The potential benefits of bilingualism for the aging brain: A comparative analysis of the white matter integrity, gray matter volume, and cognitive functioning in aging bilinguals and monolinguals

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Abstract

Cognitive decline in association with decline of white matter (WM) integrity and gray matter volume (GMV) have been associated with aging. Researchers have noticed that while some individuals are extremely susceptible to cognitive decline and age-related neural deterioration, the others seem to fare better. Further observation has led to the conclusion that seniors that participate in daily activities over an extended period of time, such as playing a musical instrument or speaking a second language, have increased cognitive outcomes as compared to individuals of the same age who did not participate in such activities. This literature review aims to examine bilingualism as a factor that modulates the white matter integrity, gray matter volume, and cognitive functioning of early aging bilinguals. Multiple studies have observed increased white matter integrity in the corpus callosum, superior longitudinal fasciculus, and inferior longitudinal fasciculus of aging bilinguals. In the gray matter volume, there were multiple studies that observed an increase in the temporal lobe, inferior parietal lobule, and anterior cingulate. These measures were further correlated to increased cognitive control in the aging bilinguals.

Keywords: French, Communication Disorders, White Matter Integrity, Gray Matter Volume, Cognitive Functioning

Introduction:

Bilingualism or the use of at least two languages by an individual or a group has been increasingly prevalent in the demographics of the United States population. Newly released census bureau data for 2017 shows that 21.8% of residents speak a foreign language at home as compared to the 11% in 1980. As the numbers of bilinguals increase steadily in the United States, there is an implication of the neurological and cognitive differences of a bilingual population from the monolingual population.

Although bilingualism is a seemingly straightforward concept, it is multidimensional in the degree of fluency, the manner and age of acquisition, and the context of the acquisition of the speaker. Further, bilingualism is a continuum and some bilinguals can have better knowledge of one language over another (Moradi, 2014, p.107). There are many classifications of bilinguals that are dependent on the stage of acquisition, the manner of acquisition, and cultural identity. This paper will focus on the classifications made due to age of language acquisition.

Early bilinguals attain their language in a period of pre-adolescence and usually attain native-like competence in both of their languages. In contrast, late bilinguals attain their second language (L2) after the age of 8 years old (Moradi, 2014, p.107). Typically, since these individuals have learned their L2 after the critical period of second language learning, which usually extends from early infancy until puberty, they use the experience of their L1 to learn their L2. They can produce structural grammatical inaccuracies and be unable to detect phonetic differences between sounds (Moradi, 2014, p.108). However, this does not mean that late bilinguals will not attain proficiency in their L2 and new research has questioned the significance of the critical language period. Research studying bilinguals who have used their L1 and L2 on an everyday basis has shown changes in the brain that can take place as a result of language learning (Pliatsikas et al., 2015, p. 1334).

Studies conducted with young bilinguals tend to show the correlation between bilingualism, white matter integrity, and gray matter volume. There is also evidence supporting the notion that greater white and gray matter have been correlated to increased cognitive performance. However, the evidence concerning white matter integrity in lifelong bilinguals is conflicting. The studies conducted with young bilinguals poses the question: Are these changes really lifelong and are they sustained in the aging bilingual population? "There is some evidence that speaking more than one language alters cognitive and attention network processes. This ability may have a beneficial effect on the maintenance of brain integrity with age" (Pliatsikas et al., 2015, p. 1334). This paper will systematically detail the observed differences both neurologically in the gray and white matter and cognitively in the aging early bilingual population compared to the aging monolingual population.

Chapter 1: White Matter

In previous research, white matter was considered a passive infrastructure that is composed of millions of communication cables or axons that are coated with myelin. Conversely, white matter is anything but passive, affects intelligence, and the deterioration of the white matter can lead to a multitude of dysfunctions in the brain (Fields, 2008, p. 54). This "neural information highway" is underneath the gray matter and fills nearly half the brain (Fields, 2008, p. 54). Information must be transmitted back and forth among different hemispheres of the brain because each center has a particular function (Fields, 2008, p. 59). The white matter is crucial for both the conduction of these impulses and for the speed of transmission of the signal (Fields, 2010, p. 768). One vital mechanism of the white matter is the myelin that coats the axons. While the axon is the part of the nerve cell along which nerve impulses are conducted, the myelin is a sheath that coats the axons and increases the speed of transmission. The myelin is laid on the axons and "is wrapped up to as many as 150 times between every node which increases the efficiency of the transmission" (Fields, 2008, p. 56). Myelinated nerves have nodes of ranvier which allow impulses to leap from node to node, which increases the velocity and thus the speed of conduction (Newman, 2017). Due to the myelination of the nerves and the nodes of ranvier, "nerve impulses race down axons on the order of 100 times faster when they are coated in myelin" (Fields, 2008, p. 56). Another example of the increased speech of conduction of the myelinated axons occurs when an impulse travels from one hemisphere to another through the corpus callosum. The corpus callosum is a bundle of nerve fibers that connects the left and the right hemispheres of the brain and is a major part of the white matter network (Fields, 2008, p. 56). While an impulse travelling to another hemisphere through myelinated axons in the corpus callosum usually takes 30 milliseconds it could take from 150 to 300 milliseconds through unmyelinated axons (Fields, 2008, p. 59). Thus, the myelinated axons have an advantage in the increased speed of transmission of the nerve impulses due to the myelin coating.

When compared to the function of the gray matter neurons that execute mental and physical tasks, the functioning of the white matter could be just as critical in the mastering of mental and social skills (Fields, 2008, p. 54). While the gray matter development peaks at age eleven or twelve, the white matter continues developing into the twenties and potentially continues to develop even longer than that (Newman, 2017). The development of the white matter into adulthood may indicate that the white matter is more affected by life experience.

Studies have shown that white matter varies as people learn and practice a new skill (Fields, 2008, p. 54).“Memory and learning occur when certain neuronal circuits connect more strongly and the myelin affects this strength by adjusting conduction velocity so that volleys of electrical impulses arrive at the same neuron simultaneously from multiple axons” (Fields, 2008, p. 59). The reason for the consideration of the white matter as passive was because it only includes axons and glia and not neuronal cell bodies or synapses. Even so, the learning of a new skill has been correlated to changes in the white matter of the brain which refutes the claim that the white matter acts as a passive infrastructure (Fields, 2008, p. 59).

Bilingualism and learning an instrument can also be compared because both of these skills have an effect on the structure of the brain and in particular on the corpus callosum (Anderson et al., 2018, p. 3). Learning involves changes in strength of synapses, the connections between neurons in gray matter, and has an effect on the white matter (Fields, 2010, p. 768).

Aging has been shown to play a role in the integrity reductions of the white matter of the senior population. Numerous structures containing white matter are susceptible to deterioration due to aging. The prefrontal white matter has been recognized to be one of the regions that is most affected by the aging process. The frontal lobe is another one of the earliest structures to undergo white matter deterioration due to aging with the executive functions decreasing as well (Byrd, 2012, p. 26). The hippocampus has also been shown to suffer age related atrophy. Further, there can be age-related changes in the myelin-producing oligodendrocytes and in the other glial cells. While various cognitive functions can be attributed to the greater organization of white matter or a greater white matter integrity the inverse is true for white matter atrophy (Newman, 2017). White matter integrity deterioration is associated with a decreased cognitive and motoric performance because of the reduction of the signal transmission between the gray matter structures (Gold et al., 2013, p. 2841). Furthermore, changes in behavioral functions of the aging population have been observed in executive and memory functioning (Olsen at al., 2015, p. 129). The age-related reductions of the white matter produce a disconnected state where age-related performance declines specifically in the domain of cognition (Liu et al., 2017, p. 76). While white matter deterioration is normal in the aging process, aged white matter is more susceptible to undergo abnormal changes due to neurological diseases. In other words, due to age-related decline of the white matter, the elderly population is more susceptible to suffer from increased atrophy if they undergo a stroke or a TBI and are increasingly susceptible to develop neurodegenerative diseases (Liu et al., 2017, p. 76). In recent studies, decreases in myelin have been associated with schizophrenia and even PTSD, which highlights the importance of myelin and the white matter functions. Since, learning and using a skill, such as a second language (L2), has been shown to strengthen neuronal connections of the white matter between certain regions of the brain it is imperative to discover if these connections remain strengthened in the aging bilingual population.

Studies conducted with young bilinguals tend to show the correlation between bilingualism and increased white matter integrity. A study conducted by Kuhl et al., used diffusion tensor imaging to compare the white matter structure between young adult American monolingual and Spanish-English bilingual adults (Kuhl et al., 2016, p. 1). "Diffusion tensor imaging (DTI) provides indirect measures of white matter integrity that indicate the degree of anisotropic water diffusion constrained by axons (fractional anisotropy, or FA), such that higher FA indicates better integrity" (Luk et al., 2011, p. 16808). This measure allows researchers to study the microstructure of white matter through the use of diffusion tensor. This study was conducted in young bilingual and monolingual adults with widespread white matter structural differences being exhibited bilaterally establishing a correlation between bilingualism and structural changes in the brain (Kuhl et al., 2016, p. 1). The findings of the study suggest that the immersion of individuals in an environment where the language is spoken induces changes in the adult brain (Kuhl et al., 2016, p. 1). Group differences in the white matter integrity were observed in the DTI measures in the cerebrum and the cerebellum (Kuhl et al., 2016, p. 4). The differences in the white matter were observed in white matter tracts associated with "language processing and production, executive function, motor function, social cognition and emotion" (Kuhl et al., 2016, p. 6). In the bilingual group, correlations between white matter changes and immersion were associated with increases in fractional anisotropy (FA) and decreases in radial diffusivity (RD) and mean diffusivity (MD) (Kuhl et al., 2016, p. 6). Fractional anisotropy can be decomposed in order to estimate the diffusivity parallel to the white matter tracts whis is axial diffusivity or perpendicular to the white matter tracts which is radial diffusivity (Luk et al., 2011, p. 16808). A greater measure of FA usually indicates increased white matter integrity. “The pattern of lower FA and higher RD is thought to reflect reduced myelin, small vessel alterations, and reductions in axonal structure/coherence.”(Gold et al., 2013, p. 2843). Decreases in the RD and MD are associated with “ higher density and packing of fibers-findings of the white matter” while increased FA indicated “processing efficiency” (Kuhl et al., 2016, p. 7). Thus, in this study the white matter had a significantly greater integrity in the cerebrum and cerebellum in the bilingual sample group as can be seen by the FA and RD measures.

Other studies further strengthen the evidence that there is an increase in white matter integrity in the young bilingual brain. Several studies reveal an increased white matter integrity in the corpus callosum which may allow bilinguals to exchange information across hemispheres in a more efficient way than monolinguals (Anderson et al., 2018, p. 1). A study conducted by Mohades and colleagues demonstrated the correspondent effects of early language learning on the white matter of 30 bilingual children (Pliatsikas et al., 2015, p. 1335). A different study conducted by García-Pentón and colleagues compared 13 Spanish-Basque early bilinguals and 13 Spanish monolinguals and revealed that the white matter networks provided connections of increased efficiency among gray matter structures in bilinguals. These networks connect language processing and control areas. The researchers concluded that it is possible that bilinguals “are more capable of transferring information more efficiently between different language-related brain areas, especially networks that are involved in tackling phonological, semantic, and syntactic competition between languages, as well as in word recognition and semantic processing" (Pliatsikas et al., 2015, p. 1335). These studies focus on the white matter tracts of early bilinguals and question if similar effects can be observed in lifelong bilingual populations (Pliatsikas et al., 2015, p. 1335). Although research indicates that increased white matter integrity is found in young bilingual brains, the evidence concerning white matter integrity in lifelong bilinguals is conflicting.

Assuming that learning and using an L2 in an immersive environment after childhood can change the white matter structure, it is possible that this mechanism can then preserve the white matter integrity in an aging bilingual population (Pliatsikas et al., 2015, p. 1334). White matter (WM) integrity is known to decrease due to aging. It can be hypothesized that lifelong bilinguals have a greater white matter integrity than monolingual individuals in the same age group due to observed increased white matter integrity in young bilinguals. A stronger white matter connectivity would indicate a better executive performance and information transfer between the different regions of the brain (Luk et al., 2011, p. 16808). Luk, Bialystok, Craik, and Grady used diffusion tensor imaging, and found higher white matter integrity in fourteen aging early bilinguals with a mean age of 70 than in their monolingual counterparts in the corpus callosum extending to the superior and inferior longitudinal fasciculus. The inferior longitudinal fasciculus is an associative white matter pathway which connects the occipital and temporal-occipital regions of the brain to the anterior temporal areas (Herbet et al., 2018). The monolingual group was found to have a higher radial diffusivity in the body of the corpus callosum and this overlapped with some of the areas in which bilinguals had an increased fractional anisotropy. Although the role of the corpus callosum in language processing is not completely understood nevertheless "it has been heavily implicated in effective interhemispheric communication and in executive functioning" (Pliatsikas et al., 2015, p. 1336). It is important to note that it is significant that the inferior longitudinal fasciculus and the corpus callosum were the areas displaying increased white matter integrity because they are two pivotal pathways that connect different parts of the brain. In this study, maintenance of white matter integrity was observed in the bilinguals due to the higher fractional anisotropy values in the corpus callosum that extended to the bilateral superior longitudinal fasciculus and to the right inferior fronto-occipital fasciculus and uncinate fasciculus (Luk et al., 2011, p. 16810). The researchers further hypothesized that "stronger white matter connections would be associated with more widely distributed patterns of functional connectivity in bilinguals" (Luk et al., 2011, p. 16808). This study also measured the resting-state functional connectivity in frontal regions that are crucial for bilingual language switching (the bilateral inferior frontal gyri and corpus callosum). The findings disclosed that bilinguals have more distributed resting-state functional connectivity in the regions that are close to where white matter differences between bilinguals and monolinguals were observed (Luk et al., 2011, p. 16813). The researchers suggest "that the enhanced structural and functional connectivity in bilingual older adults may provide at least part of the neural basis for the phenomenon of "brain reserve" (Luk et al., 2011, p. 16813). This study displays that lifelong bilingual experience leads to increased white matter connectivity. Enriched experience is further tied to the concept of a brain reserve by preserving white matter throughout the aging process. This lifelong bilingual experience could possibly even enhance cognitive control and influence the brain structure. Thus, the correlation between lifelong bilingualism, white matter integrity, and a more distributed functional connectivity is established in this study (Luk et al., 2011, p. 16813).

The study of Pliatsikas et al. revealed higher fractional anisotropy values for their bilingual group in different white matter tracts that are associated with language processing in a similar fashion as reported for both older and early bilinguals. Pliatsikas's study revealed higher fractional anisotropy values for the bilingual group bilaterally in the corpus callosum and these results extended to the inferior fronto-occipital fasciculus (IFOF), uncinate fasciculi, and superior longitudinal fasciculi (Pliatsikas et al., 2015, p. 1335). The findings of this study support the results obtained by Luk and colleagues. In the study, the bilingual participants' inferior fronto-occipital fasciculus was affected bilaterally showing increased fractional anisotropy values similarly to the study undertaken by Luk and colleagues. (Pliatsikas et al., 2015, p. 1335). The genu of the corpus callosum was also found to be affected just like in the study of Luk and colleagues. (Pliatsikas et al., 2015, p. 1336). The superior longitudinal fasciculus and the uncinate fasciculus have also been affected by bilingualism as shown both by the studies of Pliatsikas and Luk and colleagues (Pliatsikas et al., 2015, p. 1336). The superior longitudinal fasciculus and the uncinate fasciculus connect Broca's area to temporal areas. Specifically, they connect Broca's area to the superior temporal gyrus and the middle temporal gyrus which have been correlated to syntactic, semantic, and phonological processing (Pliatsikas et al., 2015, p. 1336).

Although this study investigated twenty late L2 speakers of English and twenty five monolinguals in their late twenties to early thirties, the results show that these changes may begin in the young bilingual brain and remain sustained through aging. This is demonstrated by the correlation to the results of Luk and colleagues. The results demonstrated that the young late bilingual group had increased fractional anisotropy values in a network of white matter tracts that are implicated in language (Pliatsikas et al., 2015, p. 1337). The increased fractional anisotropy values signify more efficient processing. Further, the significant effects on the corpus callosum should predict enhanced executive functioning by the same group (Pliatsikas et al., 2015, p. 1337). The researchers postulate that the white matter connectivity and increases are due to the everyday use of an L2 in an immersive environment even for late learners of a second language (Pliatsikas et al., 2015, p. 1337). Thus, the benefits of bilingualism on the white matter of the brain that can be observed in late bilinguals may be reliant on the critical period of second language acquisition to a lesser degree than on the lifelong use and immersion of the two languages (Pliatsikas et al., 2015, p. 1337). This is an important discovery concerning the lifelong use of two languages, an aging bilingual population, and the potential of an increased white matter integrity as a result.

According to Olsen et al., the aging bilinguals with a mean age of seventy showed greater frontal lobe and temporal lobe white matter volumes as compared to monolinguals of the same age and same demographics. The older bilinguals "exhibited greater fractional anisotropy in the corpus callosum and the superior and inferior longitudinal fascicule" (Olsen at al., 2015, p. 129). The study further notes that the decreasing of the white matter has been shown to decrease in the hippocampus and in the frontal lobes as a result of aging (Olsen at al., 2015, p. 129). This study may strengthen the claim of the correlation of bilingualism and the preservation of temporal and frontal lobe functions in the aging bilingual. These regions further correlate with regions that have been identified to present a possible cognitive advantage in bilinguals.

Anterior parts of the corpus callosum have been repeatedly found to exhibit increased white matter integrity in several studies concerning bilingualism. Further, postulates that changes in the inferior fronto-occipital fasciculus and superior longitudinal fasciculus are increasingly observed in studies where bilinguals are in an immersive environment. In the white matter tracts the left inferior fronto-occipital fasciculus, the left superior longitudinal fasciculus, and the corpus callosum have been identified to be correlated to bilingualism (Kuhl et al., 2016, p. 7). The left inferior fronto-occipital fasciculus deals with "cortical organization for language processing" and it is involved in speech comprehension (Kuhl et al., 2016, p. 7). The left superior longitudinal fasciculus is "a major fiber tract of a dorsal stream that is associated with sensorimotor language integration " (Kuhl et al., 2016, p. 7). A study conducted by Singh and colleagues used diffusion tensor imaging to study the cerebral white-matter microstructure. They reported differences in the mean radial diffusivity, axial diffusivity, and fractional anisotropy in the anterior thalamic radiation, right inferior fronto-occipital, and inferior longitudinal fasciculus. Axial diffusivity (AD) and has been shown to measure axon integrity, with higher values indicating better integrity" (Anderson et al., 2018, p. 1). Further, this study shows a positive correlation between L2 proficiency and mean radial diffusivity in the superior longitudinal fasciculus. Although this study incorporates young adult bilinguals it links L2 proficiency and the white matter integrity in the superior longitudinal fasciculus (Singh et al., 2018, p.995). This could indicate that even in aging bilinguals proficiency and white matter integrity in this region are linked. However, this is a supposition that would have to be supported by the replication of this study.

Some studies have inversely shown that there is also a decline in white matter integrity in aging bilingual adults such as the study conducted by Gold, Johnson, and Powell. This study showed that in the population of 20 lifelong bilinguals and 63 lifelong monolinguals at an age of about 63 or 64 with similar levels of cognitive functioning, the bilingual group exhibited a lower cerebral white matter integrity and/or higher radial diffusivity (Gold et al., 2013, p. 2841). It is important to note that a lower radial diffusivity would indicate lower water diffusion perpendicular to the white matter tracts. A higher radial diffusivity indicated age-related cognitive decline or differences (Luk et al., 2011, p. 16808). However, "the most prominent DTI-based group difference observed was lower fractional anisotropy (FA) in the bilingual group in the inferior longitudinal fasciculus/inferior fronto-occipital fasciculus (ILF/IFOF) in the fornix, and in multiple portions of the corpus callosum" (Gold et al., 2013, p. 2844). Some of the regions (ILF/IFOF, fornix, and splenium of the corpus callosum) that showed a lower FA in the bilingual group are the regions of memory circuitry and represent some of the main tracts that are affected in Alzheimer's (Gold et al., 2013, p. 2844). The researchers noted that this cross-sectional design provides a snapshot of the neurocognitive profile at a point in time and these results could indeed reflect preclinical Alzheimer's disease in their bilingual senior group. (Gold et al., 2013, p. 2845). Additionally, "the researchers point out that their bilinguals were comparable or even more efficient than the monolinguals in a series of executive tasks, as reported in a separate study, which is in accordance with previous findings on bilinguals with Alzheimer's disease" (Pliatsikas et al., 2015, p. 1337).

Similarly to the study conducted by Gold and colleagues, another investigation studying healthy senior bilinguals as compared to healthy senior monolinguals found that the monolingual group had a higher fractional anisotropy than the bilinguals specifically in the right hemisphere in the internal capsule, the anterior corpus callosum, the corona radiata, and the inferior and superior longitudinal fasciculi. However, "bilinguals, in contrast, showed widespread radial diffusivity at significantly greater levels than monolinguals in nearly all white matter brain regions. Bilinguals also had greater axial diffusivity than monolinguals, particularly in the left hemisphere, likely contributing to the lack of significance of the fractional anisotropy contrast in that region." (Anderson et al., 2018, p. 7). When the bilingual and monolingual groups were matched on background variables through statistical control only the axial diffusivity findings were determined to be statistically significant (Anderson et al., 2018, p. 7). Thus, both the fractional anisotropy and the radial diffusivity findings were eliminated which suggests that these measures confounded the results (Anderson et al., 2018, p. 7). Further, "axial diffusivity is an index of diffusion along the primary gradient that is associated with positive cognitive outcomes" (Anderson et al., 2018, p. 8). The researchers state that there is a possibility that bilingual brains and the greater white matter integrity along the axial diffusivity may reveal the cognitive reserve in bilinguals and may facilitate communication between the areas of the brain that are deteriorating (Anderson et al., 2018, p. 9). Thus, the integration of these findings in conjunction with the findings of young bilingual white matter increase signifies that there is a correlation between bilingualism and increased white matter integrity (Anderson et al., 2018, p. 10).

Although the results of these studies are somewhat conflicting, it is clear that there are white matter integrity changes that occur or have been sustained in the aging bilingual brain. Some of the findings of the studies supported each other. The corpus callosum, the superior and inferior longitudinal fasciculus were found to exhibit greater fractional anisotropy values and thus greater white matter integrity in aging bilinguals as compared to their monolingual counterparts in two studies. Further, greater functional connectivity was observed in the corpus callosum of the aging bilingual group (Luk et al., 2011, p. 16808). The frontal and temporal lobes were also regions observed to display increased white matter volume (Olsen at al., 2015, p. 129). Increased widespread white matter volume was observed in nearly all white matter brain regions in senior bilinguals in a study conducted by Anderson and colleagues. Moreover, increased axial diffusivity was observed in the left hemisphere of the aging bilingual group (Anderson et al., 2018, p. 10). However, one study produced conflictive results and findings showed a lower radial diffusivity and a lower fractional anisotropy in the corpus callosum of 20 lifelong bilinguals.

Interestingly, the results of the studies conducted by Pliatsikas and colleagues and Singh and colleagues in young adult bilinguals were very similar to the results obtained in some of the studies concerning aging bilinguals. Greater fractional anisotropy values were found in the corpus callosum and extended bilaterally to the inferior fronto-occipital fasciculus, uncinate fasciculus, and superior longitudinal fasciculus (Pliatsikas et al., 2015, p. 1337). Furthermore, greater fractional anisotropy values were found in the inferior longitudinal fasciculus of young adult bilinguals (Singh et al., 2018, p.995). The inferior longitudinal fasciculus, superior longitudinal fasciculus, and the corpus callosum increased white matter integrity has been shown in both the young and aging bilingual groups. This could signify that there is a preservation of the white matter integrity of these structures to avoid the age-related deterioration. These structures are all extremely crucial to the white matter integrity of the brain as they are some of the largest white matter tracts. "The superior longitudinal fasciculus/arcuate white matter complex (SLF/AC) is the largest and most complex white matter tract of the human cerebrum with multiple inter-linked connections encompassing multiple cognitive functions such as language, attention, memory, emotion, and visuospatial function" (Conner et al., 2018, p.S407). "The inferior longitudinal fasciculus (ILF) is a long-range, associative white matter pathway that connects the occipital and temporal-occipital areas of the brain to the anterior temporal areas. In view of the ILF's anatomic connections, it has been suggested that this pathway has a major role in a relatively large array of brain functions." (Herbet et al., 2018). Finally, the corpus callosum which is situated at the center of the human brain is the largest white matter structure of the brain and interconnects and allows communication between the right and the left hemisphere of the brain. Considering that all of these structures play integral parts in the connectivity of the brain and that these structures have been shown to have increased white matter integrity in young adult and senior bilinguals, it can be assumed that aging bilinguals have increased connectivity in their brains through the increased white matter integrity.

In many circumstances, I have come across individuals who have started as bilinguals but lost their ability to speak or use their native language due to not sufficiently speaking their L2. However, true lifelong bilinguals retain their ability to speak their L2 because they use both of their languages on a daily basis. Lifelong bilinguals must constantly manage two different languages since they have been using these two languages since childhood. In order to manage these two languages an individual requires effective cognitive management. It has been postulated that the constant recruitment of cognitively managing two languages can lead to better behavioral performance on tasks testing executive functioning. Moreover, "this prolonged bilingual experience leads to enhanced WM connectivity, which may be one mechanism underlying the bilingual advantage observed in executive function performance" (Luk et al., 2011, p. 16813). Enriched experience, such as bilingualism, can thus possibly preserve the white matter connectivity in the brain from age-related deterioration.

A study conducted by Schweizer and colleagues has compared atrophy in the brain of bilinguals and monolinguals diagnosed with Alzheimer's disease (AD). The bilingual group exhibited a greater amount of brain atrophy when compared to their monolingual peers nevertheless they performed at a comparable level on cognitive tasks when compared to their monolingual peers (Luk et al., 2011, p. 16813). This could indicate that the white matter integrity in healthy older bilinguals could possibly act as a reserve in order to compensate for deterioration of gray matter and thus sustain cognitive performance (Luk et al., 2011, p. 16813). Studies concerning the neurodegenerative disease of Alzheimer's have found the deterioration of white matter integrity to be one of the markers of the disease's progression. Both the anterior portion of the corpus callosum and the superior longitudinal fasciculi have been shown to be sensitive to this deterioration of white matter in the progression of Alzheimer's as these are regions of the brain that are highly correlated to cognitive functioning. As previously mentioned, these areas are known to undergo white matter integrity increases in young bilinguals and in some studies in senior bilinguals. Research has shown there to be a delay in the onset of dementia due to Alzheimer's in older bilingual adults as compared to monolinguals of the same age (Olsen at al., 2015, p. 129). Thus, it can be observed that the white matter integrity changes in the young bilingual brain may continue into aging and help stave neurodegeneration. However, in order to verify the results of the studies, follow up studies should be conducted with larger sample sizes in order to determine the modulations of bilingualism on age-related changes in brain structure.

Chapter 2: Gray Matter

While the white matter can be considered the communication system of the brain by transmitting nerve impulses between neurons; the outer layer of the brain or the gray matter takes on the role of "mental computation and it is composed of densely packed neuronal cell bodies which are the decision making parts of nerve cells or neurons" (Fields, 2008, p. 54). This crucial tissue extends from the brain into the spinal cord is composed of neuronal cell bodies, axons that are not myelinated, and neuron somas. The critical role of the gray matter is in the processing of the information and the release of new information through the axon signaling that is found in the white matter (Mercadante & Tadi, 2020). To the central nervous system, the gray matter is pivotal due to its role in allowing humans to control memory, emotion, and even movement (Mercadante & Tadi, 2020). Unlike the formation of the white matter which can continue well into adulthood, the formation of gray matter begins in the ectoderm and continues to increase until about 8 years of age. Additionally as humans age, the gray matter volume begins to decrease in certain areas of the brain. Further, the gray matter density increases in certain regions of the brain (Mercadante & Tadi, 2020). As the gray matter carries out such a pivotal function in the brain, abnormal levels of gray matter in the brain can have their own significant consequences. Neurodegenerative diseases can result from alterations to the gray matter due to deterioration of the gray matter volume (GMV) or a plaque build up on the gray matter of certain regions in the brain. These neurodegenerative conditions include frontotemporal dementia and the motoric symptomatology of Parkinson's disease (Mercadante & Tadi, 2020).

Typical aging of the brain has been associated with reduction in the gray matter volume, which is specifically taxing on certain structures in the brain. Although, substantial research must still be conducted to identify how age-related neurodegeneration affects different structures throughout the brain; various gray matter anatomical networks have been demonstrated to be susceptible to age related neurodegeneration. A study conducted by Hafkemeijer et al., revealed gray matter atrophy in four networks containing posterior and anterior cingulate cortices, lateral occipital, and subcortical structures in their senior population. The greatest atrophy was found in a sensorimotor network that contains the thalamus, nucleus accumbens, caudate nucleus, and hippocampus (Hafkemeijer et al., 2014, p. 1068). This is especially pertinent because these structures play an important part in the relaying of motor and sensory signals to the cerebral cortex, memory processing, rewarding stimuli, and emotion.

The gray matter has been shown to rapidly decline with age specifically in the regions of the frontal and parietal lobes (Olsen at al., 2015, p. 129). The frontal lobe controls essential cognitive skills in humans that include emotional expression and memory. The parietal lobe functions in the processing of sensory information on the location of the body as well as interpreting visual stimuli. Further, the left anterior temporal pole and the prefrontal cortex also shows increased gray matter atrophy in relation to aging (Abutalebi et al., 2014, p. 2126). The function of the left anterior temporal pole has been debated but it has been associated with cognition and language. The prefrontal cortex is located at the front of the frontal cortex and is associated with many complex cognitive skills. The functions and connections between these structures and others are still being investigated by neuroscience as their functionalities are extremely complex and intricately intertwined. Even though this was a brief overview of the multitude and complexities of the functions of these structures and regions of the brain the power they possess and the potential detrimental effects that gray matter atrophy could have is apparent.

Interestingly, it has been observed that the gray matter volume in the aging brain typically progresses in areas that are necessary for cognitive control such as the parietal and prefrontal cortices (Borsa et al., 2018, p. 59). Thus, the reduction of gray matter structures in aging populations have been associated with poorer cognitive performance (Gold et al., 2013, p. 2841). While normal aging does induce the diminishment of the gray matter volume; the extent of the deterioration may be related to experience (Abutalebi et al., 2014, p. 2126).

Since the extent of deterioration may be related to experience it is possible to postulate that a lifelong experience of bilingualism could be a factor in the amount of deterioration of the gray matter. Researcher R.K. Olsen contemplates the idea that “lifelong bilingualism may result in a different trajectory for gray matter development in a region known for its role in semantic processing, semantic retrieval and naming” (Olsen at al., 2015, p. 133). This would be an astounding finding as the changing trajectory could indicate a protection against neurodegeneration in seniors.

Bilingualism has been described as a sustained experience that induces structural changes in the cortical gray matter. A study conducted with a sample of early and late Italian bilinguals has revealed an increased density of gray matter in the left inferior parietal cortex, a region associated with L2 acquisition and verbal-fluency, and that the degree of this increase is dependent upon the proficiency of the L2. Although both of the bilingual groups showed an increased gray matter density in the inferior parietal cortex, the effect was more profound in early bilinguals in both of the hemispheres. Thus, the density of the gray matter increase in the inferior parietal cortex has a correlation with the proficiency of the speaker of the L2 (Mechelli et al., 2004, p. 757). Interestingly, as mentioned before, the parietal lobe is one of the lobes that is extremely susceptible to gray matter atrophy. Due to the fact that this study was conducted with younger bilinguals, in order to prove its applicability on an aging population, it would have to be reproduced. Although this is a pioneering field of study, studies observing the gray matter in aging bilinguals and their monolingual counterparts have been conducted with fascinating results.

The study of Olsen et al., has shown that aging bilinguals exhibited greater temporal lobe gray matter volumes. In the aging bilingual sample size, "greater grey matter volumes were found in the left anterior temporal pole" (Olsen at al., 2015, p. 129). Another study produces extremely similar results to this one: a study by Abutalebi et al., indicated that between 23 bilingual Chinese seniors and 23 monolingual Italian seniors, the bilinguals have increased gray matter in the anterior temporal lobe. Bilinguals showed increased gray matter volume as compared to their monolingual counterparts specifically in the anterior temporal lobe cluster which include the left temporal pole, the right temporal pole, and the bilateral orbitofrontal cortex (Abutalebi et al., 2014, p. 2132). The most significant increase in the GMV for the bilingual speakers and the most extensive age-related decreases were found in the left temporal pole (Abutalebi et al., 2014, p. 2126). Monolinguals in this sample were reported to have a more extended brain pattern of deterioration due to aging. Bilinguals also showed aging effects in the right caudate, bilaterally in the anterior cingulate cortex, parahippocampal gyrus, right pre-and postcentral gyrus, right superior frontal gyrus, left precuneus, left fusiform gyrus, and in the left temporal pole. Even though aging did affect the left temporal lobe for both of the sample groups, this effect was increasingly prominent for the aging monolingual population (Abutalebi et al., 2014, p. 2132). The implications of these results is significant due to the left temporal pole being one of the regions that suffers the greatest deterioration in Alzheimer's patients. The findings could suggest a protective functioning of bilingualism in the deterioration of the gray matter and thus a protection against the development of neurodegenerative diseases.

As mentioned earlier, the left inferior parietal lobule is one of the areas prone to neuroplastic changes as induced by bilingualism and contributes to attentional, linguistic, and action (Abutalebi et al., 2014, p. 3). The study conducted by Mechelli et al. was focused on a young bilingual population and needed to be replicated in order for the results to be applicable to an aging bilingual population. Abutalebi et al. have replicated this study to examine the gray matter volumes in the inferior parietal lobule in a group of thirty Chinese bilinguals with a mean age of sixty three. Their data indicates that the gray matter volume in the bilingual group leading to their conclusion that bilingualism can alter the gray matter volume in the inferior parietal lobule in the aging brain. The monolinguals exhibited reduced GMV as a function whereas the senior bilinguals did not exhibit such a correlation (Abutalebi et al., 2014, p. 7). This region has been associated with multi-domain mild cognitive impairment due to the reduction or deterioration of the gray matter. These studies do not suggest that the parietal lobules are the most sensitive to bilingualism but do imply that changes in the gray matter are plausible in the inferior parietal lobule. They further imply that the gray matter changes are dependent on the level and the frequency with which the language is used (Abutalebi et al., 2014, p. 8).

Another study also does not share the same regions of interest (ROI) as the first two studies. Borsa et al., conducted a study with a goal of examining the neurocognitive benefits that can come with bilingualism in aging seniors. The results found that bilingual seniors did not differ from the monolingual seniors in the mean gray matter volume except in the anterior cingulate cortex (Borsa et al., 2018, p. 58). The anterior cingulate cortex has been hypothesized to have a central role of cognitive functioning. This could signify that there is a level of cognitive functioning protection in the aging bilingual brain. While the monolingual seniors had extended and bilateral patterns of neural decline that were associated with chronological age; the bilingual group showed only a leftward pattern of aging effects on the same brain regions (Borsa et al., 2018, p. 58). Impressively enough, this would suggest that the neural organization in aging bilinguals favors critical right hemisphere structures. However, a plethora of studies concerning precise right hemisphere regions would have to be conducted in order to support this suggestion.

The suggestion of the protection of cognition by the modulation of the gray matter volume in the bilingual brain is strengthened by the study conducted by Heim et al. The group of bilinguals in this study, who were aged from 18 to 87, were found to have a higher gray matter volume in the right inferior frontal gyrus, the anterior cingulate cortex, and the basal ganglia (Heim et al., 2019, p. 158). The study conducted by Hein et al., showed that brain volume was higher in younger bilinguals than monolinguals of their own age group in a population group of 1316 participants aged 18 to 87. However this difference began to disappear in bilinguals older than 55 years of age (Heim et al., 2019, p. 157). During the course of aging, the gray matter volume decreased in both monolinguals and bilinguals and the decrease appears to be more pronounced for the bilingual group in the anterior parts of the brain (Heim et al., 2019, p. 162). Considering posterior atrophy of the gray matter the difference between the older bilingual and monolingual groups remains pronounced (Heim et al., 2019, p. 163). In other words, the older a bilingual person is, the more bilingualism protects the posterior regions of the brain versus the anterior. Another study conducted by Gold, Johnson, and Powell showed that there were no group differences in gray matter volumes between aging bilinguals and monolinguals.

Although these studies produced conflicting results, this may be due in part to the utilization of different regions of interest by the researchers. Most of these studies used voxel-based morphometry and the region-of interest approach in order to extract the gray matter volume. More extensive research needs to be conducted in order to reach conclusions about the entirety of the changes that occur in the gray matter structures of the bilingual aging brain. Furthermore, there are other factors that can modify the gray matter of the brain, such as gender and environment, that need to be controlled for.

Given the differences observed in the studies of greater gray matter volume in aging bilinguals in the temporal lobe and the left anterior temporal pole (Olsen at al., 2015, p. 133), the anterior temporal lobe and the left temporal pole (Abutalebi et al., 2014, p. 8), the inferior parietal lobule (Abutalebi et al., 2014, p. 2126), and the anterior cingulate (Borsa et al., 2018, p. 58) indicate that certain neural changes may reflect the demands of controlling two or more languages. Although the study conducted by Heim and colleagues displays that the gray matter volume in senior bilinguals in the anterior parts of the brain seemed to be more pronounced than that of the monolingual group, the results also show decreased posterior atrophy in the bilingual aging group. “The bilingual anterior-to-posterior and subcortical shift model states that bilinguals recruit posterior (and also subcortical) regions to a higher extent than monolinguals, thus not relying too strongly on frontal regions associated with cognitive control” (Heim et al., 2019, p. 157). The researchers further suggest “The increased gray matter volume in bilinguals is present until higher ages in posterior as compared with anterior brain regions, thus maximizing the reserve effect" (Heim et al., 2019, p. 162). This reserve will be discussed in greater detail in the next chapter. Although these studies have somewhat conflicting results, one thing remains certain: it would be wise to encourage the aging bilingual population to continue to use their second language due to the potential neuroprotective effects it can offer in both the white matter integrity and gray matter volume of various structures and regions of the brain.

Chapter 3: Cognitive tasks

Bilingualism, or speaking an L2 everyday has been associated with better performance on cognitive tasks (Borsa et al., 2018, p. 51). “Culture, education, and environment shape how well individuals perform on cognitive tasks” (Abutalebi et al., 2014, p. 2126). It is important to note that executive functioning, linguistic processing, and working memory remain important cognitive abilities that interact, which means that these different modalities may interact in bilinguals as well (Bialystok et al., 2008, p. 860). Although there is an increased amount of behavioral evidence to support a cognitive advantage to bilingualism the neural mechanism remains a mystery. “One hypothesis is that bilinguals recruit more distributed brain networks to manage two language systems and prolonged practice engages these neural systems to process information more efficiently, even when the task does not involve language” (Luk et al., 2011, p. 16808). According to Byrd,“infants exposed to bilingual environments begin to use acoustic information to distinguish their two languages, a step toward understanding that there are cognitive categories that must be distinguished”. These children learn to use language appropriately based on whom they are speaking with, which indicates that early bilingual preschoolers may have an advantage because they are able to comprehend that there are differences in the understanding of others. This is also referred to as the *Theory of Mind* (Byrd, 2012, p. 21). A greater number of young bilingual preschoolers that were presented with a false belief task, to test if the child was capable of understanding that someone can think differently and have a false belief, passed the test as compared to their monolingual peers (Byrd, 2012, p. 22). Further, young bilinguals have been reported to often perform better on tasks that require conflict management such as the Stroop Task. In this task, “people see a word and are asked to name the color of the word's font. When the color and the word match (i.e., the word "red" printed in red), people correctly name the color more quickly than when the color and the word don't match (i.e., the word "red" printed in blue). This occurs because the word itself ("red") and its font color (blue) conflict. The cognitive system must employ additional resources to ignore the irrelevant word and focus on the relevant color. The ability to ignore competing perceptual information and focus on the relevant aspects of the input is called inhibitory control." (Byrd, 2012, p.22). Furthermore, bilingual children and young adults have been reported to perform better than their monolingual peers on switching between two tasks. One example of such a task, is the one that entails individuals to switch from categorizing objects by color to categorizing them by shape. The bilinguals have been shown to perform more rapidly on these tasks than monolinguals, which reflects better cognitive control (Byrd, 2012, p. 22). Although many studies have been conducted with younger bilinguals and cognitive ability, it remains questionable if these cognitive abilities continue or deteriorate with aging.

The age-related white matter integrity decreases and the gray matter volume deterioration relates to the cognitive decline that can accompany the aging process. The decreased cognitive and motoric performance of the aging population occurs due to the reduction of the signal transmission between the gray matter (Gold et al., 2013, p. 2841). Cognitive decline happens as a result of brain apoptosis, or cell death, and results in a progressive decline of both cognitive abilities and memory (Abutalebi et al., 2015, p. 201). Further, aging has been correlated to the decline of cognition or the decrease in the ability to perform cognitive abilities due to the neurodegeneration of the temporal region of the brain (Heim et al., 2019, p. 157). However, “while neurodegenerative changes result in significant cognitive declines in some older adults, others seem to continue to function like young healthy adults” (Gold et al., 2013, p. 2841).

Some theories argue that cognitive delay in the aging population is associated with the deficiency in the inhibitory mechanisms and a decreased working memory capacity (Borsa et al., 2018, p. 59). The inhibitory mechanisms refer to a system that the brain must sometimes rely on to rapidly and actively stop undesirable thoughts and memories, unwanted motor responses, and the attention to stimuli. Such cognitive decline has been shown to not be inevitable in the aging population. Physical exercise and speaking more than one language have been shown to control for cognitive decline in the aging population (Borsa et al., 2018, p. 51). These activities may contribute to a cognitive reserve in seniors. “Higher levels of cognitive reserve are associated with a reduced risk of developing cognitive decline and a lower rate of memory decline in normal aging” (Abutalebi et al., 2015, p. 202). According to Abutalebi: “Although treatments are still lacking, studies show that the onset of cognitive decline and dementia can be significantly delayed by intellectual and life-style factors, including education, occupation level and leisure activities”. There has even been research aiming to prove that there is a correlation between controlled attention, bilingualism, and the delayment of the onset of dementia (Borsa et al., 2018, p. 51). Therefore, the effects of aging on the brain has been shown to be reduced for seniors that are engaged on the daily level in tasks that force them to practice controlled attention.

Bilingualism is just one of the factors that might build up a brain reserve in the aging population. This mechanism is due to the necessity of bilinguals to constantly switch languages and regulate different grammatical structures and vocabularies (Heim et al., 2019, p. 157). The human central nervous system has been shown to have plasticity up until adulthood and there has been an increased amount of studies that show a correlation between experience and cognitive processes (Bialystok et al., 2008, p. 859). “Lifelong bilingualism may result in enhanced neuronal connections amongst brain areas important for higher-order cognitive and language functions. Regions correspond to the cognitive functions for which bilingual advantages have been reported” (Olsen at al., 2015, p. 133). Studies have shown that in early bilinguals, both languages are activated during language production even for the production of one word (Byrd, 2012, p. 20). Research that has used eye-tracking and electroencephalography has provided evidence that languages are able to be activated in parallel in the bilingual brain (Hayakawa & Marian, 2019). Further, bilinguals might be activating both of the grammar systems when switching between languages (Byrd, 2012, p. 20).

The debate of whether bilingualism is correlated to brain reserve and can delay neurodegeneration is prevalent in today’s society due to the rising numbers of the aging population (Heim et al., 2019, p. 157). According to the United Nations and specifically data from the World Population Prospects: the 2019 review, “by 2050, one in six people in the world will be over age 65 (16%), up from one in 11 in 2019 (9%)”. This increase in the aging population creates an urgency to find ways to protect against age-related neurodegeneration. As shown throughout this thesis, the topic of bilingualism and conservation of cognitive functioning, white matter integrity, and gray matter volume is a point of contention. One theory contends that bilingualism may act as a cognitive reserve due to some evidence that points out that bilinguals that are diagnosed with dementia are usually diagnosed about four to five years later than their monolingual constituents. The cognitive reserve can be defined as “a discrepancy between observed behavioral and/or cognitive functioning and the expected (reduced) levels in typical aging" (Abutalebi et al., 2015, p. 201). This is usually measured through the use of attention and memory tasks (Borsa et al., 2018, p. 51). However, there is also a term, neural reserve, which can be defined as "a substantial proportion of seniors can tolerate greater amounts of neurodegeneration than others without obvious cognitive impairments" (Heim et al., 2019, p. 157). The neural reserve can also be defined as " a discrepancy between observed brain functioning and the expected (reduced) levels in aging particularly when accompanied by neuropathology such as Alzheimer's disease". The neural reserve is usually estimated from the levels of brain activity of the individual (Borsa et al., 2018, p. 51). Thus, the difference between a cognitive reserve and a neural reserve is that the cognitive reserve refers to the cognitive functioning while the neural reserve refers to the brain functioning when an individual suffers from neuropathology. From a neural and cognitive reserve standpoint," Perani et al. (2017) reported that bilingual speakers with Alzheimer's dementia (AD) are on average 5 years older than monolingual speakers, when first diagnosed, and they have more extended brain hypometabolism. Moreover, they consistently perform as well or better on tests of cognitive functioning than monolingual speakers. In other words, bilingual speakers appear to compensate for the dramatic neuropathology of AD in terms of the functional outcomes better than monolingual speakers" (Borsa et al., 2018, p. 51). There are studies that show the effects of bilingualism in seniors on cognition but this remains an underresearched area of study (Bialystok et al., 2008, p. 859). That said, some studies have observed behavioral advantages in senior bilinguals in their executive function performance (Olsen at al., 2015, p. 128).

There are neurostructural changes taking place in the brain that have been hypothesized to be able to protect against cognitive decline with aging (Abutalebi et al., 2014, p. 2127). The study conducted by Borsa et al., identified a significant relationship between cognitive and neural reserve in bilingual seniors from Italy who speak their L2 on an everyday basis. The patterns of decline of cognitive control is different for monolingual and bilingual speakers. There was a significant negative correlation observed between mean chronological age and mean conflict and interference effects that are two measures of nonverbal cognitive control. The mean chronological age was predictive of interference effects and interference only in the monolingual senior group. Conscious cognitive control may help with the selection of the correct language and inhibiting the other language or even switching between the two (Byrd, 2012, p. 20). The cognition of a bilingual speaker deals with the activation of the different languages and the interference of the language that is not being used, which is also known as language interference. This interference has been shown to be managed using neural networks that also play a part in cognitive control. This suggests that bilinguals may have an advantage in being able to select the relevant information quicker (Hayakawa & Marian, 2019). This mechanism helps bilinguals become more efficient at resolving linguistic conflicts, which in turn leads to less reliance on networks that deal with cognitive control (Hayakawa & Marian, 2019). For the bilingual senior group, the gray matter volume of the anterior cingulate cortex was the predictor. There was a stronger relationship between cognitive control and the gray matter integrity of the anterior cingulate cortex, which has a role in the cognitive functioning, in bilingual seniors compared to the monolingual seniors (Borsa et al., 2018, p. 60). More efficient use of the anterior cingulate cortex has been associated with more efficient monitoring of conflict on attentional network tasks. The study found that the gray matter volume in the anterior cingulate cortex was correlated to cognitive control performance in terms of conflict effects and interference, but this was only true for the bilingual senior group and not the monolingual senior group (Borsa et al., 2018, p. 60).

The neural networks that are responsible for both language control and domain general cognitive control overlap, which signifies that the maintenance of executive function by bilingualism may decrease the effect of aging on cognitive control as a bilingual (Borsa et al., 2018, p. 59). This cognitive control may reflect an increased ability to self-monitor rather than to inhibit (Borsa et al., 2018, p. 60). The bilingual cognitive control performance has been shown to be associated with the amount of exposure to the L2 (Borsa et al., 2018, p. 60). This can be explained by the fact that daily exposure to an L2 will create a more constant need to control the interference from the L1 which would increase the language conflicts. By inhibiting the language more often, the bilinguals will be more likely to "monitor the sources of perceptual interference and adjust their behavior accordingly" (Borsa et al., 2018, p. 60). If this monitoring of conflicts recruits the anterior cingulate cortex, then it can be postulated that the involvement of the anterior cingulate cortex in the language conflicts could result in an increased efficiency of the anterior cingulate cortex (Borsa et al., 2018, p. 60). The researchers further suggest that this increased efficiency of the anterior cingulate cortex should transfer then to nonverbal cognitive monitoring tasks (Borsa et al., 2018, p. 60). According to Borsa et al., their " results support the view that the routine maintenance of the mechanisms used for cognitive control specifically within the linguistic domain can mitigate the typical effects of aging" (Borsa et al., 2018, p. 60).

As previously mentioned, a study conducted by Abutalebi and colleagues found greater gray matter volumes in the anterior cingulate cortex in aging bilinguals and they posit that this may provide evidence of cognitive benefits or the cognitive reserve and neural benefits or the neural reserve. Although the researchers favored the neural explanation, they believe that their results may actually reflect a greater cognitive efficiency. It is important to remember that the cognitive reserve concept has been based on the fact that intelligent individuals that engage in lifelong learning seem to fight off cognitive decline better (Abutalebi et al., 2015, p. 201). Neurologically "brain areas underlying executive control, such as the pre-SMA/ACC (pre-supplementary motor area/ anterior cingulate cortex) and the DLPFC (dorsolateral prefrontal cortex) regions are more highly stimulated in bilingual speakers and this may result in greater cognitive reserve that compensates for the brain atrophy found in normal aging. Indeed, behavioral studies in elderly bilinguals support this notion" (Abutalebi et al., 2015, p. 209). Even though more functional studies are needed in order to support the notion of a cognitive reserve and to confirm the correlation between the Flanker task cognitive functioning and the gray matter volume of the anterior cingulate cortex for monolinguals and bilinguals; it is thought that bilingualism can enhance this reserve through the development of compensatory strategies (Abutalebi et al., 2015, p. 208).

Executive functioning can be defined as "a type of higher-level cognitive function that requires careful control of attention" (Byrd, 2012, p. 23). It is postulated that aging bilinguals have an advantage as bilingualism plays a role in the postponement of the decline of executive control in nonverbal tasks (Bialystok et al., 2008, p. 860). Tasks that require much attentional control or attentional inhibition require an individual to use their executive functioning skills

(Byrd, 2012, p. 23). The ability to use executive functioning, or to focus attention, takes place in both the frontal and the prefrontal cortex and this area is the final portion to develop through myelination (Byrd, 2012, p. 23). Brain areas that are responsible for executive control are more stimulated in bilinguals and this may result in a brain reserve that could provide compensation for the deterioration of the brain that is normal in aging (Abutalebi et al., 2015, p. 202). It is known that bilingual speakers can have attentional difficulties such as word retrieval difficulties due to their need to switch languages. They compensate for this through self-monitoring of behavioral performance or even through the use of a wider availability of strategies due to their ability to juggle multiple languages (Borsa et al., 2018, p. 59). One example of this is in the compensation of bilinguals diagnosed with Alzheimer's dementia which is shown through their functional outcomes (Borsa et al., 2018, p.59).

A study conducted by Schweizer et al., "identified greater atrophy on CT scans of the brains of bilingual speakers with AD despite equivalent levels of cognitive function and reasoned that this was due to bilingual speakers using meta-cognitive strategies to function at a relatively high level and more than would be expected from the extent of their neuropathology" (Borsa et al., 2018, p. 59). The structural changes induced in the bilingual brain in areas of the left inferior parietal lobule, the anterior cingulate cortex, and the left caudate, which are associated to an executive control network, may hint at the bilingual cognitive advantage in executive control tasks (Abutalebi et al., 2015, p. 202). Furthemore, "To maintain the relative balance between two languages, the bilingual brain relies on executive functions, a regulatory system of general cognitive abilities that includes processes such as attention and inhibition. Because both of a bilingual person's language systems are always active and competing, that person uses these control mechanisms every time she or he speaks or listens" (Byrd, 2012, p. 23).

One study tested aging bilinguals and monolinguals in congruent and incongruent trials using the Flanker task which " captures cognitive conflict resolution involving attentional control and inhibition processes" (Abutalebi et al., 2015, p. 202). The Flanker test is a set of inhibition tasks that are used to assess the ability to suppress responses that do not work in the context provided. In this task, the bilinguals outperformed the monolinguals in both of the trials. Studies have shown that bilingual seniors have performed better than their monolingual peers on cognitive control tasks. Some of these tasks include the ANT (Attentional Network Task), the Stroop task, and the Simon task. The Simon task is another measure of the interference or conflict resolution. The interference that is produced in the Simon task occurs in what is called the response-selection phase while in the Stroop task it comes from stimulus identification. "In this task participants are asked to respond to visual stimuli by making a rightward response to one stimulus (e.g., a circle) and a leftward response to another (e.g., a square). The stimuli are sometimes presented on the right side of the display and sometimes on the left. The location/side of the display on which the stimuli appear is irrelevant to accurate performance on the task, but it influences participants' patterns of responding by either matching (i.e., congruent trials) or not matching (i.e., incongruent trials) the side (left or right) of the correct button press associated with the shape." (Simon Task). To explain bilinguals' greater performance on these tasks, it is important to remember that both languages interact during speech production. Bilinguals must be exhibiting selection or attention seeing as lexical access is more difficult for bilinguals than their monolingual counterparts (Bialystok et al., 2008, p. 860).

Since bilinguals need to manage two different language systems, their working memory may be greater than that of their monolingual counterparts (Bialystok et al., 2008, p. 860). Working memory is one of the essential cognitive abilities along with executive functioning. Working memory is even crucial to tasks such as comprehension of written and spoken text and fluency in language production (Bialystok et al., 2008, p. 860). For bilinguals, since they are managing two different language systems, the demands on their working memory is greater than that of their monolingual constituents. There is a theory that this increased demand may shape the functioning of their working memory. Again, inhibition has been used to explain why this theory could be true for bilinguals. "Michael and Gollan (2005) proposed that inhibition may be the missing link that connects working memory and bilingual processing, implying that bilinguals may exhibit more efficient working memory abilities than monolinguals, because the need to manage two language systems requires inhibition of one system while the other language is being used" (Bialystok et al., 2008, p. 860). In this research, bilinguals were separated into young and older adults and their working memory was tested using self-ordered pointing tests and Corsi block span. In the forwards and backward corsi block tasks "stimuli consisted of a random array of wooden blocks spread out on a wooden base. Each block contained a number from 1 to 10 painted on the back, not visible from the front. The apparatus was placed between the experimenter and the participant, with the numbers visible only to the experimenter. In the forward condition, the experimenter tapped a sequence of blocks, and participants were required to repeat the sequence in the same order. The sequences began with two blocks and increased by one block after every second trial. Thus there were two trials at each sequence length." (Bialystok et al., 2008, p. 860). In the backward condition, the experiment was repeated in the reverse order. The self-ordered pointing task “was presented in a 12-page booklet, each page containing 12 abstract drawings consisting of lines as well as circles and other random shapes. The same 12 drawings appeared on all the pages, but with each in a different position on each page. Participants were instructed to examine each page of the booklet in order and point to one pattern on each page without pointing to the same pattern more than once. The pages were bound in a plastic binder, and the experimenter flipped the page after a drawing had been selected” (Bialystok et al., 2008, p. 860). The results of this experiment showed that the younger participants recalled more than the older without much correlation to the bilingual experience. Thus, the question of bilingualism contributing to greater working memory remains open (Bialystok et al., 2008, p. 860).

Although there remains much research to be conducted in the domain of cognitive control, executive function, and working memory in bilinguals, there is some potential that a cognitive advantage does exist. A potential cognitive advantage in bilingual adults is especially significant due to a high percent of the population aging. Thus, it is critical to understand how to promote the healthy aging of the brain and the potential benefits of bilingualism (Byrd, 2012, p. 27).

Conclusion

Numerous studies have demonstrated a correlation between increased white matter integrity and gray matter volume in both younger and older bilinguals. These studies hypothesize that bilingualism can offer cognitive benefits to the aging bilingual population. However, the exact mechanisms that contribute to the potential neuroprotective effects of bilingualism are still unknown. There are many theories of the bilingual experience enriching the lexical and semantic networks and thus creating more connections in the brain which is tied to semantic cognition and executive control. One thing is clear, there are changes that occur in the brain as adaptations to bilingual processing. Although the results of all of these studies are not conclusive and more studies must be conducted to validate these finding; it is important for society to understand and to optimize multilingualism as a potential enhancer of quality of life through old age (Heim et al., 2019, p. 164).

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