effects of bilingualism directly on AD biomarkers (Estanga et al., 2017) reported a moderation effect of bilingualism between age and the cererebrospinal fluid (CSF) biomarkers of AD t-tau protein in a cohort of 278 individuals matched on genetic, sociodemographic and cognitive profiles. Moreover, bilingualism in this study was associated with better scores on different cognitive tasks and lower prevalence of preclinical AD and it appeared to mitigate the relationship between age and worsening of EC performance. These findings suggest that bilingualism may promote both *resilience* and *resistance* to dementia and age-related cognitive decline, in general. We believe that such key neurobiological aspects of the relationship between bilingualism and cognitive aging deserve more attention in future research.

CONCLUSIONS - THE SOCIO-ECONOMIC IMPACT OF BILINGUALISM

Preservation of a healthy neurocognitive function is becoming more and more important in the steadily aging world that we live in. Taken together, the findings reviewed in this paper suggest that bilingualism may foster the development of brain and cognitive reserve during the lifespan, thus pointing to bilingual experience as an important personal, educational, and societal factor that may mitigate cognitive decline during the aging process. As a result, bilingualism may play an important

role in improving the quality of life of older populations and reducing the burden on public health. Nevertheless, it is important to secure the practices that can ensure such effects in real life. A recent study using Cantonese-English bilinguals in Hong Kong showed that the neuroprotective effect against gray matter loss may be only present in individuals who keep using and practicing their L2 after retirement (Abutalebi et al., 2015a) suggesting that governments should develop policies aiming to help maintain the second language use in senior citizens. With the difficulty to develop effective pharmacological therapies mitigating the effects of cognitive decline, “ecological” solutions such as bilingualism and other factors inducing cognitive and brain reserve should be key in promoting healthy aging.

CONFLICT OF INTEREST DECLARATION

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

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

Abutalebi, J. (2008). Neural aspects of second language representation and language control. *Acta psychologica*, *128*(3), 466-478.

Abutalebi, J., & Chang-Smith, M. (2012). Second language representation in the brain. *The encyclopedia of applied linguistics*.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S.F., & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, 22, 2076–2086.

Abutalebi, J., Rosa, P. A. D., Castro Gonzaga, A. K., Keim, R., Costa, A., & Perani, D. (2013). The role of the left putamen in multilingual language production. *Brain and Language*, 125, 307–315.

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.

Abutalebi, J., Canini, M., Della Rosa, P. A., Green, D. W., & Weekes, B. S. (2015a). The neuroprotective effects of bilingualism upon the inferior parietal lobule: a structural neuroimaging study in aging Chinese bilinguals. Journal of Neurolinguistics, 33, 3-13.

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B.

S. (2015b). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia, 69*, 201-210.

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.

Anderson, J. A., Grundy, J. G., De Frutos, J., Barker, R. M., Grady, C., & Bialystok, E. (2018). Effects of bilingualism on white matter integrity in older adults. *Neuroimage*, *167*, 143-150.

Ansaldo, A. I., Ghazi-Saidi, L., & Adrover-Roig, D. (2015). Interference control in elderly bilinguals: Appearances can be misleading. *Journal of clinical and experimental neuropsychology*, *37*(5), 455-470.

Antón, E., Duñabeitia, J. A., Estévez, A., Hernández, J. A., Castillo, A., Fuentes, L. J., ... & Carreiras, M. (2014). Is there a bilingual advantage in the ANT task? Evidence from children. Frontiers in psychology, 5, 398.

Apostolova, L. G., Steiner, C. A., Akopyan, G. G., Dutton, R. A., Hayashi, K. M., Toga, A. W., ... & Thompson, P. M. (2007). Three-dimensional gray matter atrophy mapping in mild cognitive impairment and mild Alzheimer disease. Archives of neurology, 64(10), 1489-1495.

Arce Rentería, M., Casalletto, K., Tom, S., Pa, J., Harrati, A., Armstrong, N., ... & Zahodne, L. (2019). The Contributions of Active Spanish-English Bilingualism to Cognitive Reserve among Older Hispanic Adults Living in California. *Archives of Clinical Neuropsychology*, *34*(7), 1235-1235.

Arenaza-Urquijo, E. M., & Vemuri, P. (2018). Resistance vs resilience to Alzheimer disease: clarifying terminology for preclinical studies. *Neurology*, *90*, 695-703.

Bak, T. H., Nissan, J. J., Allerhand, M. M., & Deary, I. J. (2014). Does bilingualism influence cognitive aging?. *Annals of neurology*, *75*(6), 959-963.

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. *Child development*, *87*(4), 1277-1290.

Bartrés-Faz, D., & Arenaza-Urquijo, E. M. (2011). Structural and functional imaging correlates of cognitive and brain reserve hypotheses in healthy and pathological aging. *Brain topography*, *24*(3-4), 340.

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and aging*, *19*(2), 290.

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. Neuropsychologia, 45(2), 459-464.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. Journal of Experimental Psychology: Learning, memory, and cognition, 34(4), 859-873.

Bialystok, E., Poarch, G., Luo, L., & Craik, F. I. (2014). Effects of bilingualism and aging on executive function and working memory. Psychology and aging, 29(3), 696.

Bialystok, E., Abutalebi, J., Bak, T. H., Burke, D. M., & Kroll, J. F. (2016). Aging in two languages: Implications for public health. *Ageing research reviews*, 27, 56-60.

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

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.

Canadian Institute for Health Information. (2014). National Health Expenditure Trends, 1975 to 2014. https://www.cihi.ca/en/nhex_2014_report_en.pdf

Cheng, S. T. (2016). Cognitive reserve and the prevention of dementia: the role of physical and cognitive activities. *Current psychiatry reports*, *18*(9), 85.

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., & Bergman, H. (2010). Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: evidence from a bilingual community. *Alzheimer Disease & Associated Disorders*, *24*(2), 118-125.

Clare, L., Wu, Y. T., Teale, J. C., MacLeod, C., Matthews, F., Brayne, C., ... & CFAS-Wales Study Team. (2017). Potentially modifiable lifestyle factors, cognitive reserve, and cognitive function in later life: A cross-sectional study. *PLoS medicine,* 14(3), e1002259.

Coggins Iii, P. E., Kennedy, T. J., & Armstrong, T. A. (2004). Bilingual corpus callosum variability. *Brain and language*, *89*(1), 69-75.

Colome´, A. (2001). Lexical activation in bilinguals' speech production: Language-specific or language-independent? *Journal of Memory and Language*, 45, 721–736.

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.

Costumero, V., Marin-Marin, L., Calabria, M., Belloch, V., Escudero, J., Baquero, M., ... & Ávila, C. (2020). A cross-sectional and longitudinal study on the protective effect of bilingualism

against dementia using brain atrophy and cognitive measures. *Alzheimer's Research & Therapy*, *12*(1), 1-10.

Craik, F. I. M., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease: Bilingualism as a form of cognitive reserve. *Neurology*, *75*(19), 1726-1729.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin,J.T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K., Usui,K., Green, D. W., & Price, C. J. (2006). Language Control in the Bilingual Brain. *Science*, 312, 1537–1540.

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.

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.

Del Maschio, N., Sulpizio, S., Gallo, F., Fedeli, D., Weekes, B. S., & Abutalebi, J. (2018). Neuroplasticity across the lifespan and aging effects in bilinguals and monolinguals. *Brain and cognition*, *125*, 118-126.

Dennis, N. A., & Cabeza, R. (2008). Neuroimaging of healthy cognitive aging. *The handbook of aging and cognition*, *3*, 1-54.

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited: Myth or reality?. Experimental psychology, 61(3), 234-251.

Estanga, A., Ecay-Torres, M., Ibanez, A., Izagirre, A., Villanua, J., Garcia-Sebastian, M., ... & Martinez-Lage, P. (2017). Beneficial effect of bilingualism on Alzheimer's disease CSF biomarkers and cognition. *Neurobiology of aging*, *50*, 144-151.

Fabbro, F., Skrap, M., & Aglioti, S. (2000). Pathological switching between languages following frontal lesion in a bilingual patient. *Journal of Neurology, Neurosurgery, and Psychiatry*, 68, 650–652.

Fernandez, M., Tartar, J. L., Padron, D., & Acosta, J. (2013). Neurophysiological marker of inhibition distinguishes language groups on a non-linguistic executive function test. *Brain and cognition*, *83*(3), 330-336.

Fernandez, M., Acosta, J., Douglass, K., Doshi, N., & Tartar, J. L. (2014). Speaking two languages enhances an auditory but not a visual neural marker of cognitive inhibition. *AIMS Neuroscience*, *1*(2), 145.

Filippi, R., Richardson, F. M., Dick, F., Leech, R., Green, D. W., Thomas, M. S., & Price, C. J. (2011). The right posterior paravermis and the control of language interference. *Journal of Neuroscience*, *31*(29), 10732-10740.

Fjell, A. M., Walhovd, K. B., Fennema-Notestine, C., McEvoy, L. K., Hagler, D. J., Holland, D., ... & Dale, A. M. (2009). One-year brain atrophy evident in healthy aging. *Journal of Neuroscience*, *29*(48), 15223-15231.

Frisoni, G. B., Geroldi, C., Beltramello, A., Bianchetti, A., Binetti, G., Bordiga, G., ... & Zanetti, O. (2002a). Radial width of the temporal horn: a sensitive measure in Alzheimer disease. American Journal of Neuroradiology, 23(1), 35-47.

Frisoni, G. B., Rossi, R., & Beltramello, A. (2002b). The radial width of the temporal horn in mild cognitive impairment. *Journal of Neuroimaging*, *12*(4), 351-354.

de Frutos-Lucas, J., López-Sanz, D., Cuesta, P., Bruña, R., de la Fuente, S., Serrano, N., ... & Maestú, F. (2020). Enhancement of posterior brain functional networks in bilingual older adults.

Bilingualism: Language and Cognition, *23*(2), 387-400.

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Viñas-Guasch, N., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. Frontiers in Psychology, 5, 11.

Gold, B. T., Johnson, N. F., & Powell, D. K. (2013a). Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. *Neuropsychologia*, *51*(13), 2841-2846.

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

Gollan, T. H., Salmon, D. P., Montoya, R. I., & Galasko, D. R. (2011). Degree of bilingualism predicts age of diagnosis of Alzheimer's disease in low-education but not in highly educated Hispanics. *Neuropsychologia*, *49*(14), 3826-3830.

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

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

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and cognition*, *1*(2), 67-81.

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

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.

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.

Gunning-Dixon, F. M., Brickman, A. M., Cheng, J. C., & Alexopoulos, G. S. (2009). Aging of cerebral white matter: a review of MRI findings. *International Journal of Geriatric Psychiatry: A journal of the psychiatry of late life and allied sciences*, *24*(2), 109-117.

Guzmán-Vélez, E., & Tranel, D. (2015). Does bilingualism contribute to cognitive reserve? Cognitive and neural perspectives. *Neuropsychology*, *29*(1), 139.

Heim, S., Stumme, J., Bittner, N., Jockwitz, C., Amunts, K., & Caspers, S. (2019). Bilingualism and "brain reserve": a matter of age. *Neurobiology of aging*, *81*, 157-165.

Hurd, M. D., Martorell, P., Delavande, A., Mullen, K. J., & Langa, K. M. (2013). Monetary costs of dementia in the United States. *New England Journal of Medicine*, *368*(14), 1326-1334.

Incera, S., & McLennan, C. T. (2018). Bilingualism and age are continuous variables that influence executive function. *Aging, Neuropsychology, and Cognition*, *25*(3), 443-463.

Ivanova, I., & Costa, A. (2008). Does bilingualism hamper lexical access in speech production?. *Acta psychologica*, *127*(2), 277-288.

Kalpouzos, G., Chételat, G., Baron, J. C., Landeau, B., Mevel, K., Godeau, C., & Desgranges, B. (2009). Voxel-based mapping of brain gray matter volume and glucose metabolism profiles in normal aging. *Neurobiology of Aging*, *30*(1), 112-124.

Katzman, R. (1993). Education and the prevalence of dementia and Alzheimer's disease. *Neurology*.

Kaushanskaya, M. & Marian, V. (2007). Bilingual language processing and interference in bilinguals: Evidence from eye tracking and picture naming. *Language Learning*, 57, 119–163.

Klein, D., Mok, K., Chen, J. K., & Watkins, K. E. (2014). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. Brain and language, 131, 20-24.

Kontis, V., Bennett, J. E., Mathers, C. D., Li, G., Foreman, K., & Ezzati, M. (2017). Future life expectancy in 35 industrialised countries: projections with a Bayesian model ensemble. *The Lancet*, 389(10076), 1323-1335.

Kowoll, M. E., Degen, C., Gorenc, L., Küntzelmann, A., Fellhauer, I., Giesel, F., ... & Schröder, J. (2016). Bilingualism as a contributor to cognitive reserve? Evidence from cerebral glucose metabolism in mild cognitive impairment and Alzheimer's disease. *Frontiers in psychiatry*, *7*, 62.

Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of memory and language*, *33*(2), 149-174.

Kroll, J. F., Bobb, S. C. & Wodniecka, Z. (2006). Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. *Bilingualism: Language and Cognition*, 9, 119– 135.

Kroll, J. F., Bobb, S. C., Misra, M., & Guo, T. (2008). Language selection in bilingual speech: Evidence for inhibitory processes. Acta psychologica, 128(3), 416-430.

Kroll, J. F., Bobb, S. C., & Hoshino, N. (2014). Two languages in mind: Bilingualism as a tool to investigate language, cognition, and the brain. Current directions in psychological science, 23(3), 159-163.

Kroll, J. F., Dussias, P. E., Bice, K., & Perrotti, L. (2015). Bilingualism, mind, and brain. Annual Review of Linguistics, 1(1), 377-394.

Lambon Ralph, M. A., Pobric, G., & Jefferies, E. (2008). Conceptual knowledge is underpinned by the temporal pole bilaterally: convergent evidence from rTMS. Cerebral Cortex, 19(4), 832-838.

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.

Livingston, G., Sommerlad, A., Orgeta, V., Costafreda, S. G., Huntley, J., Ames, D., ... & Cooper, C. (2017). Dementia prevention, intervention, and care. *The Lancet*, 390(10113), 2673-2734.

Ljungberg, J. K., Hansson, P., Andrés, P., Josefsson, M., & Nilsson, L. G. (2013). A longitudinal study of memory advantages in bilinguals. *PloS one*, *8*(9), e73029.

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. Brain and cognition, 74(3), 347-357.

Luk, G., Bialystok, E., Craik, F. I., & Grady, C. L. (2011). Lifelong bilingualism maintains white matter integrity in older adults. Journal of Neuroscience, 31(46), 16808-16813.

Martin, C. D., Dering, B., Thomas, E. M., & Thierry, G. (2009). Brain potentials reveal

semantic priming in both the “active” and the “nonattended” language of early bilinguals. *NeuroImage*, 47, 326–333.

McDonald, C. R., McEvoy, L. K., Gharapetian, L., Fennema-Notestine, C., Hagler, D. J., Holland, D., ... & Alzheimer's Disease Neuroimaging Initiative. (2009). Regional rates of neocortical atrophy from normal aging to early Alzheimer disease. Neurology, 73(6), 457-465.

Mechelli, A., Crinion, J. T., Noppeney, U., O'doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Neurolinguistics: structural plasticity in the bilingual brain. Nature, 431(7010), 757-757.

Mendez, M. F., Chavez, D., & Akhlaghipour, G. (2020). Bilingualism Delays Expression of Alzheimer’s Clinical Syndrome. *Dementia and Geriatric Cognitive Disorders*, 1-9.

Mitchell, E. (2016). Statistical brief# 497: Concentration of health expenditures in the US civilian noninstitutionalized population, 2014. *Agency for Healthcare Research and Quality.* Rockville, MD.

Mohades, S. G., Struys, E., Van Schuerbeek, P., Baeken, C., Van De Craen, P., & Luypaert, R. (2014). Age of second language acquisition affects nonverbal conflict processing in children: an fMRI study. *Brain and behavior*, *4*(5), 626-642.

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., & Bialystok, E. (2014). Inhibitory control in bilinguals and musicians: event related potential (ERP) evidence for experience-specific effects. *PloS one*, *9*(4), e94169.

Mummery, C. J., Patterson, K., Price, C. J., Ashburner, J., Frackowiak, R. S., & Hodges, J. R. (2000). A voxel-based morphometry study of semantic dementia: relationship between temporal lobe atrophy and semantic memory. *Annals of neurology*, *47*, 36-45.

Nakamura, A., Cuesta, P., Kato, T., Arahata, Y., Iwata, K., Yamagishi, M., ... & Fernández, A. (2017). Early functional network alterations in asymptomatic elders at risk for Alzheimer's disease. *Scientific reports*, *7*(1), 1-11.

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in cognitive sciences*, *16*, 292-305.

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.

Olulade, O. A., Jamal, N. I., Koo, D. S., Perfetti, C. A., LaSasso, C., & Eden, G. F. (2015). Neuroanatomical evidence in support of the bilingual advantage theory. *Cerebral Cortex, 26*(7), 3196-3204.

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.

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.

Perquin, M., Vaillant, M., Schuller, A.M., Pastore, J., Dartigues J.F., Lair, M.L., et al. (2013) Lifelong Exposure to Multilingualism: New Evidence to Support Cognitive Reserve Hypothesis. *PLoS ONE, 8*(4); e62030.

Pfefferbaum, A., Adalsteinsson, E., & Sullivan, E. V. (2005). Frontal circuitry degradation marks healthy adult aging: evidence from diffusion tensor imaging. *Neuroimage, 26*(3), 891-899.

Pliatsikas, C., Johnstone, T., & Marinis, T. (2014). Gray 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.

Pliatsikas, C., & Chondrogianni, V. (Eds.). (2015). Learning a non-native language in a naturalistic environment: insights from behavioural and neuroimaging research. Frontiers Media SA.

Pliatsikas, C., DeLuca, V., Moschopoulou, E., & Saddy, J. D. (2017). Immersive bilingualism reshapes the core of the brain. *Brain Structure and Function, 222*(4), 1785-1795.

Prince, M., Comas-Herrera, A., Knapp, M., Guerchet, M., & Karagiannidou, M. (2016). World Alzheimer report 2016: improving healthcare for people living with dementia: coverage, quality and costs now and in the future.

Ramakrishnan, S., Mekala, S., Mamidipudi, A., Yareeda, S., Mridula, R., Bak, T. H., ... & Kaul, S. (2017). Comparative effects of education and bilingualism on the onset of mild cognitive impairment. *Dementia and geriatric cognitive disorders*, *44*(3-4), 222-231.

Raftery, A. E., Chunn, J. L., Gerland, P., & Ševčíková, H. (2013). Bayesian probabilistic projections of life expectancy for all countries. *Demography*, *50*(3), 777-801.

Ressel, V., Pallier, C., Ventura-Campos, N., Díaz, B., Roessler, A., Ávila, C., & Sebastián-Gallés, N. (2012). An effect of bilingualism on the auditory cortex. Journal of Neuroscience, 32(47), 16597-16601.

Robertson, I. H. (2013). A noradrenergic theory of cognitive reserve: implications for Alzheimer's disease. *Neurobiology of aging*, *34*(1), 298-308.

Rodriguez–Fornells, A., Rotte, M., Heinze, H-J., Nosselt, T. M., & Munte, T. F. (2002). Brain

potential and functional MRI evidence for how to handle two languages with one brain. *Nature*, 415, 1026–1029.

Rodriguez-Fornells, A., Van Der Lugt, A., Rotte, M., Britti, B., Heinze, H.-J. & Munte, T. F. (2005). Second language interferes with word production in fluent bilinguals: Brain potential and functional imaging evidence. *Journal of Cognitive Neuroscience*, 17, 422–433.

Rodriguez-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.

Rosselli, M., Loewenstein, D. A., Curiel, R. E., Penate, A., Torres, V. L., Lang, M., ... & Duara, R. (2019). Effects of bilingualism on verbal and nonverbal memory measures in mild cognitive impairment. *Journal of the International Neuropsychological Society*, *25*(1), 15-28.

Rouillard, M., Audiffren, M., Albinet, C., Ali Bahri, M., Garraux, G., & Collette, F. (2017). Contribution of four lifelong factors of cognitive reserve on late cognition in normal aging and Parkinson's disease. *Journal of clinical and experimental neuropsychology*, 39(2), 142-162.

Saidi, L. G. (2019). Bilingual speakers postpone symptoms of cognitive deficit in parkinson's disease. *Innovation in Aging*, *3*(Suppl 1), S661.

Saykin, A. J., Wishart, H. A., Rabin, L. A., Santulli, R. B., Flashman, L. A., West, J. D., ... & Mamourian, A. C. (2006). Older adults with cognitive complaints show brain atrophy similar to that of amnestic MCI. *Neurology, 67*(5), 834-842.

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I., & Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer's disease. *cortex*, *48*(8), 991-996.

Shearer, J., Green, C., Ritchie, C. W., & Zajicek, J. P. (2012). Health state values for use in the economic evaluation of treatments for Alzheimer's disease. *Drugs & aging*, *29*(1), 31-43.

Stebbins, G. T., & Murphy, C. M. (2009). Diffusion tensor imaging in Alzheimer's disease and mild cognitive impairment. *Behavioural neurology*, *21*(1, 2), 39-49.

Steffener, J., Reuben, A., Rakitin, B. C., & Stern, Y. (2011). Supporting performance in the face of age-related neural changes: testing mechanistic roles of cognitive reserve. *Brain imaging and behavior*, *5*(3), 212-221.

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., & Wiest, R. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex, 48*, 458–465.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015-2028.

Stern, Y. (Ed.). (2013). *Cognitive reserve: Theory and applications*. Psychology Press.

Sullivan, M. D., Janus, M., Moreno, S., Astheimer, L., & Bialystok, E. (2014). Early stage second-language learning improves executive control: Evidence from ERP. *Brain and language*, *139*, 84-98.

Valian, V. (2015). Bilingualism and cognition. Bilingualism: Language and Cognition, 18(1), 3-24.

Van Heuven, W. J., Schriefers, H., Dijkstra, T., & Hagoort, P. (2008). Language conflict in the bilingual brain. *Cerebral cortex*, 18(11), 2706-2716.

Waldie, K. E., Badzakova-Trajkov, G., Miliivojevic, B., & Kirk, I. J. (2009). Neural activity during Stroop colour-word task performance in late proficient bilinguals: a functional magnetic

resonance imaging study. *Psychology & Neuroscience*, *2*(2), 125-136.

Wang, H. X., MacDonald, S. W., Dekhtyar, S., & Fratiglioni, L. (2017). Association of lifelong exposure to cognitive reserve-enhancing factors with dementia risk: a community-based cohort study. *PLoS medicine*, 14(3), e1002251.

Wei, M., Joshi, A. A., Zhang, M., Mei, L., Manis, F. R., He, Q., ... & Xue, F. (2015). How age of acquisition influences brain architecture in bilinguals. *Journal of neurolinguistics*, *36*, 35-55.

Wilson, R. S., Boyle, P. A., Yang, J., James, B. D., & Bennett, D. A. (2014). Early life instruction in foreign language and music and incidence of mild cognitive impairment. *Neuropsychology, 29*(2), 292-302.

Winblad, B., Amouyel, P., Andrieu, S., Ballard, C., Brayne, C., Brodaty, H., ... & Fratiglioni, L. (2016). Defeating Alzheimer's disease and other dementias: a priority for European science and society. *The Lancet Neurology*, 15(5), 455-532.

Wimo, A., Guerchet, M., Ali, G. C., Wu, Y. T., Prina, A. M., Winblad, B., ... & Prince, M. (2017). The worldwide costs of dementia 2015 and comparisons with 2010. *Alzheimer's & Dementia*, 13(1), 1-7.

Wodniecka, Z., Craik, F. I., Luo, L., & Bialystok, E. (2010). Does bilingualism help memory? Competing effects of verbal ability and executive control. *International Journal of Bilingual Education and Bilingualism*, *13*(5), 575-595.

Woumans, E., Santens, P., Sieben, A., Versijpt, J., Stevens, M., & Duyck, W. (2015). Bilingualism delays clinical manifestation of Alzheimer's disease. Bilingualism: Language and Cognition, 18(03), 568-574.

Yu, M., Engels, M. M., Hillebrand, A., Van Straaten, E. C., Gouw, A. A., Teunissen, C., ... &

Stam, C. J. (2017). Selective impairment of hippocampus and posterior hub areas in Alzheimer's disease: an MEG-based multiplex network study. *Brain*, *140*(5), 1466-1485.

Zhang, Y., Londos, E., Minthon, L., Wattmo, C., Liu, H., Aspelin, P., & Wahlund, L. O. (2008). Usefulness of computed tomography linear measurements in diagnosing Alzheimer's disease. *Acta radiologica*, *49*(1), 91-97.

Zheng, Y., Wu, Q., Su, F., Fang, Y., Zeng, J., & Pei, Z. (2018). The protective effect of Cantonese/Mandarin bilingualism on the onset of Alzheimer disease. *Dementia and geriatric cognitive disorders*, *45*(3-4), 210-219.

Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *Cortex*, 48, 1197–1206.

Zunini, R. A. L., Morrison, C., Kousaie, S., & Taler, V. (2019). Task switching and bilingualism in young and older adults: A behavioral and electrophysiological investigation. *Neuropsychologia*, *133*, 107186.

Figure 1

Schematic overview of the brain mechanisms underlying bilingualism-related protective effects against age-related neurocognitive decline.