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Zhang, Haoyun ; Wu, Yan Jing; Thierry, Guillaume

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Authors:

Haoyun Zhang[1], Yan Jing Wu[2], Guillaume Thierry[3]

[1] *Pennsylvania State University, University Park, PA, USA*

[2] *Ningbo University, Ningbo, China*

[3] *Bangor University, Bangor, UK*

Corresponding author

Guillaume Thierry

School of Psychology, Bangor University, Bangor, UK

Tel: +44 1248 388 348

Fax: +44 1248 383 599

E-mail: g.thierry@bangor.ac.uk

Bilingualism and aging: A focused neuroscientific review

Haoyun Zhang[1], Yan Jing Wu[2], Guillaume Thierry[3]

[1] Pennsylvania State University, University Park, PA, USA

[2] Ningbo University, Ningbo, China

[3] Bangor University, Bangor, UK

Abstract

Research has suggested that using two or more languages on a daily basis helps older adults maintain a heightened functional state and improves neurocomputational efficiency. In this review, we discuss studies that have examined the effect of life-long bilingualism on age-related cognitive and neural decline, with a focus on discrepancies between different sources of evidence. We intend to outline and characterize factors which might explain inconsistencies between studies claiming that bilingualism has neurocognitive benefits and those that failed to find such evidence. We argue that individual variation in language proficiency and exposure, especially language switching frequency and daily frequency of use of the two languages, likely account for a significant chunk of the inconsistencies found in the literature and constrain the effectiveness of bilingualism as a cognitive and brain reserve factor. Finally, we briefly review studies of cognitive intervention and speculate on the potential of developing language training protocols to increase cognitive and neural resilience in older adults.

Keywords: Aging; Bilingualism; Cognitive Reserve; Brain Reserve; Language Switching, Language Exposure.

1. Age-related decline in cognitive and brain function

Aging negatively affects people's performance in working memory (Cabeza & Dennis, 2012), language production (Burke & Shafto, 2008; Shafto, Burke, Stamatakis, Tam, & Tyler, 2007), and other cognitive tasks (Paxton, Barch, Racine, & Braver, 2008; Schaie, 1996). As compared to younger adults, older adults suffer from varying degrees of neural degradation. For instance, neuroimaging studies have revealed decreases in gray matter volume (Sowell et al., 2003; Sowell, Thompson, & Toga, 2004), loss of white matter integrity (Bartzokis et al., 2012; Imperati et al., 2011; Mwangi, Hasan, & Soares, 2013), and reduced intra- and inter-network connectivity (Andrews-Hanna et al., 2007; Betzel et al., 2014; Cao et al., 2014; Tomasi & Volkow, 2012) in the brain of elderly individuals. Furthermore, the aging brain typically displays more bilateral activation (Cabeza, 2002) and greater activation in prefrontal regions (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008), both considered to be associated with reduced neural efficiency (Ghisletta & Lindenberger, 2003; S.-C. Li, Lindenberger, & Sikström, 2001). Understanding cognitive decline in the aging brain is of utmost importance as the world's population of individuals aged 60 years and over is poised to increase by more than 50% between 2015 and 2030 according to the latest United Nations report on world population.

Encouragingly, as proposed by the Scaffolding Theory of Aging and Cognition Revised Model (Reuter-Lorenz & Park, 2014), life experiences such as musical training, education, leisure activities, and multilingualism can modify the trajectories of the effect of aging on behavioral and neural function, acting as factors of cognitive and brain reserve. As suggested by Stern (2002, 2009, 2012) and Barulli and Stern (2013), cognitive reserve refers to the fact that humans are able to maintain or recover cognitive performance in the advent of brain injury, pathology, or aging, as a result of neuroplasticity and functional reorganization. In the case of elderly individuals, a simple hypothesis is that those with higher cognitive reserve suffer less age-related decline in cognitive function (Stern, 2012). Cognitive reserve naturally depends on brain reserve, its neural basis, which varies from one individual to another depending on age-related structural changes experienced by the neural system. Superior brain reserve manifests itself as less reduction in overall brain size, more neurons and synapses, thus greater gray matter volume and density, and higher integrity of white matter tracts.

In this article, we review research that has examined the effect of life-long bilingualism on age-related cognitive and neural decline, in terms of both onset and magnitude. Other reviews on this topic have focused on behavioral indicators of cognitive reserve in patients with neuropathology or in healthy populations (Baum & Titone, 2014; Gold, 2015; Grant, Dennis, & Li, 2014; Guzmán-Vélez & Tranel, 2015; Perani & Abutalebi, 2015). Here, we consider findings from neuroimaging studies, with the aim to establish a link between behavioral performance in cognitive tasks and neural activity elicited by language processing in healthy aging individuals. In our selective review of the literature, we have tried to present both sides of the argument, that is both the evidence in favour and that against a bilingual advantage in aging, given the heated debate that has ensued. The goal is to identify the key factors likely to contribute to the discrepancies between studies showing cognitive and neural benefits of bilingualism and those that failed to find such evidence. We explore the idea that factors such as age of acquisition, learning context, proficiency, exposure, ratio of usage, and switching frequency may explain at least part of the inconsistencies in the literature and contribute to determining the effectiveness of bilingualism as a cognitive and brain reserve factor. Finally, we briefly review research on cognitive intervention and speculate on the potential of developing protocols involving language training to help protect older adults from cognitive and neural decline.

2. Bilingualism and cognitive brain reserve

2.1 Language control and executive functions

Bilingual individuals need to process information in either of their two languages and switch between them to maintain communication effective in a variety of contexts. Previous studies have shown that when bilinguals use one language (i.e., the target language), the other language (i.e., the non-target language) is also activated, spontaneously (Costa & Caramazza, 1999; Miwa, Dijkstra, Bolger, & Baayen, 2014;

Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Thierry & Wu, 2007; T. Zhang, Van Heuven, & Conklin, 2011). According to the Inhibitory Control Model (Green, 1998; Kroll & Gollan, 2014), bilinguals need to inhibit the activation of the non-target language when selecting words in the target language (Green, 1998; Guo, Liu, Misra, & Kroll, 2011; Misra, Guo, Bobb, & Kroll, 2012). Neuroimaging studies have shown that language control in bilinguals activates a neural network that largely overlaps with domain-general, executive control areas such as the dorsal anterior cingulate cortex (ACC), supplementary motor area (SMA), and dorsal lateral prefrontal cortex (DLPFC) (Abutalebi et al., 2012; Bialystok et al., 2005; Garbin et al., 2011; Guo et al., 2011; Luk, Bialystok, Craik, & Grady, 2011). This 'control network' has been hypothesized to allow bilinguals to perform dual-language speech production tasks (Abutalebi & Green, 2007, 2008; Hervais-Adelman, Moser-Mercer, & Golestani, 2011). Interestingly, this network includes areas beyond classic language production areas, such as the superior, middle, and posterior temporal gyri, but also the DLPFC, the ACC, and the basal ganglia, which have been associated with conflict resolution and monitoring in tasks tapping executive control.

The constant need for bilinguals to manage two languages and their respective representations has led to the bilingual advantage hypothesis. This hypothesis predicts a relative enhancement of neural efficiency in the language control system of bilinguals that extends to non-linguistic tasks, when the latter share underlying cognitive processes and neural mechanisms with language processing. A number of studies have provided empirical evidence supporting the bilingual advantage hypothesis, arguing that bilinguals outperform monolinguals on a variety of non-linguistic executive function tasks measuring inhibitory control, conflict monitoring, or working memory (For review, see Adesope, Lavin, Thompson, & Ungerleider, 2010; Bialystok, 2017; Bialystok, Craik, & Luk, 2012; Hilchey & Klein, 2011). It is important to note that other studies have failed to find evidence for a cognitive benefit of bilingualism, especially in the domain of executive functioning (Antón et al., 2014; Dick et al., 2019; Lehtonen et al., 2018; Paap, Johnson, & Sawi, 2014, 2015; Von Bastian, Souza, & Gade, 2016) and that the cognitive advantage in bilingualism has been framed as the fruit of a publication bias (de Bruin, Treccani, & Della Sala, 2015). However, studies that did not find positive results tended to examine relatively younger participants (e.g., college students; Paap & Greenberg, 2013; Paap et al., 2014). One explanation is that cognitive functioning in younger adults are at ceiling and, therefore, that bilingual effects are less likely to be observed (Bialystok, 2017), although recent studies have challenged this argument (D'Souza, Moradzadeh, & Wiseheart, 2018). While behavioral studies have offered mixed results (For a review, see Antoniou, 2018), neuroimaging studies have reported differences in patterns and levels of neural activation in a range of cognitive tasks and in brain regions that differ in bilinguals and monolinguals (Abutalebi et al., 2012; Bialystok et al., 2005; Cargnelutti, Tomasino, & Fabbro, 2019; Garbin et al., 2010; Luk et al., 2011; Olulade et al., 2015; Pliatsikas, Moschopoulou, & Saddy, 2015; Stein, Winkler, Kaiser, & Dierks, 2014). For instance, Garbin et al. (2010) compared Spanish monolinguals and Spanish-Catalan bilinguals using a non-verbal task-switching paradigm. Results showed smaller switching cost and reduced activation levels in language control areas (e.g., the left inferior frontal cortex) in bilingual as compared to monolingual controls. On the basis of a meta-analysis throughout the life-span, Cargnelutti et al. (2019) suggested that bilinguals tend to recruit executive function regions to a greater extent than monolinguals, likely because they constantly have to engage in cognitive monitoring and language regulation.

Overall, the existing literature suggests that bilinguals exhibit advantages in cognitive control as compared to monolinguals, but the observation is inconsistent, and the underlying mechanism has not yet been eluded. In addition, evidence from neuroimaging studies suggests that language experience shapes brain activation patterns and brain structures underlying cognitive control tasks. As compared with monolinguals, bilinguals seem to require less neural resources to support the same level of performance, indicating a more efficient system.

2.2 Bilingualism as 'cognitive reserve' and 'brain reserve' factor in aging

Given the rationale and empirical evidence for the cognitive benefits of bilingualism, life-long experience of being a bilingual could serve as factor of cognitive and brain reserve in older adults. In terms of cognitive reserve, bilinguals would show less age-related cognitive decline with comparable or even less available neural resources, as compared to monolinguals. In terms of brain reserve, bilinguals would show more efficient neural networks, especially in brain areas related to cognitive control and language. Other reviews or meta-analyses in the field have generally focused on behavioral indicators of cognitive reserve in patients with neuropathology or in healthy populations (Armstrong, Ein, Wong, Gallant, & Li, 2019; Baum & Titone, 2014; Gold, 2015; Grant et al., 2014; Guzmán-Vélez & Tranel, 2015; Perani & Abutalebi, 2015). This section provides a concise review of the evidence supporting the view that bilingualism increases cognitive and brain reserves. Details of critical studies (e.g., participant group, participant language background, methods, outcome, etc.) have been summarized in Table 1.

Age-related cognitive decline manifests when older participants (generally over the age of 60) perform tasks requiring the constant updating of new information, switch between tasks, or have to inhibit interference from task-irrelevant information (Braver & West, 2008; Lustig, Hasher, & Zacks, 2007). Therefore, one explanation for the beneficial effect of bilingualism is that using two languages on a regular basis functions as implicit training for the cognitive control system. Due to this training-like experience, elderly bilinguals should be more cognitively resilient as compared to age-matched monolinguals. Consistent with this argument, bilinguals with terminal brain diseases show a later onset of the symptoms and suffer to a lesser extent from associated cognitive deficits. For example, some studies have reported a delay of 4-5 years in the onset Alzheimer's dementia (AD) symptoms in bilinguals as compared to age-matched monolinguals (Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007; Chertkow et al., 2010; Craik, Bialystok, & Freedman, 2010; Freedman et al., 2014; Woumans et al., 2015). Additionally, following stroke, bilingual patients have been reported to recover better cognitively than monolinguals (Alladi et al., 2016). Using multiple languages from early life appears to protect against mild cognitive impairment, a sign of cognitive decline often observed before AD diagnosis (Perquin et al., 2013). Similarly, studies have shown that bilinguals with AD tend to exhibit greater brain atrophy than monolinguals when cognitive performance is matched across groups (Schweizer, Craik, & Bialystok, 2013; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). A recent study (Smirnov et al., 2019) has also shown a significant correlation between the thickness of a core cognitive control region (i.e., anterior cingulate cortex) and naming performance in the nondominant language in bilingual patients with AD, whereas no such correlation was found in healthy controls.

Healthy older bilinguals too have been shown to exhibit greater cognitive and brain reserve than monolinguals. For instance, studies have reported that older bilinguals exhibit enhanced behavioral performance in a variety of cognitive tasks, suggesting better cognitive abilities in terms of inhibitory control and task switching (Abutalebi, Guidi, et al., 2015; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Ryan, 2006; Gold, Kim, Johnson, Kryscio, & Smith, 2013). However, it has been argued that bilinguals and monolinguals might have differences in cognitive ability before any language experience is accrued (e.g., higher working memory, better executive functions), and that such difference would not only explain their success in learning another language but, by the same token, the apparent protective effect of bilingualism in old age (Bak, 2016). At this point, it is worth noting that the link between bilingualism and cognitive function efficiency in elderly people is mostly based on correlational rather than causational data, as in the case of a great majority of empirical studies. Thus, it is possible that individuals with superior cognitive abilities learn a second language more efficiently, achieve higher bilingual proficiency and are therefore more likely to become balanced bilinguals, making the relationship between bilingualism and cognitive function efficiency a chicken and egg problem. To address these concerns, Bak, Nissan, Allerhand, and Deary (2014) showed that bilinguals appear to maintain cognitive abilities better than monolinguals as they grow older based on longitudinal data, even when matching intelligence and fundamental cognitive abilities between groups since childhood.

At the neuroanatomical level, the experience of using multiple languages appears to shape dynamic aspects of neural processing and the organization of structures underlying non-linguistic, cognitive function in elderly people. For instance, a study using fMRI has found that normally aging bilinguals with lower levels of white matter integrity than monolingual controls had comparable performance in a switching task (Gold, Johnson, & Powell, 2013). This finding points to an increase of neural efficiency in bilinguals, allowing them to maintain the same level of cognitive performance as age-matched monolinguals on the basis of fewer neural resources. In the same vein, when older bilinguals and age-matched monolinguals do not differ in terms of neurofunctional correlates of cognitive processing, the former have been shown to demonstrate enhanced behavioral performance compared to the latter, suggesting more efficient neural functioning (Gold, Kim, et al., 2013). Gold, Kim, et al. (2013) tested older bilinguals (mean age = 63.9 years) and monolinguals (mean age = 64.4 years) on a task switching paradigm. The bilingual participants in this study had been speaking English and another language on a daily basis since or before the age of 10, and reported themselves as being completely proficient in both their languages. Relative to monolinguals, bilinguals exhibited smaller switching costs while displaying decreased activation in the left lateral frontal and cingulate cortices, suggesting that life-long experience of using two languages may shield individuals from both behavioral decline and neurofunctional deterioration in aging.

In addition to differences in neural activation levels or differences in performance at similar activation levels, older bilinguals and age-matched monolinguals have also been shown to recruit different neural mechanisms when engaging in the same cognitive task, whilst having comparable performance. Ansaldo, Ghazi-Saidi, and Adrover-Roig (2015) tested a group of older French-English bilinguals and a group of age-matched French monolinguals using a Simon task. Although bilingual participants reported a minimum of 30% daily usage of their second language (i.e., they had imbalanced exposure), the results showed differences in the patterns of neural activation between groups performing the same task. While bilingual participants activated the left inferior parietal lobule (IPL), monolingual participants preferentially activated the right middle frontal gyrus. In other words, as monolinguals relied on a classic inhibitory control network of the frontal lobe particularly vulnerable to aging, older bilinguals recruited brain regions not typically associated with inhibitory control, suggesting possibly heightened resilience at the neuroanatomical level. Learning and use of a second language appear to engage more distributed brain networks (i.e., language sub-networks) beyond the classic language network in the frontal lobe (García-Pentón, Fernández, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014).

Recently, task-based and resting-state functional connectivity have become popular approaches to explore neural network (Shen, 2015) and have also been applied to the study of relationships between bilingualism and aging. Berroir et al. (2017), for instance, re-analyzed the dataset of Ansaldo et al. (2015) using a task-based functional connectivity approach and showed that neural responses elicited by the Simon task decreased in intensity but were more clustered in older bilinguals relative to older monolinguals. Using a resting-state functional connectivity analysis, Grady, Luk, Craik, and Bialystok (2015) found stronger intrinsic functional connectivity in the Default Mode Network (i.e., a set of brain regions that typically deactivate during the performance of cognitive tasks) and the Prefrontal Executive Function Network (i.e., a set of brain regions that activate during executive function tasks) of older bilinguals as compared to age-matched monolinguals. Perani et al. (2017) showed the same trend when comparing older bilinguals to monolinguals with Alzheimer's Disease (AD). Critically, the level of functional connectivity was positively correlated with 1) the extent to which older bilingual participants use their two languages daily and 2) the level of language proficiency. Given that functional connectivity tends to drop in old age (Andrews-Hanna et al., 2007; Betzel et al., 2014; Cao et al., 2014; Tomasi & Volkow, 2012; H.-Y. Zhang et al., 2014), findings that older bilinguals maintain stronger connectivity as compared to monolinguals in the networks underlying executive function is consistent with the bilingual 'brain reserve' hypothesis.

Additionally, studies have shown that individual differences in functional connectivity might reflect underlying structure differences (e.g., white matter integrity) across the lifespan (Andrews-Hanna et al., 2007; Luk et al., 2011; Marstaller, Williams, Rich, Savage, & Burianová, 2015). Consistent with functional connectivity findings, bilingualism has also been associated with the ability to preserve structural brain properties in elderly people. For instance, Olsen et al. (2015) showed that older bilinguals tend to exhibit greater frontal lobe white matter volumes as compared to age-matched monolinguals. They also found that better Stroop performance is associated with greater white matter volume in the frontal lobes of older bilinguals. Moreover, studies using Diffusion Tensor Imaging (DTI), a method tracking the general organization and integrity of the white matter in the brain, have found that older bilinguals maintain higher integrity in several white matter tracts supporting language processing (e.g, the corpus callosum extending to the superior and inferior longitudinal fasciculi; Anderson, Grundy, et al., 2018; Luk et al., 2011). However, it is important to note that the above studies did not report analyses that looked at the relationship between behavioral performance and white matter volume or integrity in older bilinguals. Interestingly, Gold, Johnson, et al. (2013) found that older bilinguals with lower white matter integrity than aged-matched monolinguals in a number of brain regions, including the inferior longitudinal fasciculus and the inferior frontooccipital fasciculus (ILF/IFOF), the fornix, and multiple portions of the corpus callosum could perform on a par with their monolingual peers in a set of cognitive tests. The authors interpreted this finding as evidence for a positive effect of bilingualism on cognitive aging. In other words, older bilinguals would be able to perform as well as monolinguals with less neural resources available to them, indicating higher neural efficiency. It is important to note that background variables differed considerably between the studies of Gold, Johnson, et al. (2013), Anderson, Grundy, et al. (2018), and Luk et al. (2011), which likely accounts for contradictory findings regarding white matter integrity. The bilingual participants in the study by Gold, Johnson, et al. (2013) had a higher incidence of preclinical AD and, therefore, this particular group of bilinguals showed reduced white matter integrity when compared to healthy monolinguals, whereas elderly bilinguals in the other studies exhibited a higher degree of white matter integrity as compared to age-matched monolingual controls.

In the same vein, positive effects of bilingualism in elderly populations appear to extend to gray matter volume in the case of cognitive control areas (e.g., the anterior cingulate cortex) and classic language areas (e.g., the left inferior frontal gyrus, termporal pole and bilateral inferior parietal lobules; Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015; Abutalebi et al., 2014; Abutalebi, Guidi, et al., 2015; Heim et al., 2019). For instance, Abutalebi, Canini, et al. (2015) observed a higher gray matter volume in the IPL and the anterior cingulate cortex of lifelong Cantonese/Mandarin-English bilinguals who learned English after the age of 18 years. Despite being exposed to their second language for an average of only 4.3 hours per day, the late bilingual participants had significantly greater gray matter volume than monolingual controls (Abutalebi, Guidi, et al., 2015). Strikingly, in older bilinguals, no effect of age on gray matter volume was observed in the right IPL, an effect observed in older monolinguals. These findings are consistent with those of Abutalebi et al. (2014), who found higher gray matter volume in the left temporal pole and smaller age-related decreases in gray matter volume in the frontal and parietal regions of older bilinguals as compared to older monolinguals. On the other hand, Heim et al. (2019) reported bilinguals have higher gray matter volume in the left IFG and IPL, but this difference disappeared in older participants, and the slope of decline was steeper for bilinguals than monolinguals. Furthermore, Del Maschio et al. (2018) examined the effect of aging on gray matter volume, and tested for correlations between gray matter volume and executive control performance in the same bilingual population as in previous studies by Abutalebi, Canini, et al. (2015) and Abutalebi et al. (2014). Del Maschio et al. (2018) focused on regions of interest that are typically involved in executive control (i.e., bilateral prefrontal cortex, bilateral inferior parietal lobule, caudate nucleus, and anterior cingulate cortex), and showed that older bilinguals have greater gray matter volume in these regions than older monolinguals. More importantly, the magnitude of gray matter loss was negatively correlated with executive control performance (i.e., Flanker task) in older monolinguals but not older bilinguals, suggesting that the neural system in older bilinguals is more resilient to age-related performance decline.

To summarize, bilingualism appears to be a life factor associated with greater cognitive and brain reserve. When endowed with fewer brain resources (e.g., reduced white matter density, decreased grey matter volume, or weaker white matter integrity), older bilinguals are able to maintain cognitive performance to a level comparable with that of older monolinguals within the normal range. In addition, older bilinguals are able to leverage neural resources more efficiently as indicated by lower brain activation levels, and are more flexible in terms of recruiting additional brain regions that are not typically involved in language or cognitive tasks. Finally, lifelong experiences of using two languages on a frequent basis also help maintain gray and white matter volume, as well as white matter integrity against aging.

3. The Complex Nature of Bilingualism

Despite evidence in favor of the cognitive and brain reserve account, the actual relationship between bilingualism and age-related cognitive decline remains a matter of debate. To begin with, some studies simply failed to observe significant correlations between bilingualism and cognitive performance in young adults (Paap & Greenberg, 2013; Paap et al., 2014) and in older adults (Antón, García, Carreiras, & Duñabeitia, 2016; Crane et al., 2010; de Bruin, Bak, & Della Sala, 2015; Kirk, Fiala, Scott-Brown, & Kempe, 2014). Other studies have failed to replicate the association of bilingualism with a delayed onset of dementia or mild cognitive impairment (Clare et al., 2016; Kowoll, Degen, Gladis, & Schröder, 2015; Lawton, Gasquoine, & Weimer, 2015; Sanders, Hall, Katz, & Lipton, 2012). In the same vein, Zahodne, Schofield, Farrell, Stern, and Manly (2014) reported that bilingualism is not associated with rates of cognitive decline or dementia conversion, although it is associated with better memory and executive function at baseline. As pointed out by several authors (Calvo, García, Manoiloff, & Ibáñez, 2016; Poarch & Krott, 2019; Valian, 2015), a variety of extraneous factors can interact with bilingualism and modulate cognitive resilience. These factors include experimental task, sample size, the involvement of executive function, and individual differences such as cultural environment, socio-economic status (SES), social network structure, education, professional training, language typologies, etc. We seek to demonstrate here that language use is one of the critical factors driving age-related cognitive decline resilience in bilinguals.

There exists a large variation in the level of bilingual functioning (hereafter referred to as degree of bilingualism) characterizing individuals who speak two languages. Factors such as age of acquisition, language proficiency, language dominance, language exposure, frequency of intra-sentential and between-clause code-switching, language processing contexts, etc. are all likely to modulate the degree of bilingualism and, in turn, impact cognitive resilience in aging. Some of these factors have naturally been considered in studies on the cognitive benefits of bilingualism. Unsurprisingly, a higher degree of bilingualism, characterized for instance by an early age of acquisition, high L2 proficiency, and balanced daily exposure to both languages, has been associated with cognitive control benefits in younger adults (Brito, Sebastian-Galles, & Barr, 2015; Coderre, Van Heuven, & Conklin, 2013; Linck, Osthus, Koeth, & Bunting, 2014; Tse & Altarriba, 2014; Yow & Li, 2015). Some studies (Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016; Yow & Li, 2015) have shown that bilinguals with balanced proficiency in L1 and L2 and a rich experience of language switching tend to have enhanced executive function as compared to other, less balanced bilinguals. Ooi, Goh, Sorace, and Bak (2018) examined the interaction between language switching experiences and age of L2 acquisition using the Attentional Network Task (ANT, a combination of a cued reaction time task and a flanker task) and the Elevator Counting subtest from the Test of Everyday Attention Task (TEA, Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994). Bilingual participants were native English speakers who spoke a variety of languages as L2. Interestingly, in this study, the effects of age of L2 acquisition and language-switching experience on cognitive functioning differed. Compared to monolinguals, early bilinguals who had the opportunity to use both of their languages more frequently had better performance in conflict resolution (i.e., congruent-incongruent contrast in the ANT) than other participants. In contrast, late bilinguals who mostly used their two languages independently had better auditory attentional switching performance as measured by the TEA elevator task.

However, very few studies involving elderly bilingual adults have explicitly considered degree of bilingualism as an independent variable. It seems to us that language exposure and frequency of code-switching are the key defining components of the degree of bilingualism variable, which in turn, determines the extent of cognitive and neural changes afforded by bilingual experience.

In older adults with dementia, Nanchen et al. (2017) showed that early immersion in and lifelong exposure to an L2 environment contribute to preserving L2 ability. Similarly, bilinguals who use both of their languages equally show stronger neuroprotective effects on cognitive functions, but this effect also depends on other factors such as education level (Abutalebi et al., 2014; Gollan, Salmon, Montoya, & Galasko, 2011; Perani & Abutalebi, 2015). Interestingly, Goral, Campanelli, and Spiro (2015) found that bilinguals with imbalanced language proficiency and usage are possibly protected to an even greater extent against age-related decline in response inhibition than balanced bilinguals. The authors argued that bilinguals whose native language is more fluent and used more frequently than the L2 requires greater inhibitory efforts when individuals function in a context requiring both languages, because switching from a stronger language to a weaker language demands greater cognitive control than switching between two languages that have roughly the same strength. At a neuroanatomical level, Abutalebi et al. (2014) have established a positive correlation between naming performance in L2 and gray matter volume in the left temporal pole, a region where between-group (monolingual-bilingual) differences have been observed. Similarly, Grundy, Anderson, and Bialystok (2017) showed that the protective effect of bilingualism on gray matter volumes in the anterior cingulate cortex, parietal lobes, parts of the frontal-parietal network, and basal ganglia, is modulated by L2 proficiency and exposure. Consistent with evidence in younger bilinguals, these findings suggest that higher L2 proficiency is associated with greater brain reserve in older bilinguals. Presumably, bilinguals who acquired L2 at an earlier age and who are more proficient in L2 have a greater opportunity to use L2 regardless of the language environment in which they find themselves. Therefore, correlations between language proficiency or age of acquisition of L2 and cognitive and brain reserves in older adults should be affected by the way in which balanced bilinguals use their two languages. Taken together, empirical findings suggest that the balanced use of a bilingual's two languages should be taken into consideration when discussing evidence of bilingualism as a cognitive and brain reserve factor.

Bilinguals are likely to switch between their two languages more frequently if they are evenly exposed to them. However, this assumption is not always correct. For instance, *a priori* balanced bilinguals may use their languages separately in particular conversational contexts but not others (e.g., one language at home and the other at work). Other bilinguals may work in a multilingual context and have to switch between languages regularly, within the same day or even the same meeting. And this may happen at home too, if a bilingual parent lives in a different country as that of their citizenship and have children who were born ‘in exile’. In the latter context, bilingual parents may have to switch languages regularly at home, expressing themselves in the L1 but more or less often talking and replying to their offspring in the L2, because L2 would be the native language of the children.

To account for this variety of contexts and the ensuing bilingual diversity, Green and Abutalebi (2013) proposed the Adaptive Control hypothesis (ACH), which describes the theoretical cognitive processes underlying three different interactional contexts with a focus on bilingual production. According to the ACH, functioning in a single-language context, in a dual-language context, or in a dense code-switching context impose demands on different aspects of cognitive control. Green and Abutalebi (2013) distinguish seven independent cognitive components that may be independently or jointly affected by functioning in these different contexts, namely goal maintenance (e.g., maintaining in memory the identity of the language to speak), interference control (e.g., inhibiting irrelevant information from the environment to maintain the current task goal), salient cue detection (e.g., identifying the language to speak based on the listener identity), selective response inhibition (e.g., inhibiting the other language), task engagement (e.g., switching to a new language if the listener changes), task disengagement (e.g., disengaging from previous language representations before switching), and opportunistic planning (e.g., making use of any language affordance arising in order to achieve a goal).

A dual-language context, for example, generally involves situations in which both languages are used in a single conversation and/or speaking environment (e.g., school, home, or workplace) when speaking to several individuals. In contrast, situations in which only one language is used at a time can be considered a single language context, e.g., when a bilingual has a conversation with a monolingual exclusively in their L1 or in their L2. Bilinguals in a dual-language context more or less frequently need to switch between their two languages, whereas they will seldom switch in a single-language context. Within the framework of the ACH, Green and Abutalebi contend that compared to a single-language context, a dual-language context places higher demands on cue detection, response inhibition, task engagement, and task disengagement. On the other hand, to achieve smooth language production in a single language context, bilinguals need to put the focus of goal maintenance and interference suppression. As a result, bilingual speakers with more experience of dual-language contexts are expected to exhibit greater benefits with regard to specific aspects of cognitive control as compared to bilinguals mostly functioning in a single language context, and *vice versa*. In a dense code-switching context, bilingual speakers alternate between their two languages at a fast pace within a single conversation stream, and engage in spontaneous language switching, which Green and Abutalebi contend is conducive to opportunistic planning and tends to disengage other cognitive components.

Several empirical studies investigating the relationship between language switching frequency and cognitive control have provided evidence in support of the ACH. For instance, Soveri, Rodriguez-Fornells, and Laine (2011) found that 30–75-year-old bilinguals with a higher language switching rate in everyday life showed a reduced mixing cost in a cross-domain code-switching task, as compared to those with a lower rate of language switching. In the task used, participants were asked to either determine if a number was odd or even, or if a letter was a vowel or a consonant, depending on the location on the screen of the number-letter pair. Language switching frequency has also been associated with improved performance in cognitive flexibility (Barbu, Orban, Gillet, & Poncelet, 2018) and task reconfiguration (Hartanto & Yang, 2016), establishing a connection between dual-language processing contexts on the one hand and cue detection, conflicting monitoring (as in the cognitive flexibility task), task engagement, and task disengagement (as in the switching task) on the other. Furthermore, findings from these behavioral studies are consistent with neurofunctional evidence. For instance, Gullifer et al. (2018) showed that greater diversity of daily language use relates to greater connectivity between anterior cingulate cortex and putamen bilaterally, and also increased reliance on proactive control (i.e., cue and context monitoring) in the AX-CPT task. This could be because a more integrative language context increases the degree of cross-language activation, and it is possible that proactive control is required to preemptively select the intended meaning from a pool of co-activated alternatives. Additionally, dense code-switching experience has been positively associated with performance in the Flanker test, which measures the combined effort of monitoring and inhibitory skills (Green & Abutalebi, 2013; Hofweber, Marinis, & Treffers-Daller, 2016). Finally, simultaneous interpreters (who often operate in extreme language switching contexts) showed enhanced executive function and cue orientation as compared to early sequential bilinguals who have much experience of language switching (Sabourin & Vinetre, 2018).

While the studies reviewed above have made a case for the critical role of cross-language switching frequency in relation to the cognitive benefits of bilingualism, very few studies have directly investigated the effect of daily language use on cognitive decline in older bilinguals. To the best of our knowledge, Pot, Keijzer, and de Bot (2018) is the only study in which the intensity of dual-language functioning has been examined in the framework of the cognitive reserve hypothesis. In this study, 387 older bilinguals performed the Flanker task, which reflects conflict resolution and response inhibition abilities, and the Wisconsin sorting test (WST), which reflects set shifting abilities. While working memory was matched between participants, results showed that L2 proficiency and the degree of L2 usage in everyday life were positively correlated with the Flanker interference cost, suggesting that L2 proficiency and language switching within conversational contexts are critical factors in predicting effects of bilingualism on conflict resolution and response inhibition in older bilinguals. Bilinguals not actively using the two languages in social conversational contexts or on a daily basis showed no cognitive benefits in either of the two tasks. These results are mostly consistent with the proposition of the ACH (Green & Abutalebi, 2013) in that functioning in different interactional language contexts places different levels of demands on distinct cognitive control components. Future studies on bilingualism as a cognitive reserve and brain reserve factor in age-related cognitive decline should, therefore, take into consideration the opportunities in which older bilinguals could maintain active use of both languages and switch between two languages on a regular base.

Given the critical role of language switching frequency and balanced language use on cognitive benefits in bilinguals, an objective measurement that systematically captures the diversity and complexity of bilingual experiences, exposure and proficiency needs to be developed and applied in future studies. To date, a majority of language use measurements derived from self-assessment data. For instance, the Language Experience and Proficiency Questionnaire (LEAP-Q, Marian, Blumenfeld, & Kaushanskaya, 2007) asks questions measuring language dominance, age of acquisition, and percentage and contexts of language exposure. The LHQ (Language History Questionnaire; P. Li, Sepanski, & Zhao, 2006; P. Li, Zhang, Tsai, & Puls, 2014), on the other hand, includes questions about language history (e.g., age and context of language acquisition), language proficiency, and language usage at home. Previous studies have also developed independent measurements to quantify bilingualism based on the particular research question addressed. For instance, Hartanto and Yang (2016) used a bilingual language index to determine the frequency with which their bilingual participants used their two languages in various contexts. In an attempt to increase sensitivity in characterizing bilingual language experience, Anderson, Mak, Chahi, and Bialystok (2018) recently developed a Language and Social Background Questionnaire (LSBQ) in which the degree of bilingualism is assessed through measurement of proficiency level, percentage of L1 and L2 usage, and the social contexts in which L1 and L2 are used. An exploratory factor analysis revealed that three factors (non-English home use and proficiency, non-English social use, and English use) loaded most significantly on all items in the questionnaire, and thus represented degree of bilingualism the best. Overall, most of the current literature depends heavily on participants' self-reported measurements of language proficiency and use. However, some studies have suggested that self-reported measures may not be the best metric when comparing different bilingual groups given that different bilinguals can vary considerably on the same self-rating scale (Tomoschuk, Ferreira, & Gollan, 2018). Therefore, it is advisable to also include objective measures of language ability and use, such as picture naming latencies, lexical decision time, verbal fluency, or practice sampling such as random recording of speech. Additionally, other individual differences relating to social diversity and educational background may modulate cognitive benefits of bilingualism, especially in older adults (Barnes, De Leon, Wilson, Bienias, & Evans, 2004; Bassuk, Glass, & Berkman, 1999; Bennett, Schneider, Tang, Arnold, & Wilson, 2006; Lang & Carstensen, 1994).

4. Language interventions and benefits to executive functions

Significant efforts have been made to develop intervention protocols based on short-term training in order to help cognitive functioning resilience in older adults (Karbach & Verhaeghen, 2014; Lampit, Hallock, & Valenzuela, 2014; Park & Bischof, 2013; Zinke et al., 2014). For instance, numerous studies have demonstrated the effectiveness of computerized cognitive training (CCT) for improving cognitive performance in healthy older adults, although training efficacy differed across cognitive domains and varied with experimental parameters (Kueider, Parisi, Gross, & Rebok, 2012; Lampit et al., 2014). Some training procedures involved traditional cognitive tasks (e.g., verbal episodic memory or executive function tasks; (Ball et al., 2002; Braver, Paxton, Locke, & Barch, 2009; Dahlin, Nyberg, Bäckman, & Neely, 2008; Grönholm-Nyman et al., 2017; Kelly et al., 2014; Kueider et al., 2012; Rebok et al., 2014; Willis et al., 2006), while others involved activities thought to enhance executive function skills such as playing video games (Anguera et al., 2013; Basak, Boot, Voss, & Kramer, 2008; Maillot, Perrot, & Hartley, 2012), physical exercise (Colcombe & Kramer, 2003), or learning new skills (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007; Park et al., 2014). All of these activities have been reported to enhance different aspects of cognitive functions (e.g., inhibitory control, episodic memory, etc.) in older adults, compared to other, nonintellectual and less demanding activities. For instance, in one study, older participants (mean age = 72 years) were taught digital photography and quilting (Park et al., 2014). The training program lasted for 3 months and involved 16.5 hours per week of activities. Results showed that the acquisition of new skills or sustained engagement with novel activities that are cognitively demanding enhance episodic memory in older adulthood. These findings suggest that the neural mechanisms of memory in older people are permeable to influences of short-term, productive mental activities, a finding that encourages the idea of language-based cognitive interventions in older people.

Very few studies have looked at the effect of language-based interventions in older adults. However, in younger adults, Zhang, Kang, Wu, Ma, and Guo (2015) showed in young bilingual adults that a 10-day training session focused on language switching enhanced proactive control performance in the AX-CPT paradigm. Another study involving attendance of a one-week foreign language class by a group of monolingual speakers found significant improvement in attentional inhibition and attentional switching (Bak, Long, Vega-Mendoza, & Sorace, 2016), demonstrating that short L2 training can also enhance cognitive functioning in monolinguals. Critically, in the latter study, training effects on attention switching lasted for 9 months after the language class for participants who studied more intensively during the class. These results provide evidence consistent with previous findings that short-term foreign language training directly benefits executive control performance (Janus, Lee, Moreno, & Bialystok, 2016; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014). In the same vein, Kwon and Lee (2017) compared executive control indices in a group of Korean-English bilinguals who learned German over a six-week class and a matched group of bilinguals who did not learn a third language during the same period. The results showed that short-term learning of a third language differentially strengthened reactive inhibition control in the bilinguals learning a third language. Wu and Thierry (2013) showed that in a mixed- as compared to a single-language processing context, highly proficient Welsh-English bilinguals displayed enhanced executive performance, suggesting that having one’s two languages activated has a positive, incidental effect on inhibitory control. This evidence obtained in a within-subject design, together with findings from training studies, suggests that bilingualism training (especially high L2 proficiency in a mixed-language processing context) has the potential to contribute to the development of language-based intervention programs for cognitive maintenance and rehabilitation (Antoniou, Gunasekera, & Wong, 2013).

Taking together the outcomes of cognitive intervention in older adults and language-based training in younger adults, it is reasonable to expect that language-based intervention training will be effective in older adults in the future.

5. Conclusion and Future Research

The cognitive consequences of bilingualism have been widely studied in children and younger adults, but relatively fewer studies have focused on older populations, which are becoming the largest demographic in the world. In the current article, we discussed evidence for and against the hypothesis that lifelong experiences of using two languages serve as a cognitive and brain reserve factor. Existing findings suggest that the effect of bilingualism on age-related cognitive decline are modulated by the degree of bilingualism, especially in cases where languages use is more balanced and in mixed language processing contexts. It seems almost insufficient to accept that bilingual individuals do not form a homogeneous group. Bilingual diversity stems from factors as varied as age of acquisition, proficiency, type and length of immersion, code-switching, within and between utterances or contexts, and socio-cultural or political context of language use, and more generally exposure. While more evidence on how bilingualism affects cognitive decline in older people is needed, future studies must take into consideration the level of observed proficiency in each of the languages of the individuals studied and the particular context in which they find themselves by specifying the exact “matrices” of bilingual characteristics that (a) establish the link between language experience and the prevention of cognitive loss, (b) moderate the strength of this link, and (c) determine the conditions in which the link is damaged or obliterated. This new knowledge will constitute the foundation on which efficient cognitive intervention programs based on language training can be developed for older people.

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Patient Studies	Participants	Language Background	Method	Task	Results snapshot
Alladi et al. (2013)	**648** patients with dementia (**391** bilinguals)	Bilinguals were able to communicate fluently in two or more languages	Age at onset of first symptoms	*N/A*	Bilingual patients developed dementia 4.5 years later than monolinguals, independently of education, sex, occupation, and urban vs rural dwelling of subjects.
Alladi et al. (2016)	**608** patients with ischemic stroke (**353** bilinguals)	Bilingualism defined as the ability to communicate in two or more languages	Cognitive evaluation	Addenbrooke's Cognitive Examination–Revised (ACE-R)	A larger proportion of bilinguals had normal cognition compared with monolinguals, whereas the reverse was noted in patients with cognitive impairment, including vascular dementia and vascular mild cognitive impairment.
Bialystok, Craik, and Freedman (2007)	**184** patients with dementia (**91** bilinguals)	Bilinguals spent the majority of their lives, at least from early adulthood, regularly using at least two languages	Age of onset of cognitive impairment	*N/A*	Bilinguals showed symptoms of dementia 4.1 years later than monolinguals, all other measures being equivalent.
Chertkow et al. (2010)	**632** individuals with memory complaints subsequently diagnosed with probable AD	Immigrants vs nonimmigrants; unilingual, bi- or multilingual; Native in English/French, proficient in all languages	Age at diagnosis of AD and age at symptom onset	*N/A*	1) Protective effect of more than two languages spoken; 2) In the immigrant group, speaking two or more languages delayed the diagnosis of Alzheimer disease by almost five years.
Clare et al. (2016)	37 bilinguals and 49 monolinguals with AD	Bilingual spoke two languages for all or most of their life and were fluent in both languages, but not in any other languages	Age at diagnosis of AD	A subset of group (24 bilinguals, 49 monolinguals) performed a range of executive control tasks	1) No significant group difference in age at the time of diagnosis; but bilinguals were also significantly more cognitively impaired at the time of diagnosis. 2) No significant differences between monolinguals and bilinguals in performance on executive function tests, but bilinguals showed relative strengths in inhibition and response conflict.
Craik, Bialystok, and Freedman (2010)	**211** patients with probable AD (**102** bilinguals)	Bilinguals had to have spent the majority of life, at least from early adulthood, regularly using at least 2 languages.	Age of diagnose and age of onset of symptoms	*N/A*	Bilingual patients had been diagnosed 4.3 years later and had reported the onset of symptoms 5.1 years later than the monolingual patients.

Kowoll, Degen, Gladis, and Schröder (2015)	30 bilinguals and 39 monolinguals with MCI or AD	*Unspecified*	Neuropsychological evaluation	CERAD- NP neuropsychological assessment battery	Bilingual MCI and AD patients show a similar pattern of neuropsychological deficits as monolingual patients do.
Lawton, Gasquoine, and Weimer (2015)	81 patients with dementia (27 bilinguals)	Bilinguals spoke both Spanish and English	Age at diagnosis of AD	*N/A*	Mean age of dementia diagnosis was descriptively (but not significantly) higher in the monolingual (M = 81.10 years) than the bilingual (M = 79.31) group, as established by neuropsychological testing and formal dementia criteria.
Perquin et al. (2013)	44 patients with cognitive impairment without dementia (CIND) and 188 without CIND	All participants practiced from 2 to 7 languages	Calculated risk of CIND	*N/A*	Strong association toward a protection of multilingualism against CIND. Practicing multilingualism from early life on, and/or learning it at a fast pace is even more efficient.
Perani et al. (2017)	45 bilinguals, M = 77.13 yrs; 40 monolinguals, M = 71.42 yrs. Patients with probable AD and matched for disease duration.	Lifelong language use in bilinguals was measured. Calculated as bilinguals index. BI=1 − | %L1−%L2 |. Ranging from perfect monolingual to perfect bilinguals.	FDG-PET 1) Brain's hypometabolism of different regions 2) resting-state metabolic network connectivity	Neuropsycholo-gical testing	1) Cerebral hypometabolism was much more extended in bilingual individuals with AD in comparison with monolinguals. Bilinguals performed better on short- and long-term verbal memory and visuospatial tasks, supporting the cognitive reserve account. 2) Increased connectivity in the executive control and the default mode networks in the bilingual, compared with monolingual AD patients. 3) The degree of lifelong bilingualism was significantly correlated to functional modulations in crucial neural networks, suggesting both neural reserve and compensatory mechanisms.
Sanders, Hall, Katz, and Lipton (2012)	**390** non-native English speakers with probable AD	Participants reported mother tongue, English AOA, and current percentile-use of a non-English language.	Incidental dementia rate	*N/A*	No relationship between language use, incidental dementia, and AD

Schweizer, Ware, Fischer, Craik, and Bialystok (2012)	40 participants with a diagnosis of probable AD (20 bilinguals)	Bilinguals were fluent in a second language and had used both languages consistently throughout most of their life.	CT scan	BNA test of cognitive function	Bilingual patients with AD exhibited substantially greater amounts of brain atrophy than monolingual patients while the two groups were matched on level of cognitive performance and education, supporting the idea of cognitive reserve function of bilingualism.
Smirnov et al. (2019)	21 bilinguals with AD (M = 72 yrs); 30 control bilinguals (M = 72.5 yrs)	A bilingual index was used to quantify the relative degree of bilingualism by taking the ratio of nondominant to dominant language naming ability.	Structural T1-weighted images.	Multilingual Naming Test (MINT) in both the dominant and the nondominant language.	A significant correlation between the thickness of the anterior cingulate cortex and naming performance in the non-dominant language controlling for age and education in bilingual patients with AD, whereas no such correlation was found in healthy controls.
Woumans et al. (2015)	69 monolinguals and 65 bilinguals diagnosed with probable AD	A patient was considered bilingual when self-rated as 'good' or higher for L2 skills and spoke this L2 at least weekly before onset and currently	Time of clinical AD manifestation and diagnosis	*N/A*	Significant delay for bilinguals of 4.6 years in manifestation and 4.8 years in diagnosis
Zahodne, Schofield, Farrell, Stern, and Manly (2014)	**1067** participants, **282** having developed dementia when followed up	Spanish-English bilingualism was estimated via both self-report and a measure of English reading level	Rates of cognitive decline and dementia conversion	A range of executive function tasks	Independent of covariates, bilingualism was associated with better memory and executive function at baseline but not with rates of cognitive decline or dementia conversion when controlling for country of origin, gender, education, and length of stay in the U.S.

Cognitive Studies	**Participants**	**Language Background**	**Method**	**Task**	**Results snapshot**

Antón, García, Carreiras, and Duñabeitia (2016)	24 bilinguals (M = 69.38 yrs); 24 monolinguals (M = 68.75 yrs); and another group of 70 bilinguals (M = 69.36 yrs)	Bilinguals used both their languages every day and rated themselves as highly proficient in both	Cognitive assessments	Verbal Stroop and Numerical Stroop	Bilinguals and monolinguals were not different in monitoring or inhibitory measures; No modulation of performance in executive control functions with L2 proficiency.
Bialystok, Craik, Klein, and Viswanathan (2004)	64 younger adults (M = 42.6 yrs, 32 bilinguals); 30 older adults (M = 70.3 yrs, 15 bilinguals)	Bilinguals reported using both languages on a daily basis since school age.	Cognitive assessments	Simon Task	Both younger and elderly bilinguals showed smaller Simon effect than monolinguals.
Bialystok, Craik, and Ryan (2006)	24 younger bilinguals (M = 23.9 yrs); 24 younger monolinguals (M = 25.6 yrs); 24 older bilinguals (M = 64.5 yrs); 24 older monolinguals (M = 66.9 yrs)	*Unspecified*	Cognitive assessments	Anti-saccade task	Bilinguals resolved various types of response conflict faster than monolinguals and this relative advantage generally increased with age.
Bak, Nissan, Allerhand, and Deary (2014)	**853** participants	Bilinguals were classified as participants who reported being able to communicate in L2.	Cognitive assessments	g factor, memory, processing speed, Moray house test, vocabulary/ reading, verbal fluency	Bilinguals performed significantly better than predicted from their baseline cognitive abilities, with strongest effects on general intelligence and reading.
de Bruin, Bak, and Della Sala (2015)	28 active bilinguals (M = 71.86 yrs); 24 inactive bilinguals (M = 70.50 yrs); 24 monolinguals (M = 70.21 yrs).	Active bilinguals used both languages daily; Inactive bilinguals knew both languages, but mainly used English.	Cognitive assessments	Simon task, Task switching	Active bilinguals showed significantly smaller raw task switching costs (i.e., difference between switch and non-switch trials) compared to monolinguals. Other group differences were not significant.

Crane et al. (2010)	**2520** bilinguals (age> 70 yrs)	Second-generation Japanese-American bilinguals. Categorized based on midlife self-reported use of spoken and written Japanese	Cognitive assessments	A range of cognitive functioning tasks	Rates of cognitive decline were not related to use of spoken or written Japanese, controlling for age, income, education, smoking status, apolipoprotein E e4 alleles, and number of study visits.
Kirk, Fiala, Scott-Brown, and Kempe (2014)	32 bilinguals; 48 monolinguals (age > 69 yrs)	Bilinguals reported using both languages frequently	Cognitive assessments	WAIS and Simon Task	No group difference in overall reaction times or in magnitude of the Simon effect between bilinguals and monolinguals.

Imaging Studies	**Participants**	**Language Background**	**Method**	**Task**	**Result snapshot**
Abutalebi et al. (2014)	23 monolinguals (M = 62.2 yrs); 23 bilinguals (M = 61.9 yrs)	L1 Cantonese and L2 English for 12 bilinguals and two Chinese dialects for 11 bilinguals. Daily exposure: 3.7 hours per day and AoA in L2: 18.9.	VBM	*N/A*	1) Both groups showed age-related changes in frontal and parietal regions. Experience-dependent age-related decrease in GMV (B < M). Increased GMV in left temporal pole in bilinguals. 2) Positive correlation between naming performance in L2 and GMV in temporal pole.
Abutalebi, Canini, Della Rosa, Green, and Weekes (2015)	30 bilinguals (M = 63.2 yrs); 30 monolinguals (M = 61.8 yrs).	Picture naming in L1 and L2; Self-reported L2 exposure and AOA. Cantonese and English/Mandarin bilinguals (late learners of L2, 18+, and L2 exposure: 4.3 hours per day)	Structural T1-weighted images. VBM; Grey matter and white matter and cerebrospinal fluid volumes; ROI analysis.	*N/A*	1) Monolingual speakers showed reduced GMV in right IPL as a function of age; there were no age effects in elderly bilingual speakers; 2) Bilingual speakers compared to age-matched control showed increased grey matter volume in both inferior parietal lobules.

Abutalebi, Guidi, et al. (2015)	30 bilinguals (M = 63.2 yrs); 30 monolinguals (M = 61.8 yrs).	Picture naming task in L1 and L2; Translation task from L1 to L2 and *vice versa*. Self-reported L2 exposure and L2 AOA.	Structural T1-weighted images. VBM analysis; Grey matter (GM), White matter (WM) volumes	Flanker task, ex-Gaussian analysis	1) Bilinguals displayed better performance than monolinguals. 2) Increase in age correlated with a decrease in GMV in right DLPFC, across both groups. 3) Bilinguals showed higher GMV in ACC than monolinguals. 4) Difference between reaction times to incongruent and congruent trials (i.e., more control) was positively correlated with GMV in DLPFC for monolinguals but not bilinguals.
Anderson et al. (2018)	31 bilinguals (M = 74 yrs); 30 monolinguals (M = 75.4 yrs). Another two matched subgroups (23 bilinguals and 23 monolinguals)	Older bilinguals spoke English and another language, 72% of them continually used their second language throughout life.	DTI Tract-based spatial statistic analysis.	*N/A*	Bilinguals had greater axial diffusivity in the left superior longitudinal fasciculus in not only unmatched samples using cognitive performance as covariates, but also in subset of matched samples, supporting a neural reserve account.
Ansaldo, Ghazi-Saidi, and Adrover-Roig (2015)	10 monolinguals (M = 74.5 yrs); 10 bilinguals (M = 74.2 yrs).	Bilinguals were native French speakers who learned English from various ages (6-39 years). They reported at least 30% L2 use in daily life.	SPM, fMRI	Simon task	Elderly bilinguals and monolinguals have equivalent interference control abilities, but relay on different neural substrates (Incongruent trials: bilinguals left inferior parietal lobule; monolinguals: right middle frontal gyrus).
Berroir et al. (2017)	10 monolinguals (M = 74.5 yrs); 10 bilinguals (M = 74.2 yrs).	Native French speakers who learned English from various ages (6-39 years). Bilingual participants reported at least 30% L2 use in their daily life.	Task-based functional connectivity	Simon task	The brain network identified in monolinguals included a larger set of areas than that found in bilinguals, i.e., areas involved in visual, motor, executive functions, and interference control. In contrast, bilinguals showed greater connectivity in the inferior temporal sulcus. Interpretation suggests that bilingual brain resolves visual-spatial interference economically, by allocating fewer and more clustered regions.

Cargnelutti, Tomasino, and Fabbro (2019)	Lifespan meta-analysis of 57 studies (**227** very early bilinguals, AOA < 3 yrs; **1048** early bilinguals, AOA < 6 yrs; **1509** late bilinguals, AOA > 6 yrs)	Varied	53 MRI and 4 PET studies		L2 entailed a greater enrollment of brain areas devoted to executive functions, and this was also observed in proficient bilinguals, regardless of age of acquisition.
Del Maschio et al. (2018)	22 older bilinguals (M = 62.32 yrs); 22 younger bilinguals (M = 20.5 yrs); 22 older monolinguals (M = 62.05 yrs); 22 younger monolinguals (M = 20.86 yrs)	Bilinguals were proficient in both languages	Cognitive assessment, and T1-weighted structural images	Flanker task	1) Bilinguals had greater GMV than monolinguals in key regions of interest (ACC, Caudate, PFC, IPL) across age. 2) Executive control performance in monolingual seniors was strictly related to GMV, this was not observed for bilingual seniors or younger participants in either group. 2) Age-related cognitive decline following GMV loss in the executive control network was delayed in bilinguals.
García-Pentón, Fernández, Iturria-Medina, Gillon-Dowens, and Carreiras (2014)	13 monolinguals (M = 29.07 yrs); 13 bilinguals (M = 24.08 yrs).	Bilinguals reported daily exposure to two languages.	DTI and Graph network efficiency measures.	*N/A*	Bilinguals develop specialized language sub-networks to deal with their two languages. One of these sub-networks comprises left frontal and parietal/temporal regions, while the other comprises left occipital and parietal/temporal regions and also the right superior frontal gyrus.
Gold, Johnson, and Powell (2013)	20 bilinguals (M = 63.9 yrs); 63 monolinguals (M = 64.4 yrs).	Bilinguals had been speaking English and another language on a daily basis before the age of 10 and rated themselves as highly proficient in both their two languages	DTI; Grey Matter: Structural volumetric analyses. VBM	*N/A*	1) DTI: Bilinguals had relatively lower FA than monolinguals in the inferior longitudinal fasciculus and inferior fronto-occipital fasciculus, fornix and corpus callosum. Bilinguals showed several regions of increased RD relative to the monolingual group in similar regions. 2) VBM: No difference between bilinguals and monolinguals. 3) Since groups were matched on demographic variables and cognitive test scores, results support cognitive reserve.

Gold, Kim, Johnson, Kryscio, and Smith (2013)	20 young monolinguals (M = 32.2 yrs); 20 young bilinguals (M = 31.6 yrs); 20 older monolinguals (M = 64.4 yrs); 20 older bilinguals (M = 63.9 yrs).	Lifelong bilinguals spoke English and a variety of second languages (equally proficient), whereas lifelong monolinguals spoke only English, and had no significant exposure to a second language	fMRI, SPM	Color shape task switching	1) Older bilingual adults outperformed their monolingual peers (smaller switch cost) while displaying decreased activation in left lateral frontal cortex and cingulate cortex. 2) The lower BOLD signal in frontal regions accounted for 82% of the variance in the bilingual task-switching reaction time advantage.
Grady, Luk, Craik, and Bialystok (2015)	14 monolinguals (M = 70.6 yrs); 14 bilinguals.(M = 70.3 yrs).	Bilinguals reported using both English and another language regularly since childhood, and were dominant in English for the past 10 years.	Resting state functional connectivity	*N/A*	1) Stronger connection in default model network and fronto-parietal control network for bilinguals. 2) Bilinguals showed relatively stronger correlations between intrinsic connectivity in the PFC and task-related increases of activity in prefrontal and parietal regions.
Heim et al. (2019)	**399** life-span participants (175 bilinguals)	Bilinguals were proficient in both languages, but were not simultaneous bilinguals	T1-weighted structural images	*N/A*	Bilinguals had higher gray matter volume in the left IFG/IPL than monolinguals, which disappeared with age. The reserve disappeared earlier in the IFG than the IPL.
Luk, Bialystok, Craik, and Grady (2011)	14 monolinguals (M = 70.6 yrs); 14 bilinguals.(M = 70.3 yrs).	Bilingual reported that they had used both English and another language regularly since childhood, and were dominant in English for the past 10 years.	DTI & Resting State Connectivity	*N/A*	Higher WM integrity in older bilinguals than monolinguals. Bilinguals showed stronger anterior to posterior functional connectivity in the frontal lobe as compared to monolinguals.
Olsen et al. (2015)	14 monolinguals (M = 70.6 yrs); 14 bilinguals (M = 70.3 yrs).	Monolinguals reported English to be their only communication language, whereas older bilingual adults reported having used both English and another alphabetic language regularly since childhood (before age 11).	Structural T1-weighted Data: grey matter, white matter volume	Stroop Task	1) Bilinguals exhibited greater frontal lobe white matter compared with monolinguals. Age was negatively correlated with temporal pole cortical thickness in monolinguals only. 2) Stroop performance was positively correlated with frontal lobe white matter volume.

Note: Particularly large participant samples are highlighted in **bold**

Glossary

DTI: Diffusion Tensor Imaging. A technique using in neuroimaging to map and characterize the three-dimensional diffusion of water as a function of spatial location. Estimates of white matter connectivity patterns in the brain from white matter tractography may be obtained on the basis of diffusion anisotropy. Commonly used measures include fractional anisotropy (FA), radio diffusivity (RD), mean diffusivity (MD), and axial diffusivity (AD).

fMRI: functional Magnetic Resonance Imaging. It provides an indirect index of brain activity by detecting variations in blood oxygen level dependent signals in turn related to variations in oxyhemoglobin concentration in the blood vessels.

FDG-PET: PET is a nuclear medicine medical imaging technique that produces a 3-D image of metabolic processes in the body. A PET scan uses a small amount of a radioactive drug, or tracer, to show differences between healthy tissue and diseased tissue. The most commonly used tracer is called FDG (fluorodeoxyglucose) hence the term FDG-PET scan.

Functional Connectivity: Temporal dependency between the neural activation patterns of anatomically separated brain regions, reflecting the level of functional communication between regions. Regions with higher connectivity are likely to belong to the same functional network. Resting-State connectivity quantifies brain connectivity of spontaneous brain activity measured at rest. Task-based connectivity measures brain connectivity in participants performing a task.

GMV: Grey Matter Volume.

ROI: Region of Interest. ROI-driven data analyses in neuroimaging studies focus on *a priori* defined regions based on findings from previous studies.

SPM: Statistical Parametric Mapping refers to the building and assessment of spatially extended statistical models to test hypotheses about functional imaging data.

Structural T1-weighted Image: Such image reconstructions emphasize the contrast between gray and white matter, generally involving short repetition time and echo time, in order to maximize anatomical features.

VBM: Voxel Based Morphometry is a technique using MRI that allows the investigation of focal differences in brain anatomy, using statistical inference principles of parametric mapping.