Is the bilingual brain better equipped for aging?
Studies on neural and cognitive reserve in elderly bilinguals*

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Abstract

In the last decade, the study of the cognitive advantages stemming from bilingualism has become a major focus of research in neuroscience. The evidence suggests that bilingualism may contribute to building cognitive reserve but controversies still remain. This paper provides evidence of the so-called "bilingual advantage" by focusing on neural and cognitive reserve. Specifically, we shall discuss (a) the rationale underlying the idea that bilingualism might provide a cognitive advantage particularly in aging and (b) the evidence for two types of reserve associated with bilingualism, namely neural and cognitive reserve. In particular, we will focus on evidence from recent functional neuroimaging studies on elderly bilinguals carried out by our research group and others.

Key words: bilingualism, brain, cognitive reserve, neural reserve, aging

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Résumé

Dans la dernière décennie, l'étude des avantages cognitifs du bilinguisme est devenue un axe majeur de la recherche en neurosciences. Les données indiquent que le bilinguisme peut contribuer à la construction de la réserve cognitive, mais des controverses demeurent. Cet article fournit la preuve du soi-disant « avantage bilingue » en se penchant sur les réserves neuronales et cognitives. Plus précisément, nous allons discuter (a) des raisons pouvant expliquer pourquoi le bilinguisme peut fournir un avantage cognitif, particulièrement au cours du vieillissement et (b) des éléments de preuve pour deux types de réserves liées au bilinguisme, à savoir les réserves neuronale et cognitive. En particulier, nous allons nous concentrer sur les données des études récentes de neuroimagerie fonctionnelle portant sur des bilingues âgés, et menées par plusieurs équipes de recherche, dont la nôtre.

Mots-clés : bilinguisme, cerveau, réserve cognitive, réserve neuronale, vieillissement

Canada is a stalwart example of a multilingual-multicultural environment. Based on census data (Statistics Canada, 2012), 80% of the population in the 6 major metropolitan cities speaks a foreign language (i.e., other than French, English and aboriginal languages). The French–English bilingualism rate has increased to 17.5%, and will continue to increase in the years ahead. While acknowledging the increase in bi/multilingualism in our society, concomitantly with the increase in the elderly population of Canada — which will persist for several decades to come — this paper discusses the neural mechanisms via which lifelong bilingualism impacts brain structure and function, thus making the aging brain better equipped for cognitive function.

Why could bilingualism have an impact on brain structure and function?

Bilingualism is a complex phenomenon. Being bilingual implies dealing with two language systems that are in constant competition. Thus, even when the bilingual person is using a given language, both languages are simultaneously active and can, in some cases, affect the process of oral production. This leads to language mixing, language switching or both. Furthermore, bilinguals are able to select one or the other language — or even both, according to the communication situation. Thus, bilinguals progressively develop the ability to mix and switch between languages for effective communication. These abilities develop from childhood, and are refined throughout life.

The complexity of bilingualism as a cognitive and behavioural characteristic has very important consequences for brain structure. The human brain has a unique ability to structurally and functionally reconfigure itself, as a result of lifelong experiences (e.g., language learning, education, skill development, etc.). This structural reconfiguration in turn modifies behaviour, in response to environmental stimuli — whether novel or familiar. These interactions between brain, behaviour, and experience lead to the issues of neuroplasticity and cognitive control, both of which have been studied in reference to bilingualism over the years (Grant, Dennis, & Li, 2014; Perani & Abutalebi, 2015; Ansaldo, Ghazi-Saidi, & Adrover-Roig, 2015; Dash & Joanette, 2016).

Specifically, the ability to juggle with two languages has been reported to enhance cognitive flexibility, and not just in a linguistic scenario (i.e., switching between languages depending on the context). This cognitive flexibility also extends to the context of nonlinguistic tasks related to executive functioning, planning and goal-directed behaviour (Bialystok, Craik, Klein, & Viswanathan, 2004). This constant dealing with two languages recruits cognitive control resources, and their underlying neural circuits (Kroll, 2008), which support planning and organization: two key components of cognition which strongly influence everyday life activities. The working hypothesis is that by exercising the ability to select or inhibit a given language, and shifting from one to the other depending on the communicative situation, bilinguals become experts in dealing with interference between competing stimuli.

Evidence for cognitive and neural reserve in elderly bilinguals: Some controversies and cues to untie the knot

Aging imposes changes that hinder the neural and cognitive abilities; yet, there is evidence that bilingualism provides a "protective shield" against cognitive aging. There are two ways in which this reserve is described: cognitive reserve and neural reserve. Cognitive reserve refers to the availability of adaptive cognitive strategies that allow elderly bilinguals to perform better than their monolingual peers on specific cognitive tasks (e.g., the Stroop task, the Flanker task, negative priming tasks etc.), despite similar anatomical and physiological age-related changes (Stern, 2009). Such experimental tasks tap into cognitive abilities that are continuously put into play in everyday life, such as finding an item in a supermarket in the presence of distractors or making the best choice when deciding which route will better lead to a destination. Thus, cognitive reserve is a key element to successful aging. This ability is dependent on an array of factors, including socioeconomic status, educational attainment, occupational attainment, and experience performing cognitive and physical activities (Bialystok, Craik, & Luk, 2012; Perani & Abutalebi, 2015; Dash & Joanette, 2016). Importantly, growing scientific evidence suggests experiential benefits of bilingualism in older adults that may contribute to a cognitive reserve. These bilingual benefits are evidenced by delaying signs of cognitive aging, including those related to dementia (Guzmán-Vélez & Tranel, 2015;

Bialystok, Craik, & Freedman, 2007; Alladi, Bak, Mekala, Rajan, Chaudhuri, Mioshi et al., 2016).

As for the concept of neural reserve, it refers to the physiological and structural changes operating in the bilingual brain over the course of years. The evidence shows that bilingualism entails neural changes that result in a neuro-protective shield against age-related neural deterioration or illness (Craik, Bialystok, & Freedman, 2010). In particular, as compared to their monolingual peers, bilingual speakers show increased grey matter volume and better preserved white matter tracts in specific brain regions that are prone to age-related changes. This indicates that learning two languages results in building of neural reserve that become very useful to fight against structural and functional brain damage in cases of impaired aging, and maintaining cognitive abilities in successful aging.

In summary, neural reserve might be considered as the brain's hardware. Thus, the evidence suggests that individuals with larger brain resources will tend to have better performance, even in the presence of a given pathology (Satz, 1993). As for cognitive reserve, it could be pictured as the software of the human mind, which provides resilience against age-related neural changes that wear and tear the brain (Tucker & Stern, 2011). Both neural and cognitive reserve support successful aging. There are limited studies exploring the direct link between the two, and most of the studies have focused on one or the other.

The concept of cognitive reserve has created a fair bit of controversy in the literature on bilingualism and aging. A wide variety of studies have discussed the role of bilingualism in building cognitive reserve across the lifespan (Bialystok et al., 2012; Bialystok, Abutalebi, Bak, Burke, & Kroll, 2016; Ansaldo et al., 2015; Luk, Bialystok, Craik, & Grady, 2011), as well as in cases of dementia (Bak, Vega-Mendoza, & Sorace, 2014; Alladi, Bak, Duggirala, Surampudi, Shailaja, Shukla et al., 2013) and stroke (Alladi et al., 2016). This evidence shows better accuracy of performance and faster processing by the bilingual populations as compared to the monolingual ones on different cognitive tasks (e.g., Stroop task, Flanker task, Simon task, other neuropsychological tasks). However, other studies have failed to find such bilingual-monolingual differences, leading several authors to propose that the bilingual advantage had been exaggerated in the literature (Paap & Greenberg, 2013). It should be noted, however, that many of these studies did not always control for a number of co-related factors that have been shown to influence cognition. A careful consideration of confounding variables, as well as use of different methodologies, may help us in understanding the impact of bilingualism on cognition.

The lack of consistency in these studies is attributed to the diversity of tools used to measure the degree of bilingualism, the variability in testing methodologies, the wide array of populations (e.g., young adults, children, old adults, illiterate adults, individuals with dementia), as well as the different types of experimental tasks under study (i.e., language tasks, attentional, memory or executive function tasks). Particularly, the heterogeneity in measures of bilingualism may be the key cause of the variability of outcomes (i.e. the presence or absence of a bilingual advantage) observed in the literature (Ghazi-Saidi & Ansaldo, 2015; Hilchey & Klein, 2011; Kroll & Chiarello, 2015; Paap & Greenberg, 2013).

Particularly, many of the studies showing no bilingual advantage included young adults at the peak of their cognitive performance (Hilchey & Klein, 2011). Thus, it is possible that the cognitive control demands of the tasks used in studies with young adults were not enough to allow for the expression of the bilingual advantage. Any difference may be less apparent at behavioural levels in young adult population than with more "cognitively vulnerable" populations, such as the elderly and the very young children, where the bilingual advantage has been consistently reported (Grant et al., 2014; Luk et al., 2011; Luo, Craik, Moreno, & Bialystok, 2013). Further, behavioural measures may not be sensitive enough to detect differences. Recent studies with homogenous and well-controlled elderly monolinguals and bilingual population samples have documented a bilingual advantage, both at the behavioural (Calabria, Hernández, Branzi, & Costa, 2012) or brain level (Ansaldo et al., 2015; Calabria et al., 2012), and both with linguistic and nonlinguistic tasks.

In other words, the lack of differences shown between bilingual and monolingual groups reported in several studies (see Paap & Greenberg, 2013, for more details) may be the consequence of poor control of demographic and language learning variables other than bilingualism, which have shown to play a role on cognitive reserve. In particular, immigration and socioeconomic status, as well as education levels were not always controlled in a large majority of studies, thus jeopardizing the potential role of bilingualism on cognitive reserve (Ghazi-Saidi & Ansaldo, 2015; Ghazi-Saidi, Dash, & Ansaldo, in press). However, evidence from a recent epidemiological study shows that bilingualism helps in building cognitive reserve, irrespective of education levels, socioeconomic status, and rural versus urban dwellings (Alladi et al., 2013). One of the crucial findings of this epidemiological study (Alladi et al., 2013) was the presence of a bilingual advantage even in an illiterate sample. Poor educational skills have been consistently related to poor cognitive reserve, and, contrary to these results, critics had previously attributed this bilingual cognitive advantage to the effect of higher education in bilinguals.

Another source of variability in results comes from the heterogeneity of the trajectory in age-related cognitive decline. Not all cognitive processes (memory, attention, cognitive control, language, etc.) show a similar pattern of decline in aging (Dash & Joanette, 2016). Specifically, memory and cognitive control processes are more affected by aging, as compared to language processes. Furthermore, subcomponents of cognitive control — selection, inhibition, switching — may provide variable advantages as a function of bilingualism, and depending on the type of task (i.e., Simon task, Stroop task, flanker task, etc.; Bak et al., 2015). Therefore, the presence or absence of a bilingual advantage may vary depending upon the type of cognitive process tapped by the task in a given study (task-specific advantage). In addition, these cognitive processes may show different patterns of changes depending on language exposure — early versus late bilingualism. For example, in a recent study by Bak et al. (2015), early bilinguals showed an advantage in attention switching, whereas in late bilinguals the advantage was observed on inhibitory control. Bak et al. (2015), while showing the bilingual advantage in postponing signs of dementia, suggested that not all subcomponents of attention are equally influenced by bilingualism. Thus, there is no uniform effect of bilingualism on all the components of cognition — attention, memory, language — as well as their subcomponents such as, in this case, attentional switching and inhibitory control.

To summarize, more than a decade of research on the topic of the cognitive advantages of bilingualism has left us with both interesting findings and fuzzy conceptual boundaries. One potential source of clarification might come from acknowledging that the cognitive advantages resulting from bilingualism should not be considered as an *all or none phenomenon*, but rather is most probably a continuum. The evidence highlights a number of questions; among them, what is this reserve about? How do we conceptualize the neural and behavioural changes that can be associated with the fact of being bilingual? And — essential for research validity — how do we document these changes? Which methods are the best suited to achieve a better understanding of the impact of bilingualism on the brain and on cognition? The next section will address these questions by discussing neuroimaging evidence by our team and others.

Neural reserve: Evidenced by imaging the aging brain

Any goal-directed behaviour targets an optimal performance level. Neural reserve allows the individual to cope with age-related cognitive decline or neuropathology by maintaining a near-optimal performance level. Neuroimaging studies on the links between neural and cognitive reserve represent an important tool to bridge our understanding of the neural changes and corresponding cognitive and functional outcomes over time in the elderly population. Furthermore, a number of neuroimaging techniques have been used to investigate structural and functional differences between bilinguals and monolinguals, in-

TABLE 1

Review of different neuroimaging studies related to bilingualism (last 5 years)

Source	Participant profile	Methodology	Main findings	Brain behaviour correlation
Study on brain structure:				
• Abutalebi et al. (2014)	Italian monolingual 23 62.17y ± 5.36 Chinese bilingual 23 61.92y ± 6.80	VBM*	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.	Positive correlation between naming performance in the second language and GMV in temporal pole.
Studies on structural connectivity:				
• Luk et al. (2011)	English monolingual 14 English monolingual 14 28 participants 70.5y ±3	DTI Tract-based spatial statistics analysis.	Higher WM integrity in older people (B> M). Widely distributed pattern of structural connectivity.	Different set of brain regions involved in suppressing interference in monolinguals and bilinguals — when correlated with reaction time measures.
• García-Pentón et al. (2014)	Spanish monolingual 13 29.07y ±6.6 Spanish–Basque bilingual 13 early 24.08y ±4.62	DTI and Graph network efficiency measures.	Bilinguals develop specialized language sub-networks to deal with two languages.	
• Pliatsikas et al. (2015)	English monolingual 25 28.15y ±5.5 Bilingual late learners (different L1 background, L2 English) 20 28.15y ±5.5	DTI Tract-based spatial statistics analysis.	Higher fractional anisotropy values for bilinguals vs. monolinguals on several WM tracts related to language processing.	The effects of lifelong bilingualism on task switching are larger in older adults than young adults — based on task switching RT data.

*Key on next page.

Source	Participant profile	Methodology	Main findings	Brain behaviour correlation
Studies on brain function:				
• Gold et al. (2013)	Young monolingual 20 32.2y ±3.3 Young bilingual 20 31.6y ±4.3 Older monolingual 20 64.4y ±5.1 Older bilingual 20 63.9y ±4.0	Color shape task switching paradigm, SPM 8 was used for analysis of fMRI data	Decreased activation in left lateral frontal cortex and cingulate cortex for bilingual older adults. Similarity in performance of monolingual young adults and bilingual older adults while showing decrease in activation pattern.	Age-related over-recruitment in bilinguals was correlated with better task-switching performance. BOLD response in frontal region was able to account for 82% of the variance in the bilingual task-switching reaction times.
• Ansaldo et al (2015)	French monolingual 10 74.5y ±7.1 French–English bilingual 10 74.2y ±7.4	Simon task, SPM 8 for fMRI data analysis	Elderly bilinguals deal with interference control without recruiting circuits that are vulnerable in aging.	**Key:** aIFO anterior Insula and overlying Frontal Operculum B Bilingual BOLD Blood Oxygen Level Dependent DMN Default Mode Network DTI Diffusion Tensor Imaging FA Fractional Anisotropy fMRI functional Magnetic Resonance Imaging FPC Fronto-Parietal Circuit GMV Grey Matter Volume M Monolingual SPM Statistical Parametric Mapping SLN Salience Network PCC Posterior Cingulate Cortex RT Reaction Time VBM Voxel-Based Morphometry WM Working Memory y years
Studies on functional connectivity:				
• Luk et al. (2011)	English monolingual 14 English monolingual 14 28 participants 70.5y ±3	Resting-state functional connectivity of frontal lobe regions adjacent to WM areas with group differences in FA.	Bilinguals showed stronger anterior to posterior functional connectivity compared to monolinguals.	
• Grady et al. (2015)	English monolingual 14 English monolingual 14 28 participants 70.5y ±3	Resting state functional connectivity of FPC, SLN and DMN (two-seed approach; PCC was selected as seed for DMN and aIFO was selected for both FPC and SLN).	Stronger connection in DMN and FPC for bilinguals.	

cluding with older individuals. Table 1 presents a non-exhaustive list of studies published in the last five years related to the influence of bilingualism on neural reserve.

Globally speaking, these studies show that — as compared to bilinguals — monolinguals present decreased grey matter volume (GMV) in the brain areas associated with cognitive control processing. Moreover, bilinguals also show increased GMV on the left temporal pole. These changes in GMV were attributed to the language experience (Abutalebi, Canini, Della Rosa, Sheung, Green, & Weekes, 2014).

Similarly, fMRI studies report that, as compared to monolinguals, bilinguals show less activation in brain areas sustaining cognitive control abilities, specifically in the left lateral frontal cortex, and the cingulate cortex (Gold, Kim, Johnson, Kryscio, & Smith, 2013). The authors (Gold et al., 2013) attributed this decrease in activation to better-preserved cognitive control abilities, as reflected by faster task-switching reaction times in the bilingual group. In an fMRI study, Ansaldo and colleagues (2015), tested monolingual and bilingual elderly individuals on the Simon task, and showed no difference in accuracy rates and response times between the two groups. However, while monolinguals recruited the right middle frontal cortex, which is involved in interference control (Berroir, Ghazi-Saidi, Dash, Adrover-Roig, Benali, & Ansaldo, 2017), bilinguals recruited the left inferior parietal lobule, which supports visuospatial processing. Thus, contrarily to monolinguals, who recruited cognitive control processing areas, bilinguals could handle the processing of conflicting information, by recruiting task-specific brain regions without need to recruit the frontal cortex, which is particularly vulnerable to aging (Cabeza & Dennis, 2012). Moreover, this Simon task study rigorously controlled for the factors of second language (L2) proficiency, language use and exposure, education level, physical and leisure activities, socioeconomic status and profession, all of which have been shown to influence cognitive reserve.

Furthermore, Ansaldo et al. (2015) showed that a lack of behavioural difference between elderly bilinguals and monolinguals does not preclude the implementation of different underlying neural mechanisms to perform the task. Hence, apparently equivalent behaviour may be subserved by different neural substrates. In this specific case, the fact that elderly bilinguals perform the task without resorting to the cognitive control circuit represents an advantage, because this circuit is particularly prone to age-related neurodegeneration.

Recent advances in neuroimaging methods for a better understanding of the bilingual brain and cognition

To further our understanding of the links between the bilingual brain and cognition, fMRI-BOLD data can be analyzed from a network perspective. Two types of network approach can be distinguished, structural connectivity, namely the study of white matter tracts, and functional connectivity, which calculates correlations between the activations of ensemble of brain areas. Network configuration (structural or functional) changes according to the type of task to be performed, and the load imposed by the task on the system. Thus, different networks may be put into play, and the degree of correlation between nodes will vary.

Structural connectivity studies of bilingualism are scarce. However, the few existing studies acknowledge the presence of denser white matter tracts in elderly bilinguals as compared to their monolingual peers (Luk et al., 2011; Pilatsikas, Moschopoulou, & Saddy, 2015), along with the development of a language-specific specialized sub-network (left interconnected frontal and parietal-temporal brain regions) in bilinguals (Gracia-Pentón, Fernández, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014). The above changes are seen to be the result of managing two languages over the years. These studies provide evidence for a neural reserve in bilinguals, but further research is still required. Structural functional connectivity data, suggest that neural differences observed between monolinguals and bilinguals may differ as a function of language experience. Such neuroimaging studies are still emerging, and require more specific approaches. Thus, the advances in neuroimaging technology represent an important avenue for an in-depth analysis of the impact of bilingualism on brain function and behaviour.

As for functional connectivity, studies have been predominantly carried out on resting state data, and they report comparatively stronger anterior to posterior functional connectivity in bilinguals, as compared to monolinguals (Luk et al., 2011), and stronger functional connectivity within the default mode network (DMN) and the fronto-parietal control network (FPC) in the bilingual sample (Grady, Luk, Craik, & Bialystok, 2015).

More recently, Berroir and associates (2017) have adopted a connectivity approach to unfold this relationship, in order to look at the global benefit of bilingualism as a neuro-protective factor. A "Small-World Approach" was employed to the study of interference suppression in elderly bilinguals and monolinguals. In the Small-World Approach, each element of the system can be reached from every other element in a relatively small number of intermediate steps. In other words, the Small-World Approach is intermediate between the random network approach, and a clustered network approach (Bullmore & Sporns, 2009). Small-World Approach helps in understanding the brain networks in the presence of highly clustered short-distance connections as well as more specific long-distance connections that enable efficient communication (Sporns, 2014). Thus, Berroir et al. (2017) modelled the entire brain from each subject, and extracted the fMRI signal (from the experimental task) for each region. All emerging networks were submitted to correlational analyses, to ponder their respective degree of involvement on a given task, and comparing their interactions across the two target populations. Contrary to previous work focusing on resting state data — thus not requiring participants to perform a task (Luk et al., 2011; Grady et al., 2015) and focusing on a predetermined set of areas composing the DMN — Berroir et al. (2017) used an active condition. This required the participants to use executive, visual, and motor processing. They then used a functional connectivity analysis, the Small network explained above, applied to the whole brain. In this way, Berroir et al. (2017) characterized the bilingual and monolingual functional networks and the degree of connectivity for the performance of the Simon task.

In bilinguals, greater connectivity was observed in the inferior temporal sulcus, which plays a role in visuo-spatial processing. In monolinguals, greater correlation strength was observed within a large set of brain areas involved in visual, motor, executive functions and interference control (Berroir et al., 2017). These results show that elderly bilinguals allocate fewer brain resources and a set of task-specific brain areas to perform a complex task, thus showing better brain global efficiency, as compared to elderly monolinguals. Specifically, bilinguals recruit a network composed by two highly specialized on the task areas, while monolinguals recruit a large network including a wide variety of motor, executive and visual processing areas (for more details, see Ansaldo et al., 2015).

In summary, the variance observed in terms of a bilingual advantage calls for methodological approaches that can better grasp the complexity of this research field. Among them, neural network — structural and functional connectivity — appears as an interesting avenue for disentangling the multiple factors that play a role in the manifestation of age-related cognitive advantages.

Conclusion

A large body of research has established the phenomenon of neural plasticity as an outcome of diverse experiences (Stern, 2009). There is evidence that some individual experiences are the fundamental elements of cognitive and neural reserves, both of which most likely have reciprocal influences on each other.

Seniors account for 15% of the Canadian population and 45% of health care expenditures (Canadian Institute of Health Information, 2014). Aging in two languages has benefits not only in the social domain, but also on brain and cognitive health. Given that better cognitive health allows individuals to sustain an independent lifestyle, and considering the positive impact that this will have not only on the aging individuals themselves but on their proxies, it will be important to explore in depth the role of bilingualism as a factor of quality of life. To do so, future research on bilingualism and aging should integrate the concepts of neural and cognitive reserve into one single framework that could clearly account for both the cognitive, and the neural determinants of the bilingual advantage. Moreover, these advantages should be formulated in terms of their impact on everyday-life situations.

More research is required to increase our knowledge on this complex and fascinating issue. Learning a second language could represent a long-term cognitive investment, whose profit arrives in old age, in the form of an array of neural and cognitive resources; a reserve that can help to better cope with age-related cognitive decline, thus contributing to well-being. The outcome of this type of research has potential to provide important cues for building policies that will promote better aging, while reducing health care costs.

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