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Creating Appropriate Clinical Guidelines for The Bilingual Population with Acquired Brain Injuries

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CERTIFICATE OF APPROVAL

Clinical Research Project

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Abstract

While there is a growing bilingual demographic in the United States, relatively little is known about treating this population should they experience a brain injury. This is a growing area of interest, as research has demonstrated that the acquisition of a second language promotes neuroplastic changes that then impact brain functioning pre- and post-brain-injury. Given bilingualism's cognitive complexity, clinicians are left with challenges on how best to tailor treatment for brain-injured bilingual populations. Therefore, the focus of this review was to provide clinical recommendations to clinicians performing assessments with bilingual individuals with acquired brain injuries. The goal was for the guidelines provided to aid in the augmentation of appropriate strategies for neurorehabilitation to maximize linguistic, cognitive, and communicative improvement, leading to social readaptation and a better quality of life.

DEDICATION

I would like to dedicate this work to my family, who never doubted my potential and provided countless moments of support. This paper symbolizes the hard work and tenacity my immigrant father has put in for me to have an opportunity to become a doctor. It is also a representation of my mother's commitment to being a homemaker so that I could take advantage of academic opportunities and arrive at the position I am in now. An absolute special dedication to my fiancé, who has been the most patient supporter of all. Thank you for believing in my potential and for not letting me give up.

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TABLE OF CONTENTS

CHAPTER I: THE NEED FOR CULTURALLY APPROPRIATE TREATMENT FOR THE BILINGUAL POPULATION

Although there is a growing prevalence of bilingual speakers and individuals with acquired brain injuries in the United States, relatively little is known about the impact bilingualism has on cognitive recovery following an acquired brain injury and the best clinical practices for neurorehabilitation. Therefore, understanding how the acquisition of a second language impacts cognitive functioning is a growing topic of interest. The brain has an extraordinary ability to reconfigure structurally and functionally in response to environmental, behavioral, and cognitive demands that result in differences in the utilization of brain regions (Sharma et al., 2013). This concept is known as neuroplasticity. Bilingualism is a specific experience that has been shown to produce neuroplastic anatomical changes (Crinion et al., 2006; Jasińska & Petitto, 2013; Li & Grant, 2016; Mechelli et al., 2004) that facilitate differences in cognitive performance pre- and post-brain-injury (Faroqi-Shah et al., 2018; González et al., 2019; Ratiu & Azuma, 2017). Given the anatomical differences promoted by learning multiple languages, clinicians are faced with challenges on how best to provide the most appropriate treatment for bilingual clinical populations, particularly following an acquired brain injury. To treat clinical populations best, clinicians rely on their general understanding of structural and functional processes of the brain in normal and cognitively compromised populations while incorporating culturally appropriate research to tailor treatment to the individual (Johnson-Greene, 2018). Early intervention is essential following an acquired brain injury, as the literature has demonstrated that early intervention significantly improves outcomes compared to intervention implemented later (León-Carrión et al., 2013). The goal of this review was to begin the process of creating clinical guidelines that could be referenced when working with bilinguals with acquired brain injuries. The development of clinical guidelines can aid in the augmentation of appropriate strategies for neurorehabilitation to maximize linguistic, cognitive, and communicative improvement, leading to better social readaptation and a better quality of life.

Linguistic Diversey in the United States

Recent census data in the United States provided support for the growing bilingual demographic. More specifically, the U.S. census data reported that approximately 42.1% of the U.S. population is part of a racial/ethnic minority group (U.S. Census Bureau, 2019), and the ratio is predicted to continue to grow. The Census Bureau has estimated that in 2012, 50.4% of children under the age of 1 in the United States belonged to racial and ethnic minority groups (U.S. Census Bureau, 2012). The increase of racial and ethnic minority groups has also contributed to the growth of linguistic diversity ("Language use and English-speaking ability," 2003).

Among the linguistically diverse groups in the United States are bilinguals ("Language use and English-speaking ability," 2003). However, while the bilingual demographic in the United States is rapidly increasing, there is no uniform definition for bilingualism in the literature (Costa & Sebastián-Gallés, 2014; Mindt et al., 2008). Early definitions have either been restrictive, requiring the mastery of two languages or more flexible, considering bilingualism as an experience of alternating the use of two languages irrespective of proficiency (Bloomfield, 1935). While later definitions have begun to incorporate different levels of competency or proficiency when defining bilingualism. Some of the more common levels of bilingualism that have been identified and incorporated into the more recent definition of bilingualism include language proficiency (high or low proficiency), language competence (balanced or unbalanced), age of acquisition (early or late), the order in which languages are acquired (simultaneous or sequentially), and the context of the acquisition of languages (natural setting or a formal or instructed setting).

All of the above-mentioned levels of the bilingual experiences have made bilingualism a complex phenomenon, as the various factors have also been demonstrated to impact cognitive functioning in the bilingual brain to various degrees. Ultimately, given the vast diversity among bilinguals, researchers will need to explain all the different levels of bilingualism to understand its cognitive impact better. However, covering all bilingual groups is beyond the scope of this literature review; therefore, this review includes bilingual studies that categorize bilingualism in the more commonly observed factors: language proficiency (high or low proficiency), language competence (balanced or unbalanced), age of acquisition (early or late), the order in which languages are acquired (simultaneous or sequentially), and the context of the acquisition of languages (natural setting or a formal or instructed setting.

Neuropsychology of Bilingualism

The growing bilingual demographic in the United States has also led to a growing interest within the neuropsychology field, as research has demonstrated evidence of anatomical (Bialystok et al., 2010; Carlson & Meltzoff, 2008; Crinion et al., 2006; Jasińska & Petitto, 2013; Li & Grant, 2016; Mechelli et al., 2004), and functional (Berken et al., 2016) brain changes that influence cognitive performance (Blom et al., 2014; Gollan et al., 2005, 2007; Portocarrero et al., 2007; Rosselli et al., 2000) pre- (Blom et al., 2014; Gollan et al., 2005, 2007; Portocarrero et al., 2007; Rosselli et al., 2000) and post- (Faroqi-Shah et al., 2018; González et al., 2019; Ratiu & Azuma, 2017) brain injury in children (Sowell et al., 2001), adults, and older adults (Grady et al., 2015). The anatomical and functional changes have been labeled neuroplasticity. Neuroplasticity gives context for examining how bilingualism affects cognitive abilities and how experience modifies brain structure and brain function (Bialystok et al., 2012). Neuroplasticity, also known as brain plasticity or neural plasticity, is the brain's ability to adapt in response to changes in the environment or damage to the brain tissue (Sharma et al., 2013) by altering structural or functional aspects of the brain. (Sharma et al., 2013). Structural neuroplasticity refers to the brain's ability to change the internal structure or gray and white matter as well as cortical thickness and surface area, resulting in structural connectivity (Sharma et al., 2013). Functional neuroplasticity refers to the brain's ability to alter the functional properties of neurons resulting in permanent changes in synapses (Sharma et al., 2013).

Measuring Structural Changes in the Bilingual Brain

Neuroimaging techniques have played a pivotal role in investigating the integrity of brain structures, interconnections, development, and pathology (Smith et al., 2004) and are becoming important tools for rehabilitation research (Crosson et al., 2010). Neuroimaging techniques provide researchers and clinicians the ability to determine the effects of brain injury or disease on cognition and monitor how rehabilitation changes brain systems (Crosson et al., 2010). There are a number of noninvasive neuroimaging techniques utilized throughout the world today that allow clinicians and researchers to diagnose, interpret, and treat individuals. The techniques mentioned in this literature review include computerized tomography scan (CT), positron emission tomography (PET), magnetic resonance imaging (MRI), diffusion tensor imaging tractography, voxel-based morphometry (VBM), functional magnetic resonance imaging (fMRI), and functional near-infrared spectroscopy (fNIRS), all of which will be discussed briefly in this section for reference.

A CT scan of the brain is a noninvasive diagnostic imaging procedure using special x-ray measurements to provide horizontal or axial images (often called slices) of the brain. Brain CT scans can provide more detailed information about brain tissue and brain structures than standard x-rays of the head, thus providing more detail related to injures and/or diseases of the brain. They can show the soft tissues, blood vessels, and bones in various parts of the body. Brain CT scans can be performed with or without contrast. In some cases, a contrast dye is used to help the radiologist interpret the images. This contrast dye may be injected into the bloodstream, ingested through the gastrointestinal tract, or placed into the spinal canal. CT scans provide more detailed images than traditional radiographs (x-rays).

A brain PET scan is an imaging test that shows how the brain is functioning by using a radioactive substance called a tracer (radioactive material) to detect disease or injury in the brain. The tracer is given through a vein (intravenous) or breathed in as a gas. The tracers attach to compounds such as glucose, which is the principal fuel of the brain. Areas that are more active utilize glucose at a higher rate than inactive areas. The PET scanner detects signals from the tracer, and a computer creates 3-D images from the data for interpretation. Therefore, a PET scan allows clinicians to detect any abnormalities or differences in brain function, as it provides information such as the size, shape, and function of the brain.

MRI is a neuroimaging technique that produces high-quality images of the internal structure and function of the brain by utilizing magnetic fields and radio waves to detect proton signals from water molecules (Symms et al., 2004). An MRI provides structural information in the form of neural volume measured by the total brain volume, gray matter, and white matter volume, as well as cortical thickness and surface area (Mills & Tamnes, 2014). An MRI is typically divided into structural MRI or fMRI (Sowell et al., 2001). The core of almost every

MRI protocol includes T1- and T2-weighted sequences that identify differences and/or abnormalities in brain anatomy by utilizing signal imaging (Fischl & Dale, 2000; Symms et al., 2004; Whitwell, 2009). Fluid attenuated inversion recovery is a more recent scan described as an enhancement or replacement for T2-weighed sequencing (Symms et al., 2004).

fMRI is a series of MRI scans measuring brain function via a computer's combination of multiple images taken less than a second apart (Chen & Li, 2012). fMRI measures brain activity of blood flow by detecting blood-oxygenation-level-dependent (BOLD) signal change due to the hemodynamic and metabolic sequence of neuronal responses. This technique relies on the fact that cerebral blood flow and neuronal activity are coupled. When an area of the brain is in use, blood flow to that region increases (Chen & Li, 2012). During an fMRI, patients are asked to perform a certain activity to help map the functional areas of the brain. In addition to detecting BOLD responses from activity due to task/stimuli, fMRI can also measure resting state or a taskless state referred to as resting-state fMRI. Resting-state fMRI is used in brain mapping to evaluate regional interactions in a resting or task-negative state when an explicit task is not performed. A number of resting-state conditions are observed in the brain, one of which is the default mode network. Resting-state conditions are observed through changes in blood flow in the brain, which creates what is referred to as a BOLD signal. The resting-state approach is useful for exploring the brain's functional organization and examining if it is altered in neurological or mental disorders (Li et al., 2018).

fNIRS is a functional neuroimaging technology that monitors changes in blood oxygenation and blood volume in the prefrontal cortex. This is performed by attaching a sensor to the subject's forehead and measuring changes in the blood flow or its oxygenation levels of the brain before, during, and after a task (Herold et al., 2018)

Diffusion tensor imaging (DTI) tractography is an MRI technique measuring the rate at which water molecules travel along white matter tracts in the brain to delineate the axonal organization of the brain. The degree of anisotropic water diffusion constrained by atoms (i.e., fractional anisotropy, FA) is measured to provide a measurement of white matter integrity in the brain. FA gives information about the shape of the diffusion tensor at each voxel and describes the degree of anisotropy by recording the differences between isotropic (circular in shape; FA = 0) and anisotropic diffusion (linear or elongated in shape; FA = 1; Mori & Zhang, 2006), with higher FA indicating better integrity (Luk et al., 2011). FA can also be utilized to obtain a mean estimate of diffusivity (MD) that measures the overall magnitude of diffusion (water in a fluid-filled ventricle would have high MD whereas that in bone would have low MD), an estimate of diffusivity parallel to white matter tracts (axial diffusivity, AD) or perpendicular to white matter tracts (radial diffusivity, RD; Beaulieu, 2009).

VBM is an MRI technique detecting focal differences in brain anatomy using a statistical approach to parametric mapping. Most commonly, VBM examines gray matter concentrations in the brain at the voxel level (Ashburner & Friston, 2000; Kurth et al., 2015). While its most common use is to measure gray matter, it can also be used to examine white matter. VBM comprises three preprocessing steps: (1) tissue classification, (2) spatial normalization, and (3) spatial smoothing, followed by the actual statistical analysis (Kurth et al., 2015). The statistical analysis is used to identify differences in brain anatomy between groups of subjects, which in turn, can be used to infer the presence of atrophy or, less common, tissue expansion in subjects with disease. VBM typically uses T1-weighted volumetric MRI scans and performs statistical tests across all voxels in the image to identify volume differences between groups (Whitwell, 2009).

Advances in neuroimaging have changed the way that clinicians monitor brain function, dysfunction, and rehabilitation. Neuroimaging techniques are valuable tools utilized in combination with a neuropsychological assessment that facilitate the treatment process following an acquired brain injury. The standard rehabilitation program worldwide for patients with acquired brain injury is called cognitive rehabilitation.

The Process of Cognitive Neurorehabilitation

Cognitive neurorehabilitation has been defined as “a systematic functionally oriented service of therapeutic activities based on assessment and understanding the patient’s brain behavioral deficits” (Cicerone et al., 2000, p. 1596). The primary objective of cognitive rehabilitation is to maximize functional recovery and independence, reinstate employment, achieve functional productivity, and improve overall quality of life (Messinis et al., 2019). For rehabilitation specialists to be most effective, they rely on evidence from the initial part of cognitive rehabilitation, including a neuropsychological assessment. The neuropsychological assessment serves several purposes. To begin, neuropsychological assessments define areas of cognitive function and areas in need of treatment, as the data collected from the assessment allow clinicians to make inferences about the nature and extent of the personal cognitive dysfunction (Casaletto & Heaton, 2017). Awareness of a person’s cognitive strengths and weaknesses provides a means of targeting the cognitive domains that require remediation and capitalizing on the person’s residual cognitive ability to facilitate treatment. In addition, neuropsychological assessments provide a means for evaluating the effectiveness of treatment (Casaletto & Heaton, 2017). Neuropsychological assessments are an essential process to neurorehabilitation, as the sequela of an acquired brain injury predicts rehabilitation outcomes (Whyte et al., 2011), and early intervention after an acquired brain injury has shown to significantly improve outcomes compared to intervention implemented later (León-Carrión et al., 2013).

Acquired Brain Injuries

An acquired brain injury has been defined as brain damage occurring after birth from traumatic or non-traumatic causes that is unrelated to congenital diseases or neurodegenerative disorders (Spreij et al., 2014). Two of the leading acquired brain injuries are traumatic brain injury (TBI) and stroke. Given that TBI and stroke are two of the most prevalent acquired brain injuries, these two are the focus of this paper when discussing the cognitive impact in bilinguals following injury to the brain.

Traumatic Brain Injury

TBI has been defined as a non-degenerative, non-congenital disruption to the brain from an external physical force leading to permanent or temporary cognitive impairment, physical and psychological functions, with an associated diminished or altered state of consciousness (Silver et al., 2009; Timmons, 2012). Statistically, TBI represents the greatest contributor to death and disability globally among all trauma-related injuries (Rubiano et al., 2015).

A TBI can be categorized into three distinct levels of severity, with the severity of damage to the brain predicting recovery trajectory. Several measures are utilized to assess the level of severity (Brasure et al., 2012). Such measures include structural imaging, assessing duration of loss of consciousness, altered consciousness, and/or post-traumatic amnesia, the Glasgow Coma Scale (GCS) score, and the Abbreviated Injury Severity Scale Score. The GCS is the most widely used scale to determine severity (Brasure et al., 2012). Symptoms of a TBI vary from mild and moderate to severe, depending on the extent of damage to the brain. A mild level of severity entails normal structural neuroimaging results, a brief or no loss of consciousness (0-

30 minutes), there may be an alteration of consciousness/mental state (AOC) up to 24 hours, post-traumatic amnesia (PTA) can be present for up to a day (0-1 day) and the scores on the GCS range from 13-15. A moderate level of severity demonstrates normal or abnormal neuroimaging results, a loss of consciousness greater than 30 minutes but less than 24 hours, an alteration of consciousness greater than 24 hours, PTA is present for higher than a day but less than seven days and scores on the GCS range from 9-12. A severe level of severity demonstrates normal or abnormal results, a loss of consciousness greater than 24 hours, an alternation of consciousness/mental states (AOC) greater than 24 hours, PTA is present for more than seven days, and scores on the GCS are less than 9 (Brasure et al., 2012).

From a neuropsychological functioning standpoint, a mild to moderate TBI impairs memory, attention, processing speed, and executive functioning. Moderate to severe TBIs also demonstrate deficits in memory, attention, processing speed, and executive functioning with additional dysfunctions in communication, visuospatial processing, intellectual ability, and awareness (Rabinowitz & Levin, 2014).

Stroke

A stroke results from a blockage of blood supply to the brain or when a blood vessel in the brain bursts ("About stroke," 2020). Statistically, stroke is considered the second most common cause of death and adult disability worldwide (Katan & Luft, 2018). Implementing rehabilitation following a stroke demonstrates a significant impact on reducing stroke-related morbidity and improving outcomes. The most widely used and validated stroke scale is the National Institutions of Health Stroke Scale. Scores on the National Institutes of Health Stroke Scale range from 0-42. A score of 0 indicates no stroke symptoms, 1-4 suggests a minor stroke, 5-15 suggests a moderate stroke, 16-20 suggests a moderate to severe stroke, and 21-42 suggests a severe stroke (Al-Qazzaz et al., 2014).

From a neuropsychological functioning standpoint, cognitive impairment and memory loss are common after a stroke. Stroke impairs cognitive domains such as attention, memory, language, and orientation. With the most deficits in attention, executive functions and memory (Al-Qazzaz et al., 2014).

Purpose of the Review

As briefly discussed in the earlier sections, acquiring a second language poses more complexity to cognitive functioning. While there have been numerous studies conducted on the cognitive impact of stroke and TBI, few studies focus on the bilingual population with acquired brain injuries making it difficult to adequality and appropriately treat bilinguals. The purpose of this review is to explore the literature for the structural, functional, and neuropsychological performance differences to aid in providing clinicians a point of reference when working with bilinguals who have sustained an acquired brain injury. This review further explores the literature for specific cognitive differences in bilinguals following a stroke or TBI and identifies variables that may facilitate cognitive differences. Last, this review provides clinical pearls for reference specifically tailored to the bilingual population.

Literature Review Procedure

To conduct the literature review, various databases were utilized to locate peer-reviewed scientific articles that discuss studies with bilingual individuals at various levels of bilingual experiences pre- and post-brain-injury. Articles discussing the structural, functional, cognitive, and neuropsychological performance of bilinguals are incorporated with the inclusion of various age groups (i.e., children, adults, and older adult bilinguals), and a diversity of language experiences, which include: language proficiency (high or low proficiency), language competence (balanced or unbalanced), age of acquisition (early or late), order of languages acquired (simultaneous or sequentially) and the context of the acquisition of languages (natural setting or a formal or instructed setting). Discussing all acquired brain injures is beyond the scope of this literature review, and, as such, only two of the most prevalent acquired brain injuries (i.e., TBI and stroke) are included in this review. Based on the findings of this review, recommendations for assessing deficits and treating bilingual patients are provided.

CHAPTER II: STRUCTURAL CHANGES IN BILINGUALS

Understanding differences in the brain's integrity in a population that is rapidly growing but is not that well understood allows clinicians to be better equipped in predicting outcomes and facilitating greater recovery rates. Studies on bilingual populations reveal unique variations in the brain's integrity that differ from monolingual individuals (Bialystok et al., 2012; Costa & Sebastián-Gallés, 2014), suggesting effects of brain plasticity. Mechelli et al. (2004) are credited as the first to identify and report significant brain structure variations in bilinguals compared to monolinguals, with more recent studies demonstrating greater volume/and or density in the bilingual brain relative to monolinguals (Li et al., 2014). Given evidence to suggest that the acquisition of a second language influences the brain's integrity and the importance of gray matter and white matter integrity and brain volume in overall cognitive functioning, it is beneficial for clinicians to better understand bilingual brain differences.

Therefore, the objective of this chapter is to highlight the unique structural differences among bilinguals compared to monolinguals. To more easily identify structural differences, this chapter begins by providing a brief general overview of the traditional cortical brain regions involved in language processing. This is followed by discussing studies that have demonstrated structural differences among bilingual individuals by utilizing the various imaging techniques discussed in the introductory chapter.

Language Network Model

Our understanding of which brain regions account for different parts of language is far from complete. There is still a lot of research being conducted on this topic; however, due to the introduction of contemporary neuroimaging techniques, there has been significant advancement and understanding of language processing (Ardila et al., 2016). Research on the brain organization of language has shed light on associated networks or circuits rather than specific brain areas involved in language processing (Ardila et al., 2016).

The classical model of the neural basis of language consists of Broca's area (the motor speech center), Wernicke's area (the sensory speech center) and the arcuate fasciculus (a bundle of nerve fibers connecting the above two cortical areas; Ardila et al., 2016; Fujii et al., 2016). Research on language functioning has further grown to include a larger and more complex language model that includes frontal (inferior frontal gyrus), temporal (superior temporal gyrus and the middle temporal gyrus), and parietal (inferior and superior parietal lobe) language areas (Ardila et al., 2016; Fujii et al., 2016). Broca's area consists of the pars triangularis and opercularis of the inferior frontal gyrus, corresponding to Brodmann area 45 and 44, respectively. Wernicke's area is the cortical area of the posterior portion of the superior temporal gyrus and a part of the supramarginal gyrus, corresponding to Brodmann area 22 (Ardila et al., 2016; Fujii et al., 2016).

Language processing is comprised of two major pathways, the dorsal stream and the ventral stream. The dorsal stream is supported primarily by the superior longitudinal fasciculus and the arcuate fasciculus, which are associated with phonological processing. The ventral stream is primarily supported by the inferior frontal-occipital fasciculus and is associated with semantic processing (Ardila et al., 2016; Fujii et al., 2016).

While research supports a universal language pathway, studies with bilingual individuals have revealed differences in language and non-language processes. The remaining sections of this chapter focus on highlighting studies that have demonstrated structural differences in language and non-language brain regions in bilingual individuals. Studies on gray/white matter and cortical thickness, and brain volume with bilingual individuals are essential in understanding the impact learning a second language has on brain development and progression throughout the lifespan. Therefore, bilingual studies covered in this chapter include those that found gray and white matter differences and changes in brain volume and cortical thickness.

Gray Matter Volume/Density Studies

Using Whole Brian Approach

Mechelli et al. (2004) compared 25 early English-Italian bilinguals who started to learn their second language (L2) before the age of 5 (mean < 5 years), 33 late bilinguals who started to learn L2 between 10 and 15 years old (mean age 10-15 years), and 25 English monolinguals who had little or no exposure to a second language. Procedures utilized included the VBM analysis of the gray matter density using the statistic parameter mapping software package. Bilinguals demonstrated significantly higher gray mater density in the left inferior parietal cortex relative to monolinguals (z-score = 7.1; $p < 0.05$, corrected for multiple comparisons across the whole brain), with greater effects for early bilinguals in the left hemisphere (z-score = 3.5; $p < 0.001$ uncorrected) compared to monolinguals (Mechelli et al., 2004). While increased gray matter density was demonstrated in the inferior parietal cortex for both early and late bilinguals, the effect was greater in the left (z-score = 3.5; $p < 0.001$, uncorrected) and right (z-score = 3.5; $p < 0.001$, uncorrected) hemispheres in early bilinguals and in higher proficient (z-score = 4.1; $p < 0.05$, corrected after 10mm small volume correction) bilinguals (Mechelli et al., 2004). Researchers have suggested the left inferior parietal lobe is an important area for phonological working memory, lexical learning, and semantic integration. In summary, increased gray matter in the left inferior parietal lobe may, therefore, be related to processing larger vocabulary in the bilingual individual (Mechelli et al., 2004).

Pliatsikas et al. (2013) investigated whether speaking a second language affects the brain's structure while focusing on the areas that have been proposed to be related to the processing of grammatical rules in a second language, such as the cerebellum. Two groups were compared: 17 Greek-English bilinguals (mean age = 27.5 years; range = 99-37 years, mean L2 age of acquisition = 7.7) and 22 English monolinguals (mean age = 24.5 years; range = 20-38 years). To track changes in brain structure, a between-group whole brain, voxel-by-voxel comparison of the gray matter volume using the FRMB Software Library VBM protocol was conducted. Results revealed that early acquisition of a second language demonstrates increased gray matter density in the cerebellum bilaterally ($p < 0.001$), a structure that has been related to the processing of grammatical rules and procedural memory (Pliatsikas et al., 2013). Given that the cerebellum has been suggested to play a role in processing grammatical rules in L2, this study also investigated whether increased GM volume would reflect efficient linguistic rule application in L2 learners. Gray matter volume was calculated from the cerebellar cluster from the VBM analysis and Pearson's corrections between participants' cerebellar GM volume and their reaction times in a task tapping grammatical processing task. Results revealed a significant negative correlation between GM volume and reaction times in L2 learners ($r = -0.60$, $p = 0.014$). In summary, the results from this study suggested that early L2 acquisition increases the gray matter volume in the cerebellum, which promotes more efficient processing of grammatical rules in the second language (Pliatsikas et al., 2013).

Olulade et al. (2016) compared 15 young-adult simultaneous English-American Sign Language bilinguals, also referred to as bimodal bilinguals since they learned two languages in different modalities; mean age = 26.4 years and 16 early Spanish-English unimodal bilinguals also referred to as learning two spoken languages; mean age = 22.3 years, age of acquisition less than 6 years old with 15 English monolinguals; mean age = 25.9 years. To assess structural brain differences in each group, high-resolution T1-weighted MRI images were acquired, and analysis of the gray matter was performed using an automated segmentation/normalization algorithm (SPM8). A two-sample *t*-test was utilized to obtain two separate between-group comparisons, and gray matter volume was compared between unimodal bilinguals and monolinguals. Images were assessed using a statistical threshold at the highest level of $p < 0.005$ and corrected for multiple comparisons at a threshold of $p < 0.05$ with a non-stational cluster correction. An analysis of total intracranial volume was also performed, and there was no difference between groups. Results further revealed greater gray matter volume bilaterally in unimodal Spanish-English statical parameter mapping. An analysis of total intracranial volume was also performed, and there was no difference between the groups. Results revealed greater gray matter volume bilaterally in unimodal Spanish-English bilinguals relative to the English-speaking monolinguals, with greater gray matter volume bilaterally in areas in the dorsolateral prefrontal cortex and parietal cortex. The dorsolateral prefrontal cortex and parietal cortex are involved in the executive control network (Seeley et al., 2007) and attention (Behrmann et al., 2004), more specifically, working memory, attentional control (Curtis & D’esposito, 2003), conflict resolution (Bunge et al., 2002), and inhibition (Ridderinkhof et al., 2004). Greater gray matter volume was shown in the right precentral gyrus (BA4), which extended both anteriorly into the inferior frontal gyrus and frontal operculum and posteriorly into the inferior parietal cortex. A second right hemisphere cluster was found in the middle frontal gyrus (BA 11) that extended into the medial and superior frontal gyri (BA10/11), and a third cluster in the superior temporal gyrus (BA 22) that extended into the middle temporal gyrus (BA 21/22). Left hemisphere clusters were not as extensive. The largest cluster was located in the middle frontal gyrus (BA 10), extending into the inferior frontal gyrus (dorsolateral prefrontal cortex/ventrolateral prefrontal cortex). Another cluster was located in the left occipital lobe's middle (BA 18), inferior (BA 18), and superior occipital gyri (BA 19), and the cuneus (BA 19), which extended into the posterior aspects of the middle temporal gyrus (BA 19). A smaller cluster was found in the left precentral gyrus (BA4). Results demonstrated that regions involved in executive control, outside of traditional language processing areas, are affected by unimodal bilingualism. The extensive differences in the right dorsolateral prefrontal cortex and parietal cortex demonstrate the recruitment of right-sided executive control and attention brain regions (Olulade et al., 2016).

Burgaleta et al. (2016) investigated structural brain differences among 42 young simultaneous Catalan-Spanish bilinguals (mean age = 21.6 years; *SD* = 2.17) and 46 Spanish monolinguals (mean age, 21.9 years, *SD* = 4.13). To assess structural brain difference in each group, high-resolution MRI images were acquired using a 1.5T scanner and analysis of subcortical shape was performed using the FIRST tool that is part of the FSL package and analysis of the gray matter was performed using an automated segmentation /normalization algorithm (SPM8) and a threshold-free cluster enhancement technique to correct the family-wise error at $p < 0.05$), with an underlying voxel level of $p < 0.005$ to a cluster-size criterion of at least $k = 347$ voxels. Analysis of subcortical structures demonstrated regional differences between bilingual and monolingual groups in the basal ganglia bilateral putamen ($p < 0.05$), left globus pallidus ($p < 0.1$), and right caudate nucleus ($p < 0.05$), and bilaterally in the thalamus in bilinguals relative to monolinguals ($p < 0.01$). VBM results demonstrated a large increase of gray matter volume for bilinguals bilaterally in the frontal, temporal, and parietal lobes, the cerebellum, and the left Hechl's gyrus (Burgaleta et al., 2016). The putamen's involvement in language production and perception has been well documented (Bohland & Guenther, 2006;

Murdoch, 2001; Oberhuber et al., 2013; Robles, 2005; Tettamanti et al., 2005). The thalamus is a structure commonly activated in naming or word generation (Indefrey & Levelt, 2004) and in lexical decision-making and reading tasks (Llano, 2013). Last, the globus pallidus is a brain structure shown to play a role in speech production tasks (Murdoch, 2001). Burgaleta et al.'s (2016) analysis revealed significantly expanded subcortical structures in bilinguals compared to monolinguals, localized in the bilateral putamen, thalamus, left globus pallidus, and right caudate nucleus. Results suggest that the acquisition of a second language may lead to greater development of a subcortical brain network for language processing (Burgaleta et al., 2016)

Using a whole-brain approach in older adults, Abutalebi et al. (2014) used structural MRI and VBM to measure gray matter volume in bilingual and monolingual individuals in the left anterior temporal pole. The study chose to focus on the left temporal since it is a region subject to strong cognitive aging-related decreases and has also been indicated in the involvement with second-language picture-naming performance (Baldo et al., 2013). Participants included 23 older adult bilinguals (12 Cantonese-English and 11 Cantonese-Mandarin; mean age = 62.17 years; mean L2 age of acquisition = 18.87) and 23 Italian monolinguals (mean age = 61.92 years). Results from an independent sample *t*-test revealed a significantly higher gray matter volume among the bilingual group relative to monolinguals in the anterior portion of the left inferior temporal gyrus ($t = 2.45$, $p = 0.02$). The authors of this study concluded that bilingualism may promote an overall neuroprotective effect to the left temporal pole, an area most vulnerable to aging effects. Therefore, these findings suggest that acquiring a second language can be a preventative measure for healthy cognitive aging (Abutalebi et al., 2014).

In summary, the studies with adult bilinguals demonstrated differences mostly in three regions: the left/right inferior parietal lobule (Burgaleta et al., 2016; Mechelli et al., 2004;

Olulade et al., 2016), the cerebellum (Burgaleta et al., 2016; Olulade et al., 2016; Pliatsikas et al., 2013) and the left inferior frontal gyrus (Burgaleta et al., 2016; Hosoda et al., 2013; Olulade et al., 2016). However, it is important to note when interpreting the results that studies used different family-wise error-controlling methods (i.e., random theory or threshold-free cluster enhancement and permutations) and different levels of inferences (i.e., voxel-level or cluster-level), which creates differences in levels of sensitivity, therefore, influencing significant levels.

The studies reviewed thus far have highlighted utilization of traditional language-involved brain regions (e.g., inferior parietal lobe, left inferior frontal gyrus) in bilinguals but with greater utilization and recruitment of brain regions not traditionally found in language processing (e.g., cerebellum). Results suggest bilingualism promotes a more complex language processing model for language management. The next section reviews studies that limit their analysis to a region or volume of interest to demonstrate if more significant results appear when comparing monolingual and bilingual brain differences.

Using ROI Based Approach

Ressel et al. (2012) conducted a study investigating the effects of early language exposure on the Heschl's gyrus by comparing 22 young Catalan-Spanish bilinguals with early age of acquisition beginning at the age of seven (mean age = 23.1 years) to 22 Spanish monolinguals (mean age = 21.5 years). The Heschl's gyrus is a structure that has been known to be involved in processing phonological information (Jacquemot et al., 2003). VBM was performed using the diffeomorphic anatomical registration through the exponentiated Lie algebra procedure implemented in source-based morphometry 8. The MRI images were segmented into GM, WM, and CSF using the standard unified segmentation model in SPM8. Significant differences among the two groups were not seen at a whole-brain analysis (voxel-level threshold *t* = 5.22, $p < 0.05$, family-wise error corrected for multiple comparisons). However, when a small volume correction ($t = 3.3$; $p < 0.001$ voxel-based, uncorrected) was performed, bilinguals demonstrated greater gray matter volume in the Heschl gyri bilaterally compared to monolinguals (Ressel et al., 2012). The authors concluded that the significant effect of gray matter in the Heschl gyri in Catalan-Spanish bilinguals is likely due to the differences in phonology in the two languages, therefore, leading to the recruitment of the auditory cortex region. This is important to note, as researchers working with bilinguals whose languages may differ in their phonology may also differ in the regions of recruitment for language processing (Ressel et al., 2012).

Zou et al. (2012) compared structural brain images between bilingual and monolinguals using the VBM analysis toolbox in source-based morphometry 5 to identify potential differences of the caudate nucleus, a cortical region for successful language control. A sample *t*-test was subsequently performed on the date from each voxel for bilinguals and monolinguals. Clusters with more than 100 voxels of activation along with an uncorrected voxel size threshold of $p < 0.001$ and corrected to $p < .05$ using a small volume correction were considered to be statistically significant. Participants included 14 bimodal (individuals who are fluent in a sign language and a spoken language) Chinese-Chinese Sign Language adult bilinguals (mean age = 49 years; mean L2 age of acquisition = 19; 29 years of experience with Chinese Sign Language) and 13 Chinese monolinguals (mean age = 48 years). Following a small volume correction, results demonstrated increased volume in the left caudate nucleus ($p < .05$, corrected) in the bilingual group relative to monolinguals. The increase in gray matter in the left caudate nucleus suggests this brain region is critical for language switching in bimodal bilinguals (Zou et al., 2012).

Mårtensson et al. (2012) investigated the influence of the acquisition of a foreign language on brain organization. Participants included 14 native Swedish interpreter students (mean age = 19.9 years) who took a 3-month intensive language course focusing on vocabulary for different languages (i.e., 4 Arabic, 8 Dari, and 2 Russian) and 17 native Swedish non-learners (mean age = 20.6 years) as a control group. Images were acquired using A GE Discovery MR 750, 3 T scanner with a 32-channel phased-array head coil. The data volumes were then analyzed using FreeSurfer, a semi-automatic software package that performs cortical reconstruction and volumetric segmentation of T1-weighted images. Hippocampal volume estimates were then exported to SPSS version 17 and analyzed with a 2 (group; interpreters vs. controls) by 2 (time; pretest vs. posttest) by 2 (hemisphere; left vs. right) mixed analysis of variance (ANOVA). The threshold for statistical significance was $p < .05$. Volume measures were restricted to the left and right hippocampus. Results revealed larger volume on the right side of the hippocampus for interpreters than for controls ($F(1,29) = 2.92$, $p > .098$, $r = .61$). Results suggest learning a second language in adulthood promotes structural changes in language-related brain regions (Mårtensson et al., 2012), particularly the hippocampus, an area involved in vocabulary acquisition (Davis & Gaskell, 2009).

Using a region of interest analysis, Abutalebi et al. (2014) recruited a group of 23 senior Chinese bilingual speakers (mean age = 62.2, *SD* = 5.36). Twelve bilinguals spoke Cantonese and English, and 11 bilinguals spoke Cantonese and Mandarin. The monolingual group consisted of 23 senior Italian individuals (mean age = 61.9, *SD* = 6.80). Processing procedures for bilinguals included the following: (a) visual inspection of MRI, (b) automatic reorientation of structural images according to the default tissue probability map; (c) image segmentation using VBM 8; (d) application of the DARTEL approach for further normalization and modulation; and

(e) smoothing using an 8mm Gaussian kernel. An independent sample *t*-test performed on the GM volume demonstrated greater gray matter in the left temporal pole ($p = 0.05$), right temporal pole ($p = 0.006$) and left/right orbitofrontal cortex ($p = 0.001$) in the bilingual group, relative to the monolingual group (Abutalebi et al., 2014). The temporal pole has been shown to be involved in lexical retrieval (Tranel, 2009) and has also been subject to reduced cortical thinning due to aging, resulting in difficulties with object naming, word recall, and word learning (Baldo et al., 2013). Among the bilingual population specifically, Abutalebi et al. (2014) demonstrated a positive correlation between second-language picture naming and increased gray matter. The authors of this study concluded the acquisition of a second language exerts a neuroprotective effect on age-affected regions.

Abutalebi et al. (2015) examined the effect of aging on the inferior parietal lobe in older adult bilingual speakers from Hong Kong. Participants included 30 bilinguals who spoke either Cantonese and English (16 of 30) or Cantonese and Mandarin (14 of 30), with a mean age = 63.2 years; *SD* = 5.86; age range = 55-75 years who started to learn L2 at a mean age = 18.3 years. The bilingual groups were then compared to 30 older Italian monolinguals with a mean age = 61.9 years, *SD* = 6.71. Brain images were acquired using a 3T Achieva Philips MR scanner. An axial high-resolution structural MRI scan was acquired for each participant, and the VBM 8 toolbox was used to segment reoriented images into GM, WM, and CSF. The region of interest was the left and right inferior parietal lobes. To investigate age-related differences in GM volume in the regions of interest, GM volume extracted from the left/right inferior parietal lobes was correlated with age in each of the groups. A Fisher's *Z* transformation test was then conducted to assess the significance of the difference in these correlation coefficients. This was followed by a two-sample *t*-test to compare the mean differences of GM volume for each region of interest. Results revealed a significant negative correlation between age and GM volume for monolinguals ($r = -.65$, $p < 0.001$) but not for bilinguals ($r = -.04$, $p = .85$. Fisher's test showed that these correlation coefficients were statistically different (Fisher's $Z = 2.69$, $p < .01$). Older adult bilinguals demonstrated significantly greater volume in the left inferior parietal lobule ($p = .02$) and right inferior parietal lobule ($p < .001$) relative to the monolingual group (Abutalebi et al., 2015). The inferior parietal lobe has been shown to contribute to linguistic attentional and action-related functions (Abutalebi et al., 2015). At a microanatomical level, the inferior parietal lobe is divided into the supramarginal gyrus and the angular gyrus. In the left hemisphere, the more caudal portion of the left inferior parietal lobe (left inferior parietal lobe) has been shown to be active during language-related tasks, focusing on semantic and phonological issues (Vigneau et al., 2006). The left inferior parietal lobe has also shown involvement in verbal short-term memory (Zatorre et al., 1992) and attentional processing (Rushworth et al., 2001; Todd & Marois, 2004). This study revealed that while older adult monolinguals showed reduced GM volume in the right inferior parietal lobe, this was not the case for older adult bilinguals. Instead, the bilingual group demonstrated increased GM volume bilaterally in the inferior parietal lobe, suggesting that the acquisition of a second language promotes neuroprotective aging effects in the inferior parietal lobe bilaterally. Therefore, the enhanced gray matter in the inferior parietal lobe may promote intact semantic, phonological, attentional, and verbal short-term memory processing skills (Abutalebi et al., 2015).

In summary, when studies performing VBM with young adults limited their analyses to the scope of certain regions of interest, effects were shown in the right hippocampus (Mårtensson et al., 2012), Heschl's gyri (Ressel et al., 2012), and the left caudate nucleus (Zou et al., 2012). Studies with older adults demonstrated effects in the right/left temporal pole, orbitofrontal cortex

(Abutalebi et al., 2014), and the inferior parietal lobule (Abutalebi et al., 2015). Results demonstrate utilization of typical language processing brain regions (i.e., the temporal pole and the inferior parietal lobule) but with increased recruitment of brain regions in the frontal (i.e., orbitofrontal cortex) and temporal (i.e., right hippocampus and Heschls gyrus) lobes. Bilinguals also demonstrated further recruitment of a subcortical region of the brain (i.e., left caudate nucleus). With regard to the temporal lobe regions, the increased gray matter in the right hippocampus demonstrates its importance in vocabulary acquisition in second-language learners (Davis & Gaskell, 2009), and increased gray matter in the left Heschls gyrus demonstrates its importance in processing phonological information for L2 learners. The increased gray matter in the orbitofrontal cortex in older adults was also an interesting finding. It is an area involved in lexical retrieval and has been shown to be vulnerable to age-associated tissue loss in older adults. Therefore, the increased gray matter in the orbitofrontal cortex in older adult bilingual individuals suggests acquiring a second language may play a role in promoting cognitive reserve.

The next section of this chapter discusses studies that have evaluated cortical thickness in bilingual individuals. The thickness of the cortex is a useful measure for identifying changes in brain regions and possibly for assessing treatment. It can also be a way to study how the normal brain develops, ages, and how it may be influenced by environmental experiences (Hutton et al., 2008). Cortical thickness studies with bilingual participants can provide clinicians greater insight into how second-language learning can promote differences in brain development.

Cortical Thickness Studies

Klein et al. (2013) examined the effects of age of language acquisition on brain structure. Three French-English bilingual groups were compared: 12 early simultaneous bilinguals (mean age = 23; the age of acquisition ≤ 3 years old), 25 early sequential bilinguals (mean age = 26; L2 age of acquisition, after 4 years old and before 7 years old; mean L2 age of acquisition = 5 years old), and 29 late sequential bilinguals (mean age = 28 years; L2 age of acquisition, after 8 years old and before 13 years; mean L2 age of acquisition = 10 years), with a control group of 22 English monolinguals (mean age = 25 years). T1-weighted whole-brain scans were acquired on a Siemens Sonata 1.5T MRI scanner, and the acquired MR images were processed using the CIVET imaging processing pipeline developed at the Montreal Neurological Institute to generate cortical thickness measurements for each subject. Analyses were performed using a general linear model: (a) cortical thickness contrasts of groups of bilinguals compared to each other and to a group of monolinguals, and (b) a series of cortical thickness regression analysis with the group of 66 bilingual subjects, taking age of second-language acquisition, proficiency, and years of language experience as the primary factors in each regression. All statistical analyses were performed using an in-house MNI-developed software package that links to the statistical toolkit "r." Statistical thresholds for cortical thickness analyses were corrected for multiple comparisons using the FDR technique at a level of $p = 0.05$. For each statistical comparison, all p-values were pooled across all cortices to determine the FDR threshold. Results demonstrated greater cortical thickness for early ($t = 2.51$; $p = 0.03$) and late ($t = 2.88$; $p = 0.003$) sequential bilinguals compared to monolinguals in the anterior regions of the brain (pars triangularis and pars opercularis) of the left inferior frontal gyrus (Klein et al., 2013). The sequential bilingual group also demonstrated significant positive correlations between the early age of acquisition of L2 and greater cortical thickness in the left inferior frontal gyrus. The pars triangularis and pars opercularis are found in the inferior frontal gyrus and are involved in processing speech and language in Broca's area. The authors of this study concluded that learning a second language after gaining proficiency in the first (sequential bilinguals) modifies the brain's structure, and the later in childhood the second language is acquired, the greater the thickness of the left inferior frontal cortex. Simultaneous, second-language learning did not demonstrate significant effects on brain development. Greater cortical thickness in the inferior frontal gyrus in sequential L2 learners may demonstrate the need for greater involvement of cortical areas to master the second language compared to simultaneous L2 learners. Therefore, simultaneous L2 learning may involve less recruitment of cognitive regions.

Mårtensson et al. (2012) also performed a vertex-wise general linear model analysis from the cortical thickness data to investigate group differences among the foreign language participants and monolingual participants. Vertex-wise general linear model analysis was performed to investigate group differences in cortical thickness changes, which reduces to an independent-samples *t*-test. These analyses were then followed by an independent *t*-test on cortical thickness to investigate potential group differences on baseline cortical thickness. The threshold for statistical significance was $p < .001$. The analysis was complemented with an independent *t*-test on the different images. These analyses were complemented with an independent *t*-test on cortical thickness at pretest to investigate potential group differences on baseline cortical thickness. The threshold for statistical significance was $p < .001$. Participants included 14 native Swedish interpreter students (mean age = 19.9 years) who took a 3-month intensive language course focusing on vocabulary for different languages (i.e., 4 Arabic, 8 Dari, and 2 Russian) and 17 native Swedish non-learners (mean age = 20.6 years) as a control group. Results revealed significantly different amounts of cortical thickness in three left hemisphere regions ($p < .001$; cluster size > 100): the dorsal medial frontal gyrus, inferior frontal gyrus and superior temporal gyrus (Mårtensson et al., 2012). The left frontal-temporal cortex regions are involved in a variety of language tasks. Specifically, the inferior frontal gyrus is involved in the articulatory network (Hickok & Poeppel, 2007) and mapping the meaning of new words (Ye et al., 2010). The superior temporal gyrus is involved in acoustic-phonetic presses (Démonet et al., 2005; Hickok & Poeppel, 2007; Price, 2010). Last, the dorsal medial frontal gyrus is part of the articulatory network and planning and control of articulatory processes (Hickok & Poeppel, 2007). The authors of this study concluded that learning a foreign language in adulthood changes the structure of language-related brain regions, specifically in the frontal-temporal cortex of the left hemisphere (Mårtensson et al., 2012).

In a study with older adults measuring the cortical thickness in 14 lifelong bilinguals (mean age = 70.4 years) and 14 monolinguals (mean age= 70.6 years), significant differences were found in the entorhinal cortex and temporal pole. The current study utilized T1-weighted MRI to estimate volumetric differences. A significant negative correlation was demonstrated between the cortical thickness of the temporal pole and age in the monolinguals ($\beta = -0.02$, SE = 0.01, $t = -2.61$, $p = 0.02$, $R^2 = 0.34$) but not for bilinguals ($\beta = 0.01$, SE = 0.01, $t = 1.03$, $p < 0.05$, $R^2 = 0.10$). The temporal lobe was a specific region of interest in this study, given that it is affected by normal aging as well as semantic dementia and is thought to play a critical role in lexical retrieval, while the entorhinal cortex is thought to be involved in memory (Tranel, 2009). Results were hypothesized to suggest that bilingualism may attenuate age-related reductions in the entorhinal cortex and temporal pole in older adults (Olsen et al., 2015).

In summary, the young adult cortical thickness studies demonstrate the inferior frontal gyrus is a target region of cortical changes in bilinguals. A study with older adult lifelong bilinguals has demonstrated that acquiring a second language promotes age-related reduction in the entorhinal cortex and temporal pole, suggesting potential cognitive reserve.

The next section discusses white matter changes in bilinguals. While gray matter and cortical thickness studies provide clinicians the ability to identify brain region differences, white matter studies add additional understanding of the neural networks involved in cognitive processes. Therefore, exploring white matter studies that focus on bilingual individuals can provide clinicians a more thorough understanding of brain development with this population.

Table 1

Areas of Increased Gray Matter Density/Volume or Cortical Thickness with Group Comparisons of Bilinguals Versus Monolinguals and Associated Cognitive Processes

Brain Region Differences	Associated Cognitive Process	Groups	N	Age	Study
Frontal					
Pars opercularis	Speech production	Early simultaneous & early sequential bilinguals vs. late sequential bilinguals vs. monolinguals	88	Adults	Klein et al., 2013
Pars triangularis	Speech production	Early simultaneous & early sequential bilinguals vs. late sequential bilinguals vs. monolinguals	88	Adults	Klein et al., 2013
Left dorsal medial frontal gyrus	Part of the articulatory network, planning & articulatory control	Foreign language intense course groups vs. monolinguals	31	Adults	Mårtensson et al., 2012
Inferior frontal gyrus	Involved in the articulatory network & mapping of the meaning of new words	Foreign language intense course groups vs. monolinguals	31	Adults	Mårtensson et al., 2012
Orbitofrontal cortex*	Lexical retrieval involvement	Bilinguals vs. monolinguals	46	Older Adults	Abutalebi et al., 2014
Dorsolateral prefrontal cortex*	Involved in the executive control network	Early unimodal bilinguals vs. monolinguals	31	Adults	Olulade et al., 2016
Parietal					
Left inferior parietal cortex	Phonological working memory, lexical learning & semantic integration	Early vs. late bilinguals vs. monolinguals	83	Adults	Mechelli et al., 2004
Inferior parietal lobule*	Linguistic attentional and action-related functions	Bilinguals vs. monolinguals	60	Older Adults	Abutalebi et al., 2015
Parietal cortex*	Part of the executive control network	Early unimodal bilinguals vs. monolinguals	31	Adults	Olulade et al., 2016
Temporal					
Temporal lobe*	Lexical retrieval and subject to cortical thinning due to aging	Late bilinguals vs. monolinguals	46	Older Adults	Abutalebi et al., 2014
Heschl's gyrus*	Processing phonological information	Early bilinguals vs. monolinguals	44	Adult	Ressel et al., 2012
Right hippocampus	Vocabulary acquisition	Foreign language intense course groups vs. monolinguals	31	Adult	Mårtensson et al., 2012
Superior Temporal gyrus	Acoustic-phonetic presses	Foreign language intense course groups vs. monolinguals	31	Adult	Mårtensson et al., 2012
Temporal pole	Lexical retrieval	Lifelong bilinguals vs. monolinguals	28	Older Adults	Olsen et al., 2015
Entorhinal cortex	Memory	Lifelong bilinguals vs. monolinguals	28	Older Adults	Olsen et al., 2015
Cerebellum					

Brain Region Differences	Associated Cognitive Process	Groups	N	Age	Study
Cerebellum*	Processing of Grammatical rules and procedural memory in bilinguals	Early bilinguals vs. monolinguals	39	Adults	Pliatsikas et al., 2013
Subcortical areas (deep gray matter)					
Left caudate nucleus	Language control involvement	Bimodal bilinguals vs. monolinguals	27	Adults	Zou et al., 2012
Putamen*	Language production & perception	Simultaneous bilinguals vs. monolinguals	88	Adults	Burgaleta et al., 2016
Thalamus*	Naming or word Generation, lexical decision & reading	Simultaneous bilinguals vs. monolinguals	88	Adults	Burgaleta et al., 2016
Globus pallidus *	Semantic monitoring of speech production	Simultaneous bilinguals vs. monolinguals	88	Adults	Burgaleta et al., 2016

Note. Table 1 summarizes bilingual studies discussed thus far that have revealed gray matter density, volume or cortical thickness differences. Brain regions are organized by cortical and subcortical sections, divided into specific brain regions, accompanied by brief information on the associated cognitive process and the participants in each study for reference. * Reflects bilateral differences found in the specific brain region.

White Matter Studies

Pliatsikas et al. (2015) performed a study with 20 sequential late bilinguals (mean age= 31.9 years; mean age of acquisition = 10.2 years; *SD* = 8.06) with various L1 backgrounds and compared them to 25 English monolinguals (mean age = 28.2 years; *SD* = 5.33). A tract-based spatial statistical analysis was used. Results revealed higher FA values for the sequential bilinguals in four tracts. The first white matter tract affected in the bilingual group was the inferior fronto-occipital fasciculus bilaterally ($p < 0.05$, corrected). This tract has been heavily implicated in L2 learning (Pliatsikas et al., 2015) and semantic processing (Leclercq et al., 2010). Therefore, the authors of this study took this to suggest that higher FA in the inferior fronto-occipital fasciculus bilaterally may result in more efficient semantic processing in bilinguals. The second white matter tract identified was the genu of the corpus callosum, including the genu, the body, and the anterior part of the splenium bilaterally ($p < 0.05$, corrected). While the role of the corpus callosum in language processing is not fully understood, it has been implicated in effective interhemispheric communication and executive functioning (Just et al., 2006; Zhang et al., 2014). The authors suggested the results may indicate enhanced executive functioning in bilinguals due to increased FA in the corpus callosum. The final two tracts found to be affected by bilingualism in this study were the superior longitudinal fasciculus ($p < 0.05$, corrected) and the uncinate fasciculi ($p < 0.05$, corrected). The uncinate fasciculi and the superior longitudinal fasciculus white matter tracts constitute, respectively, a dorsal and ventral white matter pathway connecting Broca's area to temporal areas (i.e., the superior temporal gyrus and middle temporal gyrus), which have been implicated to be involved in phonological, semantic, and syntactic processing (Friederici, 2012). Therefore, increased white matter in the uncinate fasciculi and the superior longitudinal fasciculus would suggest improved phonological, semantic, and syntactic processing in bilinguals (Pliatsikas et al., 2015).

Schlegel et al. (2012) utilized longitudinal DTI to track the structural white matter changes in the brain that occur with learning a new language. Monthly DTI scans were performed on each participant over nine months. Participants included a training group of 11 English monolingual learners, who took a 3-term intensive modern standard Chinese language course and a control group of 16 English monolingual non-learners, with a mean age of 20.05 for both groups. White matter changes were found both within and beyond traditional language processing regions in the learning group relative to the control group ($p < .05$, after FDR correction for multiple comparisons). Language learners demonstrated greater FA in traditional left hemisphere language tracts between language areas, their right hemisphere analogous, areas in the temporal region, and across the genu of the corpus callosum (Schlegel et al., 2012). Single region networks (i.e., BA45-transverse frontopolar gyrus and sulcus; planum polare-Anterior superior temporal gyrus; planum temporale-Posterior superior temporal gyrus) and between region networks were found (i.e., transverse frontopolar gyrus and sulcus-Caudate nucleus, Frontomarginal gyrus and sulcus-Caudate nucleus, anterior superior temporal gyrus-Frontomarginal gyrus and sulcus). The authors of this study concluded that structural plasticity plays a role in language learning, even among adults. They further added that the changes observed between frontal cortical regions and the caudate nucleus support previous findings that language learning entails developing control networks to mediate switching between languages. Last, results from this study were implicated in supporting adult brain plasticity. The adult brain demonstrates the capacity to reorganize and learn by expanding the functionality of networks by altering the underlying anatomy.

Luk et al. (2011) conducted a study with 28 healthy older adults. Fourteen participants were monolingual speakers, and 14 were lifelong bilinguals (L2 acquired before 11) with a mean age of 70.5 years between groups. DTI results demonstrated significantly increased FA values for bilinguals compared to monolinguals in the corpus callosum ($p < 0.05$, corrected) that extended to the superior and inferior longitudinal fasciculus ($p < 0.05$, corrected). It was hypothesized that the engagement of more distributed brain networks in older adults may reflect stronger working memory connectivity between brain regions, facilitating information transfer, which may be one mechanism underlying the bilingual advantage observed in executive function performance (Luk et al., 2011).

Overall, bilingualism appears to facilitate greater white matter changes in traditional language areas (i.e., frontal and temporal regions) and the implementation of regions not typically found to be involved in language processing (i.e., corpus callosum). The white matter differences appear to be found in both adults and older adult bilinguals (Luk et al., 2011; Pliatsikas et al., 2015; Schlegel et al., 2012). The bilingual experience further appears to facilitate creating a more complex integration of various brain regions to manage both languages in both adults (Luk et al., 2011; Pliatsikas et al., 2015). Therefore, results from the gray matter bilingual studies may suggest the acquisition of a second language facilitates reorganization, and stronger connectivity between brain regions, facilitating information transfer. Table 2 summarizes the white matter tract findings by brain region and associated cognitive process.

The next chapter continues to build on our understanding of the changes in the bilingual brain. Studies discussed include research on functional activation differences within eight core cognitive areas: language, executive functioning, visuospatial, working memory, memory, attention, motor and sensory. Functional activation research makes important contributions to our understanding of changes in functional anatomy occurring as a result of our experiences. Knowledge of how the brain responds to an experience such as acquiring a second language is critical, as it aids in our understanding of the mechanisms of repair and cognitive recovery. Understanding neuroanatomical, neurochemical, and functional changes may also facilitate and implement appropriate rehabilitation interventions (Crosson et al., 2010; Smith et al., 2004).

Table 2

White Matter Tracts in Bilingual Populations

Brain Region	Associated Cognitive Processes	Groups	N	Age	Study
		Networks within a region			
Frontal					
BA45 /TFPG	Lexical-semantic production retrieval of long-term memories	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012
Temporal					
PP*/ aSTG*	Connectivity with aSTG phrase structure, syntactic violations, high temporal details of speech	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012
PT*/ pSTG*	Connectivity with pSTG Syntactic/semantic integration, semantic violations	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012
		Networks between regions			
CC*	Effective interhemispheric communication and executive functioning	Sequential late bilinguals vs. Monolinguals	45	Adult	Pliatsikas et al., 2015
SLF/ UF	Connects Broca's area to temporal areas phonological, semantic and syntactic processing	Sequential late bilinguals vs. Monolinguals	45	Adult	Pliatsikas et al., 2015
Frontal/subcortical					
TFPG* /CN*	Retrieval of long-term memories lexical-semantic control	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012
FMGS* /CN*	Retrieval of long-term memories lexical-semantic control	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012

Brain Region	Associated Cognitive Processes	Groups	N	Age	Study
Frontal/temporal					
aSTG/	Phrase structure, syntactic violations, high temporal details of speech	L2 foreign language Learners vs. monolinguals	27	Adults	Schlegel et al., 2012
FMGS	Retrieval of long-term memories				
Frontal/occipital					
IFOF *	L2 learning & semantic processing	Sequential late bilinguals vs. monolinguals	45	Adult	Pliatsikas et al., 2015
Frontotemporal/frontoparietal					
CC & SLF	Producing and understanding language	Lifelong bilinguals vs. monolinguals	28	Older adults	Luk et al., 2011
Ipsilateral temporal / Occipital					
CC &ILF	Visual processing and language comprehension, semantic processing	Lifelong bilinguals vs. monolinguals	28	Older adults	Luk et al., 2011

Note. Abbreviations include: inferior fronto-occipital fasciculus (IFOF), corpus callosum (CC) connecting the left and right cerebral hemispheres, superior longitudinal fasciculus (SLF) ects the frontal, occipital, parietal, and temporal lobes, uncinate fasciculi (UF) connects parts of the limbic system such as the temporal pole, Transverse frontopolar gyrus and sulcus (TFPG) frontal, Frontomarginal gyrus and sulcus (FMGS) frontal, BA 45 (triangular part of IFG) frontal, Caudate nucleus (CN) subcortical area, Anterior superior temporal gyrus (aSTG), Posterior superior temporal gyrus (pSTG), Planum temporale (PT) temporal, Planum polare (PP)-temporal, Superior longitudinal Fasciculus SLF, Inferior longitudinal fasciculus (ILF), inferior longitudinal fasciculus/inferior fronto-occipital fasciculus bilaterally ILF/ IFOF*

Chapter III: DIFFERENCES IN FUNCTIONAL ACTIVATION IN BILINGUALS

Exploring functional activation patterns is essential for identifying brain injury or disease on cognitive systems and developing appropriate rehabilitation treatments (Crosson et al., 2010; Smith et al., 2004). Functional imaging techniques provide clinicians the opportunity to localize brain function and understand how experiences, such as the acquisition of a second language, influence cognitive utilization. Identifying functional brain activation patterns in healthy demographic groups allows for establishing a comparison group for baseline functioning and identifying cognitive deficits better. More appropriate guidelines for treatment can then be established and implemented.

Functional imaging studies in bilinguals continue to rapidly grow, with research demonstrating differences in functional activation patterns compared to monolinguals (Costa & Sebastián-Gallés, 2014). Given the importance of identifying baseline patterns to identify deficits in functioning, this chapter focuses on summarizing articles on functional activation patterns in healthy bilingual individuals. The goal of this portion of the review is to allow the reader to identify the unique functional activation patterns to aid in establishing more adequate treatment guidelines for brain-injured bilinguals.

This chapter begins by briefly discussing functional activation patterns in the universal language network, leading to discussing bilingual functional imaging studies. Bilingual studies have been organized into eight core cognitive areas: language, executive functioning, visuospatial, working memory, memory, attention, motor and sensory. However, it is important to note that the brain's high interconnectivity and cohesiveness make it difficult to parcel out the overlapping effects of the various domains of cognition, especially parceling out executive functioning, which often plays a large role in numerous tasks. Last, this chapter provides clinicians with a table for reference that summarizes the differences in functional activation patterns in each of the eight cognitive domains (i.e., language, executive functioning, visuospatial, working memory, memory, attention, motor and sensory).

Effects of Bilingualism on Language Functioning Brain Regions

Concerning language processing, research has demonstrated that humans possess only one brain circuitry for language, primarily in the left hemisphere (Friederici, 2012), with bilinguals also demonstrating usage of this circuitry to process their two languages (García-Pentón et al., 2014). While findings have demonstrated the utilization of a universal language circuity, differences in the amount of activation in the classic language regions and the integration of other brain regions have been demonstrated in bilingual brains (García-Pentón et al., 2014). To understand activation differences in the language circuitry better, a brief discussion of the classic linguistic system is discussed, followed by highlighting differences in activation patterns in bilinguals.

The Universal Language Network

As discussed in the previous chapter, there is a consensus on a classic language processing model. The model consists of a motor speech center (i.e., BA 44 and BA 45), the sensory speech center (i.e., Wernicke's area), and a bundle of nerve fibers (i.e., arcuate fasciculus) that connects the motor and sensory speech centers (Ardila et al., 2016; Fujii et al., 2016), all of which are typically left-lateralized in most individuals (Catani et al., 2005). Language processes also integrate frontal (inferior frontal gyrus), temporal (superior temporal gyrus and the middle temporal gyrus), and parietal (inferior and superior parietal lobe) language areas (Ardila et al., 2016; Fujii et al., 2016).

Broca's area consists of the pars triangularis and opercularis of the inferior frontal gyrus, corresponding to Brodmann's areas 45 and 44, respectively. Wernicke's area is the cortical area of the posterior potion of the superior temporal gyrus and a part of the supramarginal gyrus, corresponding to Brodmann's area 22 (Ardila et al., 2016; Fujii et al., 2016).

The classical language areas are interconnected and are part of two major pathways. The major pathways include the dorsal stream and the ventral stream. The dorsal stream is supported primarily by the SLF and the arcuate fasciculus, which are associated with phonological processing. The ventral stream is primarily supported by the inferior frontal-occipital fasciculus and is associated with semantic processing (Ardila et al., 2016; Fujii et al., 2016). Both pathways are activated for speech comprehension and production (Catani et al., 2005). Additionally, speech draws on brain areas such as the caudate nucleus, superior frontal gyrus, and superior longitudinal fascicle (Friederici & Gierhan, 2013). While reading utilizes visual brain areas such as the fusiform gyrus and the angular gyrus (Golestani, 2012), and sentence comprehension includes the temporal lobe (superior temporal gyrus and middle temporal gyrus consisting of Wernicke's area BA 39 and BA 40) and frontal lobe (inferior frontal gyrus consisting of Broca's area (BA 44 and BA 45/Ardila et al., 2016), written language utilizes the angular gyrus (BA 39/Ardila et al., 2016).

When processing auditory language, sounds are first processed in the left middle portion of the superior temporal gyrus, words are recognized, and lexical-semantic integration occurs (Friederici, 2012; MacGregor et al., 2012). Once the phonological word has been identified, syntactic and sentential information needs to be retrieved. Information travels to the frontal lobe for syntactic processing in the pars opercularis (BA 44) and the frontal operculum for further semantic processing (in BA 45 and BA 47) via different pathways. Ultimately, linguistic information goes back to the temporal lobe for semantic and syntactic integration and optimal sentence comprehension (Friederici, 2012). To then articulate speech, the premotor cortex is activated (Pulvermüller et al., 2006). The highly dynamic and interactive language cycle has been shown to occur in monolinguals and bilinguals when language is processed. However, bilinguals demonstrate differences in the amount of activation in classic language regions (i.e., Broca's area and Wernicke's area) and integrate other brain regions to manage their multiple languages (Jasińska & Petitto, 2013; Kovelman, Shalinsky et al., 2008; Li & Grant, 2016). Differences in cognitive processes in bilinguals appear to be influenced by the constant joint activation of L1 and L2. Research has demonstrated that bilinguals are not able to switch off a language; instead, L1 and L2 are in constant competition (Abutalebi & Green, 2007). The next few sections focus on studies that have identified differences in language processing in bilinguals.

The Bilingual Impact on The Universal Language Network

Phonological Processing Differences in Bilinguals

García-Pentón et al. (2014) conducted a study measuring structural brain network differences between early bilinguals and monolinguals. Participants included 13 native Spanish monolinguals (mean age = 29.1 years, *SD* = 6.60) and 13 early Spanish-Basque bilinguals (mean age =24.1, *SD* = 4.62). Eleven of the bilinguals acquired L2 simultaneously from birth, and two started to acquire L2 before preschool. Diffusion-weighted MRI tractography techniques and a network-based statistical analysis were utilized to detect significantly different networks between groups ($p < 0.01$ corrected). Two primary networks were reported to have stronger connectivity in bilinguals than monolinguals ($d = 1.17$). The first network was comprised of the left frontal, parietal, and temporal regions (insula, superior temporal gyrus, pars triangularis of the inferior frontal gyrus, the supramarginal gyrus, par and pars opercularis of the inferior frontal gyrus and the medical superior frontal gyrus $p = 0.006$), all of which are related to language processing (Binder & Desai, 2011) and have demonstrated involvement in bilingualism Grogan et al., 2012). This network is potentially involved in phonological, syntactic, and semantic interference between languages (García-Pentón et al., 2014; Wong et al., 2016). The second network involves the occipital gyrus and parietal-temporal regions (left superior parietal gyrus, right superior frontal gyrus, left superior parietal gyrus, left superior temporal pole, and left angular gyrus $p = 0.008$). The left superior temporal pole and the left angular gyrus have been associated with language processing (Binder & Desai, 2011), the left superior occipital gyrus has been found to play a role in the high-level visual processing of letters and words (Carreiras et al., 2009), the right superior frontal gyrus in language control (Abutalebi & Green, 2007) and the superior parietal gyrus has been reported to play a role in the visual-spatial processing during visual word processing (Sun et al., 2011). This second network is potentially involved in visual word recognition, reading, and semantic processing (García-Pentón et al., 2014; Wong et al., 2016).

In summary, phonological processing areas show some differences between bilinguals compared to monolinguals. The authors took the results to suggest the early simultaneous acquisition of a second language facilitates the development of more graph-efficient subnetworks to accommodate extra language demands. The development of more graph-efficient subnetworks may be devoted to language monitoring, avoiding interference between the two languages, and facilitating the processing of both languages (García-Pentón et al., 2014).

Lexical Sematic Processing in Bilinguals

Semantics is the area that is most concerned with the representation and processing of the meaning of words. Acquiring a second language has been shown to increase the complexity of semantic processing in bilinguals, as the way in which each language is represented in the brain, and the relationship between L1 and L2 differs compared to monolingual individuals. Therefore, this section discusses studies that have found differences in semantic processing in bilingual populations.

Kovelman, Shalinsky et al. (2008) conducted a study investigating semantic processing in bilingual adults compared to monolinguals. Patients included 10 right-handed Spanish-English balanced bilinguals (mean age = 19 years) and 10 right-handed monolinguals (mean age = 20 years). fNIRS imaging was utilized to measure blood flow changes in the brain. Kovelman, Shalinsky et al. (2008) found that early bilinguals showed greater signal intensity in the dorsolateral prefrontal cortex and inferior frontal cortex compared to monolinguals, while also recruiting similar language areas such as Broca's 44/45; ($F(1,19) = 13.9$, $p < 0.01$). Differences occurred when bilinguals had to use both or either of their languages. When bilinguals had to use one language only, they showed greater signal intensity, as measured by changes in oxygenated hemoglobin in the dorsolateral prefrontal cortex and inferior frontal cortex areas ($p < 0.05$; Kovelman, Shalinsky et al., 2008). Bilinguals demonstrated greater activation in the left inferior frontal cortex (Broca's 44/45) when processing English relative to the English monolinguals (t $(1,9) = 4.30$; $p < .00$). Greater activation of Broca's 44/45 when processing English in the bilingual group may suggest a functional separation of L1 and L2 (Kovelman, Shalinsky et al., 2008).

Jeong et al. (2010) conducted a study with 44 healthy right-handed native adult Japanese speakers (mean age = 21.6 years) to investigate the cortical representation of L2 vocabulary acquired in different modes. Jeong et al. (2010) manipulated whether L2 Korean words by Japanese learners were learned through situation-based (real-life) dialogue or from print (written translations learning). Brain activity was measured during subsequent retrieval of words with fMRI. A two-level approach for event-related fMRI data was adopted using SPM5, and a voxel-by-voxel multiple regression analysis was used. Statistical interference on contrasts of parameter estimates was also performed using a second-level between subject's model using a one-sample *t*-test. The statistical threshold in the voxel-wise analysis was corrected $p < 0.05$ for family-wise error. Last, a region of interest analysis was obtained with a threshold of $p < 0.05$, without correction for multiple comparisons. A two-way repeated measure ANOVA was conducted to evaluate the effect of the type of learning, the type of test, and the interaction effect between the two (i.e., learning and test), with a pairwise comaprision using a Bonferroni correction. Jeong et al. (2010) reported that L2 vocabulary retrieval activated the left inferior, middle, and superior frontal areas, anterior cingulate cortex, temporal areas, parietal lobule, bilateral insula, and basial ganglia ($p < 0.05$ without correction for multiple comparisons). Results further revealed a significant main effect for leaning type (F(1.26, 37.86 = 7.46, $p = 0.006$). Pairwise comparisions following the significant main effect, using a Bonferroni correction revealed that the right supramarginal gyrus was more active for second language words learned in a social situation ($p < 0.001$, $p = 0.024$) while the latter manner (words spoken by a person holding a board on which the Japanese translation was written) of learning grew greater activation in the left middle frontal area during the retrieval test ($p = 0.03$). Further, when words that were learned in one condition were tested in the other condition (e.g., situation-learned, print tested), results elicited significantly more activity in the left triangular part of the left inferior frontal gyrus, $F(1.38, 41.56) = 6.43$, $p = 0.009$), supporting the role of the inferior frontal gyrus in flexible retrieval of language two vocabulary. Results reveal that acquiring a second language involves the recruitment of multi-element cognitive processes. The left frontal is involved in executive aspects of linguistic information during learning and remembering (Gabrieli et al., 1998). The left temporal region, including the hippocampus, is involved in semantic memory, which is related to storing the meaning of words (Breitenstein et al., 2005). The left parietal area is associated with phonological storage (Paulesu et al., 1993), and the anterior cingulate cortex is associated with attention during a verbal task (Jeong et al., 2010).

Kovelman, Baker et al. (2008) conducted a study to determine whether bilinguals process language differently from monolinguals and sought to identify brain areas recruited during a language task. The study consisted of 11 Spanish-English right-handed bilinguals and 10 English right-handed monolinguals. fMRI was utilized to measure brain activity during a syntactic "sentience judgment task." fMRI analysis revealed bilingual participants demonstrated greater BOLD signal intensity and extent in the left inferior frontal cortex; t (1,10) = 2.86, $p < .001$, uncorrected). Furthermore, bilinguals elicited a significantly greater increase in blood oxygenation in the left inferior frontal cortex when processing the English language, more so than the monolingual group during a semantic judgment task, t (1,9) = 4.30, $p < .001$ (Kovelman, Baker et al., 2008). The authors of this study took the results to suggest that early acquisition of a second language promotes greater activation of similar language processes as monolinguals with differentiated neural patterns of activation for each language.

Overall, studies assessing differences in semantic processing in bilinguals revealed that the acquisition of a second language promotes greater activation of similar language processes as monolinguals but with differentiated neural patterns of activation for each language (Jeong et al., 2010; Kovelman, Baker et al., 2008). Greater activation appears to happen when processing L2. Greater activation and the recruitment of other brain regions (i.e., bilateral insula and basial ganglia; Jeong et al., 2010) may suggest differential patterns and functional separation of L1 and

L2. The following section discusses differences in functional activation in brain regions utilized for executive function skills.

Executive control is a set of cognitive skills based on limited cognitive resources for such functions as inhibition, switching attention, and working memory (Miyake et al., 2000). Executive control emerges late in development and declines with age, and supports such activities as high-level thought, multitasking and sustained attention. Several studies have suggested the executive function enhancement is due to bilinguals continuously activating both languages while inhibiting the nontarget language (Bialystok et al., 2012; Costa & Sebastián-Gallés, 2014; Kroll et al., 2013). This parallel activation of both languages has been demonstrated to occur when bilinguals listen, speak, read, and write in either of their two languages (Bialystok et al., 2012; Costa & Sebastián-Gallés, 2014; Kroll et al., 2013). The joint activation results in constant interaction between the two languages in the form of interference and/or support of each language (Jasińska & Petitto, 2013; Kroll & Bialystok, 2013). The language interaction has also been demonstrated to be bidirectional from the dominant to the less dominant language and vice versa (Jasińska & Petitto, 2013; Kroll & Bialystok, 2013). In bilinguals, this constant process of joint language activation has demonstrated greater activation of the left dorsolateral prefrontal cortex and the anterior cingulate cortex (Abutalebi & Green, 2007), which regulate language switching and general executive functions such as conflict, control, monitoring, selective attention, and inhibition (Bialystok et al., 2012; Costa & Sebastián-Gallés, 2014; Kroll & Bialystok, 2013).

Grady et al. (2015) examined resting-state and task-based fMRI connectivity in 14 older adult monolingual English speakers (mean age = 70.6 years) and 14 lifelong bilinguals (mean age = 70.3 years) with age of acquisition before 11 years old. Functional connectivity in two brain networks typically involved in executive functions—the frontoparietal control network and the salience network—was examined along with the default mode network. To assess functional connectivity, the processed resting-state data were analyzed with seed partial least squares. Seed PLS is a data-driven multivariate statistical technique that reveals functional activity across the entire brain that correlates with some external variable (Grady et al., 2015). Results demonstrated stronger intrinsic functional connectivity in the frontoparietal control network; t (62) = 3.7, p = 0.001) and the default mode network in bilinguals, t (62) = 3.2, p = 0.002) relative to monolinguals (Grady et al., 2015). Overall, the older lifelong bilinguals in this study demonstrated enhanced network activity relative to their monolingual peers. Enhancement was demonstrated in stronger functional connectivity within networks that influence cognitive control (Grady et al., 2015).

Li et al. (2015) evaluated differences in functional connectivity patterns in language control regions in spoken language (i.e., dorsal anterior cingulate cortex and the left caudal nucleus) among 14 highly proficient Mandarin Chinese Sign Language bimodal bilinguals (mean age = 49.5 years) and 15 monolinguals (mean age = 43.5 years). Participants were asked to perform a picture-naming task with spoken language or were in a resting state. Differences in resting-state functional connectivity in bimodal bilinguals were compared to monolinguals with task-related fMRI and resting-state fMRI. Task-related fMRI results were analyzed using a two-sample t-test to conduct the group difference in activation. For resting-state fMIR results, group comparisons were conducted using a two-sample t-test to detect the functional connectivity differences between bilinguals and monolinguals. The criteria for multiple comparison correction were determined by AlphaSim. A corrected alpha level of 0.05 was set. Results demonstrated bimodal bilinguals who used spoken, and sign language demonstrated decreased resting-state functional connectivity between the dorsal anterior cingulate cortex and the left superior temporal gyrus (regions involved in spoken language) and left Rolandic operculum ($p < 0.05$) but demonstrated stronger functional connectivity among these regions when performing the task. The researchers concluded that bimodal bilinguals may have less synchronized language suggesting that the neural substrates of the two languages do not necessarily overlap. (Li et al., 2015). The decreased activation of brain regions involved in spoken language (i.e., dorsal anterior cingulate cortex and the left superior temporal gyrus) in this study may suggest that bimodal bilinguals may not need much control compared to monolinguals because the potentially nontarget language is in a different modality (sign language). Unlike unimodal bilinguals, whose two spoken languages compete for output, bimodal bilinguals can produce two languages simultaneously so that there is probably much less competition between language outputs.

Berken et al. (2016) sought to investigate whether an early versus late second-language acquisition would be associated with different patterns of functional connectivity. Participants included 16 French-English simultaneous (mean age = 23.3 years) and 18 sequential bilinguals (mean age = 25.7 years, L2 age of activation > 5 years). For the resting-state fMRI analysis, data were acquired using a T2-weighted EPI sequence. Analysis was performed using a seed-driven approach with the CONN software package. Regions of interest included the left and right inferior frontal gyrus pars triangularis and BA45. Significant correlations in functional connectivity survived a height threshold of uncorrected $p < 0.001$ and an extent threshold of FEW-corrected $p < 0.05$ at the cluster level. The inferior frontal gyrus plays a significant role in speech production and language processing, as well as in nonlinguistic domain-general cognitive processes, such as executive control (Berken et al., 2016). Results demonstrated simultaneous bilinguals demonstrated stronger functional connectivity between the left inferior frontal gyrus and its right counterpart, as well as the right dorsolateral prefrontal cortex and bilateral inferior parietal lobule. Simultaneous also demonstrated greater resting-state functional connectivity between the right inferior frontal gyrus and its left counterpart as well as the left inferior parietal lobule and the cerebellum. In addition, a regression analysis with the age of acquisition in sequential bilinguals demonstrated a significant negative correlation with age of acquisition between the left and right inferior frontal gyrus ($r = -0.64$; $p = 0.0001$) and the right inferior parietal lobule ($r = -0.72$; $p = 0.02$). Results suggest the brain is shaped differentially depending on the L2 age of acquisition. The earlier the second language is acquired, the greater the resting-state connectivity between the left and right inferior frontal regions and the right inferior parietal region. Acquiring L2 later in life leads to different functional circuitry to attain second-language expertise, as evidenced by greater left lateralization of the inferior frontal gyrus (Berken et al., 2016).

Overall, brain development in bilinguals appears to be influenced by the age at which L2 is acquired. Lifelong bilinguals have demonstrated greater functional connectivity (Grady et al., 2015) and resting-state connectivity (Berken et al., 2016) within executive function networks. However, it has also been found that differential language modalities in bilinguals (i.e., sign language versus spoken language) play a role in utilizing brain regions (Li et al., 2015). For example, Li et al. (2015) found decreased resting-state activation of brain regions involved in spoken language. (i.e., dorsal anterior cingulate cortex and the left superior temporal gyrus in bimodal bilinguals). These results suggest differential language representations if the modalities are different, as the cognitive demand is unique to each language. Unlike unimodal bilinguals, whose two spoken languages compete for output, bimodal bilinguals can produce two languages simultaneously so that there is probably much less competition between language outputs (Li et al., 2015).

Attention control is another executive function skill that allows for the ability to focus and shift attention selectively (Diamond, 2013). Neuroimaging studies offer insight into group differences that may not be manifested as behavioral differences in experimental task performance (Kroll et al., 2013). Research has shown that the experience of acquiring a second language promotes changes in attentional control regions in bilingual speakers. Studies evaluating attentional control brain regions are discussed further in the next section.

Effects of Bilingualism on Attention Functioning Brian Regions

Dash et al. (2019) investigated the neurofunctional correlates of the subcomponents of attention in 20 healthy young bilinguals (mean age = 32.6 years) and 18 older adult bilinguals (mean age = 73.9 years). Variables such as L2 age of acquisition, language usage, and proficiency were all taken into account. The fMRI version of the Attention Network Test was utilized and speed, accuracy, and BOLD data were collected. The Attention Network Test is a combination of a cueing paradigm and the Flanker task. Participants were presented with five white arrows on a black background and asked to determine the direction of the target arrow in the middle, left or right of the computer screen. MR imaging was performed using a 3T MRI Siemens Prisma Fit scanner with a standard 64-channel head coil. To conducted a whole-brain analysis, the general linear model in SPM was used. Only effects surviving an uncorrected voxel-level threshold of $p < 0.001$ and/or a cluster-level family-wise error corrected threshold of $p < 0.05$ were interpreted. The relationship between measures of bilingualism and attention was examined by conducting a Pearson correction analysis with adjusted *p*-values controlling for multiple comparisons. fMRI results demonstrated increased neurofunctional activity in the ventrolateral prefrontal cortex (*p* = 0.001 uncorrected) and the right superior parietal gyrus close to the temporal-parietal junction (*p* = 0.001 uncorrected) in older adult bilinguals relative to the young bilinguals.

Additionally, L2 proficiency was negatively correlated with activation in the frontal region and faster reaction times were negatively correlated with activation in frontal and parietal brain regions ($r = -0.517$ $p = 0.01$). Overall, results demonstrate increased brain activity in the frontal and parietal areas during alerting and orienting subcomponents of attention in older adult bilinguals. Older adult bilinguals' advantage in maintaining an alert state was associated with increased L2 proficiency on discourse tasks. The authors suggested that results demonstrating the benefits of lifelong bilingualism may result in a greater ability to sustain alertness for upcoming stimuli (Dash et al., 2019). Another component of executive function that has been found to be impacted in bilingual populations is working memory (Lin et al., 2011). Therefore, differences in working memory processes are discussed in the following section.

Effects of Bilingualism on Working Memory Functioning Brain Regions

Lin et al. (2012) investigated the neural correlates involved in working memory in bilingual individuals when tasks were presented auditorily in either L1or L2. Participants included 11 Chinese-English bilinguals (mean age = 26.9 years). The 11 participants heard 2-digit addition problems that required exact or approximate calculations. An fMRI scan was performed on a .5-T MR scanner using SPM5 software to analyze the data. Differences in activation patterns were considered significant if the voxel-level *p*-value was less than 0.001 (uncorrected) and if a cluster-extent threshold of at least 10 contiguous voxels was found. fMRI results demonstrated bilateral inferior parietal and inferior frontal region activation in both L1 and L2. With greater activation in the left inferior frontal area when L2 was used when performing the exact addition task, suggesting that mental calculation performed in L2 may also rely on similar brain regions but with an extra load on language processing during mental addition in L2 (Lin et al., 2011). Bilinguals' functional activation patterns in memory are discussed in the next section.

Effects of Bilingualism on Memory Functioning Brain Regions

In an fMRI study, Majerus et al. (2008) sought to investigate the neural activation patterns in order short-term memory and item short-term memory in German-French bilinguals, who differed in second-language lexical proficiency (i.e., high and low level of proficient). Participants included 11 highly proficient German-French bilinguals (mean age = 19.4 years) and 11 low proficient German-French bilinguals (mean age = 19.6). Each trial consisted of an encoding phase of visual and sequential presentation of four German words, followed by a maintenance phase. The retrieval phase consisted of an array of two German words ordered horizontally. Participants were required to indicate whether the probe words matched the target information in the memory list. In the order memory condition, participants determined whether the probe word presented on the left of the screen occurred before the probe word presented on the right relative to the order of presentation of the two words in the memory list. In the second condition, participants judged whether the probes were identical to the words in the memory list. Data collected were processed and analyzed using SPM5 software in MATLAB version 7.0.4. A one-sample t-test was utilized to assess the functional connectivity pattern differences for the order encoding task, with a $p < 0.05$ threshold for whole-brain volume and a small volume correction at $p > 0.05$ for a priori locations of interest (Majerus et al., 2008). Results revealed that high proficiency bilinguals demonstrated greater activation in the left orbitofrontal cortex ($p < 0.05$) during order encoding and the superior frontal areas ($p < 0.05$) during order retrieval.

Studies have shown that lateral orbitofrontal areas are involved in executive processes during working memory tasks while updating compared to inhibition or shifting (Collette et al., 2005; Elliott, 2000). The involvement of the orbitofrontal cortex has also been shown to be activated during a short-term memory task of sequential information presented in a grouped manner (Henson & Rugg, 2003) and is involved in higher-order cognitive skills. Therefore, the authors suggested that the recruitment of higher-order functions in highly proficient bilinguals may lead to more efficient encoding of serial order information. Furthermore, functional connectivity analysis demonstrated recruitment of the intraparietal sulcus ($p < .05$) and the right and left temporoparietal areas ($p < .05$) during order encoding in the low proficient group, relative to the high proficient group. Previous research has shown that these areas are involved in the phonological analysis of item information in short-term memory. The authors noted the highly proficient bilinguals incorporated greater updating processes, specifically during order encoding for a short-term memory task, relative to low proficient bilinguals (Majerus et al., 2008). The authors of this study interpreted the results to suggest that low-proficient bilinguals activated short-term memory networks in a less efficient and differentiated manner relative to highly proficient bilinguals. These results may also provide evidence to explain low proficient bilinguals' poorer storage and learning capacity for verbal sequences (Majerus et al., 2008). The next section discusses studies on visuospatial functional activation in bilinguals.

Effects of Bilingualism on Visuospatial Functioning Brain Regions

Bilinguals' functional activation patterns in visuospatial brain regions is an area that is lacking research. In reviewing the literature, it was difficult to find a study that only focused on measuring brain regions involved in visuospatial functions in bilinguals. However, Ansaldo et al. (2015) indirectly found activation differences in brain regions involved in visuospatial functions during an assessment of interference control among bilinguals and monolinguals. The study's objective was to examine the behavioral and neural activation pattern differences of nonverbal interference control in older adult bilinguals and monolinguals. Participants included 10 French monolingual speakers (mean age = 74.5 years) and 10 late French-English bilinguals (mean age = 74.2 years). To measure activation patterns, all participants were tested with the Simon task during an event-related fMRI session. Event-related fMRI BOLD responses were collected with a 3T Siemen's scan, and accuracy rates and response times were recorded for congruent and incongruent conditions of the Simon task.

In the Simon task, participants were presented with yellow or blue squares on the left or right side of a computer screen. Participants were instructed to press the left key if a yellow square appeared and a right response key if a blue square appeared. Congruent trials were those in which the stimulus was on the same side as the correct response key. Incongruent trials were those in which the reverse was true. Imaging data were analyzed separately using SPM5. Regions of four or more contiguous pixels above $p = .005$ (corrected) detected within the time window of 1 to 5 seconds after the stimulus were regarded as activated areas (*t*-test analysis). An ANOVA was also conducted to evaluate each trial across groups and conditions. Results from the incongruent condition of the Simon test resulted in monolinguals demonstrating recruitment of the prefrontal cortex network, an area known to be involved in the control of interference. Alternatively, bilinguals recruited the left inferior parietal lobule (BA 40; $p < .001$), an area known to be involved in visuospatial tasks. This suggests bilinguals do not need to resort to a cognitive control circuit to resolve visuospatial conflict, whereas monolinguals did. The authors suggested that lifelong bilingualism can promote more efficient use of cognitive control brain mechanisms (Ansaldo et al., 2015). The next section discusses functional activation patterns in motor regions in bilingual individuals.

Effects of Bilingualism on Motor Functioning Brain Regions

Concerning functional activation patterns in motor functioning brain regions, Raboyeau et al. (2010) found greater functional activation of the left premotor cortex and the cerebellum among bilinguals relative to monolinguals. The cerebellum has been found to be involved in language tasks, such as phonological and semantic fluency, word naming, and reading and writing (Smet et al., 2007). The purpose of Raboyeau et al.'s (2010) study was to investigate activation patterns of second-language lexical acquisition while controlling for learning phase (early and consolidation phase) and word type. Participants included 10 native French speakers who learned 80 Spanish words (mean age = 22.7 years) by means of a computer program. The words included 40 cognates and 40 noncognates. Data on the neural substrates of lexical learning data on activation patterns were obtained with two fMRI scans. fMRI scans were completed at the end of each learning phase (i.e., early phase and consolidation). The first scan took place after a five-day computerized lexical learning period (i.e., complete an overt picture-naming task in both languages), which was considered the early learning phase. The second fMRI scan was completed after the participant attained a 100% success rate of naming Spanish words for which the participants had been trained. BOLD signal increases related to the learning phase were significant at $p < 0.005$. Results demonstrated that the involvement of the left premotor cortex and cerebellum along with the supramarginal were essential in the consolidation of second-language phonetic representations (Raboyeau et al., 2010).

Crinion et al. (2006) also found differences in a brain region involved in movement functions. Crinion et al. (2006) performed a semantic priming task with highly proficient bilinguals. Participants included 1 group of 11 German-English bilinguals, a second group of 14 German-English bilinguals, and a third group of 10 Japanese-English bilinguals. The first group of German-English bilinguals participated in a PET experiment, while the other two groups participated in fMRI experiments. The study was designed to identify language-dependent neuronal responses at the level of word meanings. Results demonstrated left anterior temporal cortex activity was reduced with semantic primes (compared with unrelated primes) regardless of the language and regardless of whether the prime and target were in the same language ($p > 0.05$). In contrast to this language general effect, a whole-brain fMRI analysis found language-specific effects in the head of the left caudate nucleus ($p < 0.05$) after a small volume correction for multiple comparisons), where only semantically related word pairs that were presented in the same language showed reduced activity. Other conditions with different language pairs showed increased activity in the caudate nucleus. This suggests that the caudate nucleus plays a role in monitoring and controlling the language in use (lexical-semantic control), which the authors interpreted as a possible mechanism for regulating output given variations in language input (Crinion et al., 2006). The next section discusses functional activation patterns in brain regions utilized for sensory functions in bilinguals.

Effects of Bilingualism on Sensory Functional Brain Regions

Studies that measure functional activation in sensory brain regions have been identified at this time. While neuroimaging studies discussed thus far provide clinicians with information on how acquiring a second language impacts the development and utilization of brain regions in bilinguals, neuropsychological tests take it a step further. Neuropsychological tests are designed to provide the clinician with information on how the brain performs with various cognitive skills. The next chapter discusses performance differences in bilinguals in eight cognitive areas (i.e., language, executive function, attention, memory, visuospatial, working memory, motor and sensory).

Table 3

Functional Activation Patterns in Bilinguals

Functional Network	Associated Cognitive Process	Groups	N	Study
Language				
Left frontal, parietal & temporal regions	Control phonological, syntactic and semantic interference between languages	Early acquired, proficient adult bilinguals	26	García-Pentón et al., 2014
OFG & parietal, temporal regions	Word recognition, reading and semantic processing	Early acquired, proficient adult bilinguals	26	García-Pentón et al., 2014
DLPFC & IFC/with greater activation of BA 44/45 when processing L2	May suggest a functional separation of L1 & L2	Early, young adult, balanced bilinguals	20	Kovelman, Shalinsky et al., 2008
left inferior, middle & superior frontal areas, anterior cingulate cortex, temporal areas, parietal lobule, bilateral insula and basial ganglia	L2 vocabulary retrieval	Late, adult bilingual training study	44	Jeong et al., 2010
Right SMG was more active for L2	L2 words learned in a social situation	Late, adult bilinguals training study	44	Jeong et al., 2010
Left inferior frontal cortex when processing L2	Semantic judgment	Adult bilinguals	21	Kovelman, Baker et al., 2008
Decreased resting-state functional connectivity between the dorsal anterior cingulate cortex and the left superior temporal gyrus & left Rolandic operculum	Regions involved in spoken language	Highly proficient bimodal adult bilinguals	29	Li et al., 2015
Executive				
Fronto-parietal control network and the default mode network	Executive control	Older adult /lifelong bilinguals	28	Grady et al., 2015
left/ right IFG & right DLPFC and bilateral inferior parietal lobule	speech production & language processing, & executive control	Early simultaneous bilinguals	34	Berken et al., 2016
Bilateral IFG & left IPL & cerebellum	Resting-state functional connectivity	Early simultaneous bilinguals	34	Berken et al., 2016
Attention				
Ventrolateral prefrontal cortex & right superior parietal gyrus	Ability to sustain alertness for upcoming stimuli	Older adult bilinguals	38	Dash et al., 2019
Working Memory				
Bilateral inferior parietal and inferior frontal region activation in both L1 and L2	Exact Addition Task	Adult bilinguals	11	Lin et al., 2011
Memory				
Left orbitofrontal cortex	short-term memory network in order encoding	High proficient bilinguals	22	Majerus et al. (2008)
Superior frontal areas	short-term memory network in order retrieval	High proficient bilinguals	22	Majerus et al. (2008)
Visuospatial				

Functional Network	Associated Cognitive Process	Groups	N	Study
LIPL	Visuospatial Processing	Adult bilinguals	20	Ansaldo et al., 2015
Motor				
left premotor cortex and right cerebellum	consolidation of L2 phonetic representations	Late, young adult bilinguals training study	10	Raboyeau et al., 2010
Reduced left ventral anterior temporal lobe activity increased activity in the head of the left caudate nucleus	This suggests that the caudate nucleus plays a role in monitoring and controlling the language in use (lexical-semantic control)	Highly proficient adult bilinguals	25	Crinion et al., 2006
Sensory Studies that measure functional activation in sensory brain regions have been identified at this time				

CHAPTER III: HOW DOES NEUROPSYCHOLOGICAL TEST PERFORMANCE DIFFER IN BILINGUAL INDIVIDUALS?

Neuropsychological assessments are fundamental tools utilized to clarify how an injury has altered the brain's ability to process information, explain specific changes in behavior, and monitor the progression of disease and brain injury on cognitive functioning. Test results further aid in determining rehabilitation needs and guide treatment (Harvey, 2012). Normative comparisons are critical in interpreting neuropsychology assessments, as they allow for more accurate detection of cognitive improvement or decline. Normative date serves as a reference group, matched by age, gender, ethnicity, and educational attainment (Harvey, 2012).

To adequately assess an individual's abilities, the norms for the test being used should reflect similar demographic characteristics to those of the individual being tested (Stricks et al., 1998). However, often this is not the case. For example, while the bilingual population is increasing in the United States (U.S. Census Bureau, 2012), bilinguals are often given tests normed for native monolingual speakers (Portocarrero et al., 2007). This practice puts into question the validity of test findings and recommendations made by the examiner. Therefore, to more appropriately provide services to the increasing bilingual population, it is crucial to learn about the performance of bilinguals on standardized cognitive measures that were normed using monolingual English speakers.

This chapter's objective to summarize studies on bilinguals' cognitive performance on neuropsychological assessments routinely used in clinical practice. The chapter is organized into six broad cognitive skills (i.e., language, executive functioning (i.e., attention, working memory), memory, visuospatial, motor and sensory) to more efficiently cover several primary areas of cognitive functioning.

Neuropsychological Performance on Language Tasks

Commonly used tests to assess language functioning include the Controlled Word Association Test (COWA) that assesses verbal fluency and phonemic and semantic fluency Gollan et al., 2002), the Boston Naming Tests (BNT; Roberts et al., 2002), which assesses picture naming and the Peabody Vocabulary Test-II (PVT-II; Portocarrero et al., 2007) that assesses receptive and expressive vocabulary. Studies utilizing these tests with bilingual populations and other non-routine tests are discussed to further explore language performance in bilingual populations.

Portocarrero et al. (2007) sought to investigate how nonnative bilingual college students who immigrated to the United States and speak English performed on standardized measures of English vocabulary and verbal fluency that were normed with monolingual samples. Participants included 39 monolingual and 39 bilingual college students. Bilinguals were further divided into those who arrived early (before age 10) or late (at age 10 or later). To assess receptive and expressive vocabularies, the Peabody Vocabulary Test-III (PPVT-II) and Expressive Vocabulary Test (EVT) were administered and to assess verbal fluency, the phonetic and semantic fluency takes of the COWA were administered. Performance differences among the bilingual and monolingual groups on the Peabody Vocabulary Test-III, EVT, and COWA were assessed by conducting two-tailed independent sample *t*-tests. Scores on the PPVT-II and EVT are presented on standard scores, with a mean of 100 and a standard deviation of 15. These scores were derived using the normative data provided by each of the test manuals.

The relationship between age of arrival to the United Sates and performance on the measures of English vocabulary was assessed with a two-tailed Pearson's *r* correlation. Phonemic fluency of the COWA, standard scores were derived using A compendium of neuropsychological tests. Result demonstrates that while both monolingual and bilingual groups performed within the average range in expressive and receptive vocabularies, there were significant differences. On the PPVT-III (receptive vocabulary), mean standard scores for the monolingual and bilingual groups were 109.8 and 98.7, respectively (t (74) = 5.1, $p < .001$). On the EVT (expressive vocabulary), the mean standard scores for the monolingual and bilingual group were 107.3 and 94.9, respectively (t (74) = 3.8, $p <.001$). When the bilingual group was split, there were also significant differences between the bilinguals who arrived early ($n = 22$) compared to those who arrived late ($n = 17$). The mean scores for the early and late bilinguals on the PPVT-III were 103.9 and 93.2, respectively (t (35) = 2.9, $p < .01$). The mean scores for the early and late bilinguals on the EVT were 99.3 and 89.3, respectively (t (37) = 2.1, $p < .05$). This finding indicates that the earlier the second language is learned, the better the ability. Differences in English vocabulary between the early bilingual group and monolinguals also demonstrated significant differences in both the PPVT-III (t (58) = 3.3, $p < .01$), and EVT (t (57) = 2.2, p < .05. Monolinguals performed about one-half of one standard deviation higher than the early bilingual group. These results suggest that even when bilinguals arrive in the United States at a relatively young age, significant differences in English vocabulary are seen when compared to native monolinguals. To determine whether there were significant differences in verbal fluency, three independent 2x2 ANOVAs were performed using the participant type (monolingual and bilingual) as a between-subjects factor and semantic category (i.e., animals, kitchen, animals) as repeated measures factors. Results demonstrated significantly greater mean performance in monolinguals relative to bilinguals (monolingual mean = 21.9, bilingual mean = 17.2) in the animal category semantic task ($F(1,64) = 4.9$, $p < .05$) mean performance between monolinguals. There were no differences found in mean standard scores for total number of words produced in phonetic fluency (t (76) = .97, p = .33). English vocabulary and verbal fluency were also compared to the age of arrival. Results indicated that the younger the age of arrival the better they performed on the PPT-II ($r = -.59$; $p < 0.01$) and EVT ($r = -.55$; $p < .001$). These findings suggest that the age of arrival is significantly correlated with English vocabulary. Overall, it appears that age of acquisition is an important factor for the development of receptive and expressive language skills in bilinguals. Lower scores on verbal fluency performance on the animal category semantic task may have been due to cultural differences. It is possible that the bilingual group did not know the English translation (Portocarrero et al., 2007).

Gollan et al. (2002) sought to explore semantic and letter fluency performance in Spanish-English bilinguals compared to monolingual populations. Participants included 30 young adult English-speaking monolinguals and 30 young adult Spanish-English bilinguals. The bilingual group reported being proficient in both languages and having a history of early acquisition of the second language. However, bilinguals differed on the amount of usage. Fifteen (50%) of the bilingual speakers reported speaking exclusively Spanish at home with their parents, 9 (30%) reported speaking exclusively Spanish with at least one parent, and 5 (17%) reported using both Spanish and English with both parents. Each participant was tested individually, and all responses were both written down by the examiner and autotyped. Standard instructions for the verbal fluency task were provided; participants were told to say as many items as possible that belonged to each category without proper names and without using the same words with different endings. Unless otherwise indicated, an alpha level of .05 was used for all statistical tests; when *t*-tests were reported, they were two-tailed tests. A 2x2 ANOVA was used with participant type (bilingual and monolingual) and category types as repeated measures factors (semantics and letters). Results demonstrated bilinguals produced significantly fewer correct responses relative to monolinguals ($F(1, 58) = 18.99$, $p < .01$) with bilinguals showing the most difficulty with semantic trials ($F(1, 58) = 5.21$, $p < .05$). Monolinguals produced more correct responses in all category types including semantic ($t\ (58) = 5.14$, $p < .01$), letter ($t\ (58) = 2.16$, $p < .05$), and proper name ($t\ (58) = 3.26$, $p < .01$) categories. The difference between correct responses between monolinguals and bilinguals was more than twice as large on semantic categories as it was on letter categories.The difference in proper name categories was in between. Overall, early proficient bilinguals demonstrated poorer performance in verbal fluency semantic skills relative to monolinguals. The authors suggested that the bilingual and monolingual performance differences could have been attributed to language dominance. While the bilingual group in this study all acquired the language early and were proficient in the second language, they used the second language less often than the first. In this study, English was the language they were tested in, which was the bilinguals' second language. Less usage of the second language may have created cross-language interference, as the bilingual group had to quickly activate the less often used language.

Roberts et al. (2002) performed a study evaluating bilinguals' performance on the BNT, a widely used picture-naming test. Participants included 3 groups of adults: 42 monolingual English speakers, 32 proficient Spanish-English bilinguals, and 49 proficient French-English bilinguals. All participants were administered the Bosting Naming Test and asked to name all 60 pictures in English. Strict (responses listed in the BNT booklet) and lenient types of scoring were used. Eighteen item variants were used, in which synonyms were accepted. Mean scores for the monolingual group were high: 50.9 (strict) and 53.9 (lenient), and both the bilingual groups obtained much lower scores. Mean scores for the Spanish group were: 42.6 (strict), 43.9 (lenient). Mean scores for the French group were: 39.5 (strict) and 41.34 (lenient). An ANOVA indicated that the 3 groups differed with strict scoring ($F(2, 12) = 35.74$, $p < .0001$). Lenient scores also differed among the groups ($F(2,120) = 41.61$, $p < .0001$). The Tukey HSD test for unequal group sizes further confirmed that the monolingual group demonstrated higher scores than both bilingual groups ($p < .002$) for both strict and lenient scoring. The bilingual groups did not demonstrate differences among each other ($p > .15$). The authors suggested the results provided support that the BNT norms should not be used by clinicians when working with bilinguals, even when they are equally proficient in each language. Results also demonstrated differences among the bilingual groups, suggesting further research is needed to determine variables that may be potential influencers. Differences in cultural backgrounds were suggested to be a potential factor.

In summary, bilinguals appear to perform poorer on receptive (PPVT-II) and EVT relative to monolinguals even when bilinguals acquire the language early. However, there appears to be a greater difficulty when the second language is acquired late (Portocarrero et al., 2007). Bilinguals also demonstrated poorer performance on semantic category tasks (Gollan et al., 2002; Portocarrero et al., 2007), with particularly greater difficulty on the animal category semantic task (Portocarrero et al., 2007). Bilinguals further demonstrated poorer performance on picture-naming tasks. However, it is important to consider that, as indicated in Gollan et al. (2002), factors such as the history of usage may influence the quality and speed of activation of lexical skills in bilinguals. Receptive and expressive language skills are also culturally influenced, as mentioned as a potential explanation for poorer picture-naming performance in the bilingual group, due to a lack of exposure to certain items presented (Roberts et al., 2002).

A considerable body of evidence has further accumulated to suggest that bilingualism promotes cognitive differences beyond the linguistic domain. This is evidenced by bilinguals' performance on a variety of neuropsychologic tests. The next section further identifies bilingual studies in seven cognitive domains (i.e., executive functioning, attention, memory, working memory, visuospatial, motor, and sensory skills).

Neuropsychological Performance on Executive Functioning Tasks

Executive functions consist of a set of cognitive processes that aid in planning, organizing, and initiating to achieve the desired goal. Executive functions also help sustain attention and promote the regulation of emotions. Literature with bilingual individuals has shown evidence suggesting that the acquisition of a second language enhances executive functions compared to monolingual individuals (Bialystok et al., 2008, 2010; Carlson & Meltzoff, 2008; Gold et al., 2013; Salvatierra & Rosselli, 2010). Bilinguals have demonstrated advantages in executive control in studies with children (Bialystok et al., 2010; Carlson & Meltzoff, 2008) and older adults (Bialystok et al., 2008; Gold et al., 2013; Salvatierra & Rosselli, 2010). Studies supporting the bilingual executive function advantage have also been found in young adults; however, results were mixed. Some studies found an advantage in executive functions in bilingual adults (Bialystok, 2007), while others failed to find evidence to support the executive function advantage (Paap & Greenberg, 2013). Mixed results among bilingual adults may be due to more variability in the maturing or declining brain than young adults operating at peak efficiency, making it difficult to demonstrate group differences. Bilingual studies that have demonstrated enhancement in executive functions have attributed this enhancement to bilinguals' constant practice with selectively attending to one language, suppressing the nontarget language and switching back and forth from L1 to L2. This language process is a critical system for effective communicating for bilinguals (Bialystok, 2007; Green & Abutalebi, 2013).

Inhibitory control is an aspect of executive function that involves the intentional process of focusing one's attention when there is conflicting information and only selecting the relevant information (Bialystok et al., 2008; Carlson & Meltzoff, 2008). Research has suggested that inhibitory control may be involved in the management of multiple linguistic systems and that bilinguals utilize inhibitory control to manage their languages. More specifically, inhibitory control involvement in language processing in bilinguals has been suggested to result from bilinguals continually inhibiting the nonrelevant language when speaking (Bialystok et al., 2008; Carlson & Meltzoff, 2008).

A study by Bialystok et al. (2008) revealed that bilinguals performed better on executive inhibitory control tasks relative to monolinguals. There were 96 participants divided among 24 young monolinguals (mean age = 20.7 years), 24 young bilinguals (mean age = 19.7), 24 older monolinguals (mean age = 67.2 years, and 24 older bilinguals (mean age = 68.3) years). The bilinguals included a wide range of languages. Bilingual participants also varied in the age of acquisition of the second language. Fourteen acquired the second language early, 16 acquired the second language late. All bilingual groups reported having high proficiency in the second language. Executive control tasks administered included the Simon arrows task, the Stroop color-naming task and the sustained attention to response task (SART). The Simon task is a computer test with three tasks using directional arrows as stimuli and conditions that vary in their demands for cognitive control. The tasks include a control task, a measure of response inhibition or ability to override a habitual response to a familiar stimulus, and a conflict condition. The Stroop color-naming task was also a computer-administered test that included four conditions. It consists of a control (color-naming speed), word reading control, congruent color naming, and word reading in conflicting colors. The SART is a measure of sustained attention. For the SART's task, numbers 1-9 are presented in the center of a computer screen in random order. The participant is asked to press the response key as quickly as possible, except when the number three appears. Means on the SART include reaction time to respond to each new stimulus and the number of errors committed by responding when the digit is a three.

Results demonstrated bilinguals performed better on executive control tasks. A two-way ANOVA for age and language on the Simon task revealed monolinguals demonstrated higher error rates ($F(1, 92) = 5.28, p < .02$). A two-way ANOVA for age and language on the Stroop effect revealed smaller Stroop effects among bilinguals ($F(1, 44) = 7.74, p < .008$). Overall, all participants made very few errors in the SART test. Young monolinguals produced an average of 3.8 errors ($SD = 3.5$), young bilinguals produced 4.1 errors ($SD = 2.7$), older monolinguals produced 3.1 errors ($SD = 3.2$), and older bilinguals produced 5.3 errors ($SD = 5.4$). Error rates did not differ among any language group ($F(1, 92) = 1.92$), or age group ($F < 1$). For reaction time, younger participants were faster relative to older participants ($F(1, 92) = 28.17, p < .0001$), with no difference between language groups ($F < 1$). The authors attributed the bilingual advantage in executive function to bilinguals' constant need to suppress interference from L2 (Bialystok et al., 2008). However, results also demonstrated no differences among groups on the SART task, a test of response inhibition. The authors took these results to suggest that bilingualism has different effects on interference suppression and response inhibition. It is suggested bilinguals rely more on inhibition suppression than response inhibition processes.

Another important cognitive skill that has been linked to executive functioning is working memory. Working memory refers to a system required to maintain information in an accessible state in the face of concurrent processing, distraction, and/or attention shifts (Conway et al., 2002). Research has demonstrated that working memory is a process involved in foreign language and native language processes (Engel de Abreu, 2011). Assessments most often utilized to measure working memory include simple span tasks that require maintaining information over a short period and with complex span tasks that, in addition to storage, also involve an explicit concurrent processing task. While there is little research investigating working memory in bilinguals, there is a report of more efficient working memory processing in bilinguals.

Neuropsychological Performance on Working Memory Tasks

A bilingual advantage has previously been shown on nonverbal working memory but not verbal working memory (Luo et al., 2013). Luo et al. (2013) investigated whether younger and older monolingual and bilingual adults demonstrate performance differences on verbal and spatial working memory tasks. The memory tasks varied from simple to complex span tasks involving either verbal or spatial material. Participants included 58 younger adult monolinguals, 99 younger adult bilinguals, 60 older adult monolinguals, and 60 older adult bilinguals. The word span and alpha span tasks were used to assess verbal memory span. Each task consisted of 14 lists of common concrete nouns, which varied in length from 2 to 8 words, with 2 lists of each length. In the word span task, participants recalled the words in the original order; in the alpha span tasks, participants mentally rearranged the words to recall them in alphabetical order. Alpha span was considered to be the more complex task.

The Corsi block test was used to assess spatial memory span. Ten blue locks secured on a white platform were numbered 1-10; the numbers were only visible to the examiner. The examiner tapped on the blocks in a predetermined sequence. The task consists of forward and backward subtasks, with sequences varying in length from two to nine blocks. The task was to repeat the sequence in its original order in the forward condition and in reverse order in the more complex backward condition. Results demonstrate bilinguals outperformed monolinguals on spatial span tasks (*F*(1,274) = 8.44, *p* < .004), but remembered fewer items than monolinguals in verbal span tasks (*F*(1, 272) 4.14, *p* < .04). The authors argued that the advantages demonstrated are not due solely to advantages in working memory. Rather, they claimed the tools needed to outperform on such tasks result from bilingual advantages in executive functions such as switching (Bialystok et al., 2008; Luo et al., 2013). Results may also suggest working memory advancements appear to only be exhibited in nonverbal working memory skills and that when language is incorporated, it compromises bilinguals' performance.

Neuropsychological Performance on Visuospatial Tasks

Concerning bilingual visuospatial abilities, Blom et al. (2014) revealed that low-SES bilingual children outperformed monolinguals on visuospatial tasks. The study utilized data collected as part of a study conducted in Messer (2010). In Messer's study, Turkish-Dutch bilingual children and monolingual Dutch children were compared at ages four years (wave one), five years (wave two), and six years (wave three). Twenty children in the monolingual group were removed due to their parents being foreign-born and sometimes using Dutch. Two children in the bilingual sample were also removed due to no interview data. Therefore, participants in the study included 68 bilingual Turkish-Dutch children (mean age = 2.6 years) and 52 monolingual Dutch children (mean age = 2.1). Visuospatial working memory was assessed with the dot-matrix task and odd-one-out task. In the dot-matrix task, a dot appears on the compeer screen for two seconds. After two practice trials, the test begins with a block of six trials. The participant is first only presented with one dot in the matrix, which increases to a block of six trials with a sequence of seven dots presented across the matrix. In the odd-one-out task, three shapes are presented in different boxes presented in a row. The participant is to identify the odd-one-out shape. Both the dot-matrix and odd-one-out task items to remember increase progressively over successive blocks. Verbal working memory was assessed with forward digit recall and backward digit recall. Digit recall tasks were selected because it was assumed that recalling digits is less dependent on language level than (non) word or listening recall (Messer, 2010). At age six, bilinguals demonstrated overall better performance relative to monolinguals ($F(4, 105) = 4.40$, $p = .003$). A univariate analysis of covariance (ANCOVA) demonstrated significant differences in performance on the dot-matrix task ($F(4, 105) = 4.0$, $p = .04$), backward digit recall ($F(4, 105) = 17.1$, $p = <.001$), and the odd-one-out task ($F(4, 105) = 3.5$, $p = .06$). However, the authors of the study believed that the visuospatial advantage may be due to the involvement of executive control and did not represent an actual advantage in visuospatial processes (Luo et al., 2013).

Neuropsychological Performance on Memory Tasks

Concerning bilinguals' performance on memory tasks, studies suggested bilinguals demonstrate poorer performance relative to monolinguals. However, bilingualism's memory performance has been suggested to be largely dependent on executive function skills (Luo et al., 2013). Memory assessments are commonly based on verbal recall and recognition. Examples are tasks that require an individual to recall a list of words over various different trials, such as the Rey Auditory Verbal Learning Test (RAVLT). Several studies have revealed that bilinguals recall fewer words than monolinguals on verbal recall and recognition tasks (Gollan & Kroll, 2001; Kroll & Groot, 2005), which may impact performance on verbal memory learning tasks. However, researchers have not determined if bilingualism's negative effect on verbal recall and recognition is due to actual poor verbal memory or deficits in verbal processing.

Ransdell and Fischler (1987) conducted a study to investigate bilingualism's influence on memory skills. Participants included 28 native English-speaking bilinguals and 28 native English monolinguals. Age ranged from 17-35 years. Only English words were used in the study to avoid activation of the second language, given that both groups were native English speakers. Each participant was tested on four verbal memory tasks: episodic, recognition, lexical decision object naming, and free recall. The four tasks were administered on a computer screen with stimuli presented in the center of the screen. Stimuli for the picture-naming tasks were presented on paper, and naming times were measured manually by the examiner. A 2x2x2 mixed test ANOVA was performed, and a significance level of $p < .05$ was adopted. Evidence demonstrated monolinguals were significantly faster in responding relative to bilinguals ($F(1, 54) = 6.40$, $p < .02$) and bilinguals demonstrated slower performance on the list recognition task ($F(1,54) = 12.93$, $p < .001$) and lexical decision task ($F(1,54) = 11.31$, $p < .001$; Ransdell & Fischler, 1987). Results show that even when bilinguals and monolinguals are compared in their native dominant language, there is still a bilingual disadvantage in verbal memory skills, suggesting poor performance relative to monolinguals (Ransdell & Fischler, 1987).

However, when nonverbal memory skills were assessed in bilinguals, a slight bilingual advantage in older adult bilinguals was revealed (Wodniecka et al., 2010). Wodniecka et al. (2010) investigated nonverbal memory skills in bilinguals when compared to monolinguals. Participants included 44 young adults (mean age = 20.5 years) and 39 older adults (mean age = 71.9 years). In each age group, about half of the participants were monolingual English speakers, and the other half were bilingual speakers. Bilingual speakers rated being highly proficient in both L1 and L2. Participants were shown a series of L2 adult faces consisting of 80 critical and 40 filler items. The facial stimuli were presented at a rate of two seconds each. Following the presentation of the items, a list of 140 faces was presented for recognition under either inclusion or exclusion instructions. A group mixed ANOVA (age x lag x language) on recollection scores demonstrated a bilingual advantage in recollection scores ($F(1, 79) = 2.58$, $p = 0.11$). A follow-up lag x language group ANOVA for each group was conducted. Results revealed the older bilingual group demonstrated a significant effect on lag ($F(3, 111) = 13.04$, $p < 0.001$) and a nonsignificant trend, suggesting higher recollection scores for bilingual participants ($F(1, 37) = 2.79$, $p = 0.11$; Wodniecka et al., 2010). Results demonstrated that when verbal portions of memory tasks are removed, bilinguals' performance increases, suggesting interference from language skills.

While additional research needs to be conducted, current studies suggest that bilinguals' verbal memory skills are poor relative to monolinguals, even when bilinguals are tested in their native dominant language (Ransdell & Fischler, 1987). However, bilinguals' performance on memory tasks appears to be influenced by language overload. This is evidenced by their improved performance on nonverbal memory tasks (Wodniecka et al., 2010). The next section discusses studies found on bilinguals' performance on visuospatial tasks.

Neuropsychological Performance on Motor Tasks

Concerning motor functioning, the cerebellum was traditionally considered to be exclusively involved in the coordination of voluntary movement, gait, posture, balance, and motor speech. However, more recent findings provide evidence of a cerebellar contribution to linguistic function. Smet et al. (2007) demonstrated the cerebellum's involvement in various linguistic functions, such as semantic fluency, agrammatism (at morphological and sentence level), word naming and word finding, and reading and writing problems. However, the precise nature of the cerebellum contribution is still unclear. No studies that measure motor performance have been identified at this time.

Neuropsychological Performance on Sensory Tasks

Concerning bilinguals' performance on sensory tasks, Marian et al. (2018) investigated whether the experience of acquiring a second language shapes the way individuals process auditory and visual information. The study was based on the McGurk effect that discovered that when people hear a speech sound (e.g., "ba") and see a conflicting lip movement (e.g., "ga"), they recognize it as a completely new sound (e.g., "da"). This finding suggesting that the brain fuses input across auditory and visual modalities demonstrates that what we hear is profoundly influenced by what we see. Participants included 17 monolinguals (mean age = 21.7 years), 18 early bilinguals (mean age = 20.4 years), and 16 late bilinguals (mean age = 21.4 years). Stimuli consisted of audiovisual and auditory-only speech syllables (e.g., "ba"), and there were congruent and incongruent audiovisual conditions. In the congruent condition, the auditory and visual input matched. In the incongruent condition, the auditory input was a sound produced with the lips (i.e.," ba," or "pa"), and the video input was of a sound produced at the velar position (i.e., "ga" or "ka"). The audiovisual stimuli were presented within-subjects in a quiet condition (i.e., no background noise) and noisy auditory conditions (i.e., six-talker babble). The audiovisual stimuli were used to assess the extent to which individuals attended to the visual information to perceive auditory inputs. Auditory-only allowed examiners to test for a standard speech-in noise deficit and served as a baseline for auditory congruent and incongruent conditions. Results demonstrated bilinguals experienced significantly more audiovisual-integration relative to monolinguals ($F(1,28) = 6.97$, $p = 0.01$), with no main effect of English proficiency ($F(1,44) = 0.54$, $p = 0.47$). A pairwise comparison of each language group was then conducted with Bonferroni corrections for multiple comparisons ($p < 0.016$ was considered significant). Results demonstrated late bilinguals experienced significantly more audiovisual-integration than monolinguals ($F(1,28) = 6.97$, $p = 0.01$), with no effects or interactions with English proficiency (both $p > 0.4$). The same results were observed with early bilinguals ($F(1,31) = 6.60$, $p = 0.02$), with no effects of English proficiency or interactions (both $p > 0.2$). Last, early and late bilinguals did not differ from each other ($F(1,29) = 0.43$, $p = 0.88$), nor was there a main effect or interaction with English proficiency (both $p > 0.5$). The authors suggested that bilinguals rely on visual information more than monolinguals to comprehend speech and that this bilingual effect was not impacted by the level of proficiency (Marian et al., 2018).

Overall, research has demonstrated that bilinguals show a disadvantage on verbal tasks but demonstrate an advantage on nonverbal memory, working memory, and executive function tasks (i.e., inhibitory control) compared to monolinguals. Bilinguals outperformed monolinguals on nonlinguistic tasks with greater audiovisual integration during speech sound tasks. It appears that managing multiple linguistic systems involve greater integration of both visual and audio stimuli to adequality process language, compared to monolinguals. Given that the tests administered to bilinguals in the studies included in this review are normed for monolingual individuals, further research should be conducted in this area to determine moderating variables in performance. While the studies summarized in this portion of this review provide clinicians with insight into bilinguals' cognitive processes, it does not provide an accurate representation of bilinguals' true performance in each cognitive category. Administering neuropsychological tests to bilingual populations that have been normed for monolingual individuals creates an additional overload on bilinguals' cognitive systems that monolinguals are not faced with, given that they do not have two competing language systems while performing the test. However, hypotheses can be drawn from the data collected that can aid in developing more appropriate measures for individuals with multiple linguistic systems. Summarizing bilinguals' performance on neuropsychological tests normed for monolinguals, Table 4 is provided for reference.

Table 4

Neuropsychological Performance Differences in Bilinguals

Neuro-Test	Cognitive Task	Significant Differences	Age	Study
Language				
PPVT-II	Receptive and expressive vocabularies	Early > late bilinguals	Adults	Portocarrero et al., 2007
EVT	Receptive and expressive vocabularies	Early > late bilinguals	Adults	Portocarrero et al., 2007
PPVT-II	Receptive and expressive vocabularies	Early bilinguals < monolinguals	Adults	Portocarrero et al., 2007
EVT	Receptive and expressive vocabularies	Early bilinguals < monolinguals	Adults	Portocarrero et al., 2007
COWA	Semantic animal verbal fluency	Monolinguals > bilinguals	Adults	Portocarrero et al., 2007
BNT	Picture naming	Monolinguals > Bilinguals	Adults	Roberts et al., 2002
Executive functions				
Simon arrows test	Inhibitory control	Younger and older monolinguals < younger and older proficient bilinguals	Adult	Bialystok et al., 2008
Stroop	Inhibitory control	Younger and older monolinguals < younger and older proficient bilinguals	Adult	Bialystok et al., 2008
SART	Response inhibition	No differences among proficient bilinguals and monolinguals	Adult	Bialystok et al., 2008
Working memory				
Word span task	Verbal working memory	Younger & older monolinguals > younger and older bilinguals	Adult	Luo et al., 2013

Neuro-Test	Cognitive Task	Significant Differences	Age	Study
Corsi block test	Nonverbal spatial span memory	Younger and older bilinguals > younger & older monolinguals	Adult	Luo et al., 2013
Forward digit recall	Verbal working memory	Bilinguals > monolinguals	Children	Blom et al., 2014
Memory				
RAVLT	Verbal memory	Monolinguals > bilinguals	Adults	Gollan & Kroll, 2001; Kroll & Groot, 2005
Visual computer and paper test	Verbal memory test	Monolinguals > bilinguals	Adults	Ransdell & Fischler, 1987
Face recognition	Nonverbal memory	Monolinguals < older proficient Bilinguals	Adult	Wodniecka et al., 2010
Visuospatial working memory				
Dot-matrix task		Bilinguals > monolinguals	Children	Blom et al., 2014
Odd-one-out tasks		Bilinguals > monolinguals	Children	Blom et al., 2014
Motor				
No studies that measure motor performance have been identified at this time				
Sensory tasks				
Audiovisual conditions of speech sounds	Audiovisual integration	Late and early proficient bilinguals > monolinguals	Adults	Marian et al., 2018

CHAPTER IV: BILINGUALS COGNITIVE RECOVERY PATTERNS FOLLOWING AN ACQUIRED BRAIN INJURY

Cognitive impairments are common consequences of an acquired brain injury and are often observed after TBI or strokes (Barman et al., 2016; Heshmatollah et al., 2020). Such impairments may significantly impact the patient's social functioning and quality of life (Barman et al., 2016; Heshmatollah et al., 2020). While many cognitive processes may be influenced by an acquired brain injury, language impairments are among the most frequently reported, with diverse patterns found in bilingual patients. Given the complexity of cognitive impairment in bilinguals and the significant impact on social functioning the experience of cognitive deficits has on an individual, it is imperative to understand differences in bilingual recovery patterns. Exploring and identifying influencing factors in cognitive recovery in bilinguals will allow clinicians to better tailor treatment for more successful outcomes. This chapter discusses recovery patterns in bilinguals following a TBI and stroke while identifying how bilingual particularities may influence cognitive recovery.

Bilingual Differences in Cognitive Outcome After Traumatic Brain Injury

As mentioned in the first chapter, a TBI is an acquired injury or trauma resulting from an external physical force that damages the brain. A TBI can be mild, with little (i.e., a mild concussion) to no symptoms or moderate to severe, with major symptoms (i.e., unconsciousness, coma, and even death; Silver et al., 2009; Timmons, 2012). From a neuropsychological functioning standpoint, a mild to moderate TBI impairs memory, attention, processing speed, and executive functioning (Brasure et al., 2012). Moderate to severe TBIs also demonstrate deficits in memory, attention, processing speed, and executive functioning with additional dysfunctions in communication, visuospatial processing, intellectual ability, and awareness (Rabinowitz &

Levin, 2014). Concerning bilingualism's influence on cognitive functioning following a TBI, recent studies have demonstrated greater deficits in language and executive function skills (Ratiu & Azuma, 2017, 2019).

Ratiu and Azuma (2017) examined the effect of a mild TBI (mTBI) on executive functions and language processing in adult bilinguals using a behavioral eye-tracking measure. The study consisted of 22 bilinguals with a history of MTBI and 20 healthy control bilinguals. Each participant was administered executive functioning and language processing tasks. Results demonstrated that the MTBI bilingual group elicited higher rates of language processing errors compared to the healthy bilingual group. Significant differences were seen in the reading aloud task, which was driven by language control errors in the form of cross-language intrusions ($F(1,39) = 8.3$, $p = 0.006$,) and accent errors ($F(1,39) = 6.67$, $p = 0.01$) than the healthy controls. Cross-language intrusions occurred when a participant produced a word in the nontarget language. An accent error occurred when a participant produced the target word but used the nontarget language pronunciation. Results suggest bilinguals with a history of a MTBI appear to experience language control impairments, specifically in language switching contexts. Deficits were also demonstrated in executive function tasks, more specifically on the Flanker go/no go task ($F(1,40) = 3.38$, $p = 0.07$) and the task-switching task ($F(2, 72) = 3.79$, $p = 0.03$). Participants were less accurate in the switching condition than the shape condition ($t\ (38) = 3.63$, $p = 0.001$). The MTBI group also demonstrated different patterns of eye movements during a reading task compared to healthy control bilinguals ($F(1, 39) = 14.35$, $p = 0.005$). Healthy controls were less likely to fixate on error words than individuals with mTBI. Results from Ratiu and Azuma (2017) suggested that in addition to executive function deficits commonly associated with mTBI, bilinguals may also manifest language control impairments. Language errors seen in mTBI bilinguals have been proposed to result from the reliance on executive function skills to manage or control their languages. Therefore, deficits in executive control make it difficult for bilinguals to control interference from the nontarget language (Green & Abutalebi, 2013).

A more recent study examining executive function skills in bilingual adults with a history of mTBI demonstrated greater deficits in problem-solving and reasoning and inhibition skills than a healthy control bilingual group (Ratiu & Azuma, 2019). Participants included 20 healthy control adult bilinguals (mean age = 20.8 years, *SD* = 3.6) with no history of mTBI, memory, language or neurological problems and 22 bilingual adults (mean age= 20.1 years, *SD* = 3.7) with a self-reported history of mTBI. To measure executive function skills, all participants were administered the FAVRES and the Flanker task (test of inhibition). Participants included 22 bilinguals with a history of mTBI (mean age = 21.1, *SD* 3.7) and 20 control bilinguals (mean age = 20.8, *SD* = 3.6). For the FAVRES assessment, the study used a 2x4 mixed-factor design with group as the between-subjects factor, assessment area as the repeated factor, and standardized scores as the dependent factor. For the Flanker task, a 2x3 mixed-factor design was utilized, with group as a between-subjects factor and Flanker condition as the repeated factor. The conflict effects in reaction time and accuracy were analyzed with one-way ANOVAs with group as the between subject's factor. Results demonstrate that bilingual adults with mTBI injuries demonstrated higher executive function deficits on both the FAVRES and the inhibition task (Flaker task) when compared to the healthy controls. Performances on the FAVRES assessment revealed the healthy control group had significantly better performance than the MTBI group for accuracy ($F(1, 31) = 5.23$, $p = 0.03$), rational ($F(1, 31) = 7.76$, $p = 0.009$), and reasoning ($F(1,31) = 8.06$, $p = 0.008$). For the Flanker test, the healthy control group had faster reaction times than the MTBI group ($t(40) = 2.67$, $p = 0.01$; Ratiu & Azuma, 2019). Overall, the bilingual mTBI group revealed decreased inhibition ability and greater difficulty in higher-order cognitive executive deficits when compared to healthy bilinguals. Results further demonstrate the FAVRES is a sensitive indicator of mTBI in a small bilingual sample, making it a potentially useful assessment tool with more diverse populations (Ratiu & Azuma, 2019).

Overall, it appears that bilinguals with a mTBI demonstrate greater deficits in language control (i.e., switching), problem-solving, and reasoning and inhibition skills relative to healthy bilinguals (Ratiu & Azuma, 2019). Deficits in executive function skills such as inhibition and switching have been proposed to be contributing factors in the dysfunction of language control, which results in language errors. This is due to bilinguals' overreliance on executive function skills (i.e., inhibition and switching) to manage and control the two languages (Green & Abutalebi, 2013).

The next section discusses the literature on bilinguals with a history of stroke. While research in this area is still in its infancy (Fabbro, 2001; Faroqi-Shah et al., 2018), recent studies have demonstrated that bilingualism does indeed have an influence on cognitive recovery (Alladi et al., 2016; Paplikar et al., 2018). Differences have been seen in patterns of cognitive and language impairment (Paplikar et al., 2018), the severity of deficits (Alladi et al., 2016; Paplikar et al., 2018), and recovery patterns of translation abilities. There is also evidence of relevant variables to moderate recovery. Such variables include language similarity (Ansaldo & Saidi, 2014), pre- and postmorbid level of proficiency (Kurland & Falcon, 2011; Roberts & Deslauriers, 1999), and the status of the cognitive control system (Abutalebi et al., 2009; Abutalebi & Green, 2007).

Bilingual Differences in Neurocognitive Patterns Following a Stroke

As mentioned in Chapter One, a stroke occurs when the blood supply to the brain is interrupted or reduced due to blockage or a blood vessel that has burst in the brain ("About stroke," 2020). A stroke often alters communication with its location, influencing what will be affected. While a variety of cognitive deficits (i.e., decreased attention, distractibility, and the inability to inhibit appropriate behavior; Holland & Schmidt, 2015) are often experienced, stroke is the most common cause of aphasia (Holland & Schmidt, 2015). Aphasia has been defined in the literature as an acquired language disorder that impairs the ability to formulate, retrieve, or decode aspects of language (Weekes, 2010). Bilingual aphasia is becoming increasingly frequent, as the bilingual population has increased in the United States (Ansaldo & Saidi, 2014). Bilingual aphasia is complex, however, and studies on the recovery trajectory following stroke have been mixed. Some studies have found less severe cognitive outcomes (Alladi et al., 2016; Paplikar et al., 2018), while others have found more severe cognitive symptoms (Hope et al., 2015).

Stroke Studies on the Severity of Recovery

In a stroke cohort study, bilingualism was associated with a significantly better cognitive outcome in stroke patients ($p < 0.0001$; Alladi et al., 2016). Alladi et al. (2016) examined 608 patients with an ischemic stroke from a large stroke registry and studied the role of bilingualism in predicting poststroke cognitive impairment. To perform this, subjects were compared using independent sample *t*-tests for continuous variables and χ^2 test for categorical variables. A series of binary logistic regressions were performed to identify significant variables. Statistical analysis was performed using SPSS 20.0, and significance was set at $p < 0.05$. Bonferroni-adjusted *p*-values were used to correct for multiple testing issues. This apparent protective effect is thought to result from the lifelong practice of using two languages and switching between them while inhibiting the nontarget language (Alladi et al., 2016).

A recent study by Paplikar et al. (2018) provided supportive evidence that bilinguals demonstrate less severe aphasia symptoms following a stroke. Participants in the study included 38 bilingual and 27 monolingual aphasia patients who participated in a longitudinal hospital-based stroke registry and were evaluated for 3 months poststroke. Performance on language and other cognitive functions was evaluated using Addenbrooke's Cognitive Examination-Revised (ACE-R). Results were compared after accounting for confounding variables such as age, gender, education, occupations, and medical and stroke characteristics. Results demonstrated aphasia severity was significantly higher in monolinguals than bilinguals as measured by the language domain subscores in the ACE-R ($p = 0.008$; $d = 0.69$). Bilinguals performed significantly better in areas of attention ($p = 0.002$; $d = 0.81$), memory ($p = 0.003$; $d = 0.78$), and visuospatial skills ($p = 0.004$; $d = 0.76$). A univariate general linear model analysis also revealed that bilingualism was significantly associated with higher language domain scores on the ACE-R after adjusting for confounding variables ($F(1)$, $63 = 9.41$, $p = 0.003$). Results demonstrate that while bilingual speakers have a similar risk of developing aphasia after stroke, their aphasia is likely to be less severe. The authors suggest that while bilingualism does not change the risk of poststroke aphasia, it plays a role in influencing the severity (Paplikar et al., 2018).

In contrast to Paplikar et al. (2018), Hope et al. (2015) found that bilingual nonnative English speakers, who were immigrants, performed worse on a range of language tasks compared to monolinguals (t (128) = 16.24, $p = < 0.001$). This was even the case when administered in both their native and nonnative language. Participants included 174 stroke patient who were monolinguals ($M = 53.0$ years; $SD = 12.2$) and 33 stroke patients who were bilinguals 9 (*M* = 49.0 years; *SD* = 13.2). Data were extracted from the PLORAS database, which associates stroke patients, tested over a broad range of times poststroke with demographic data, behavioral test scores from the comprehensive aphasia test and high-resolution T1-weighted MRI brain scans. Languages in the bilingual group were diverse, with a mean of 3.3 for the age of acquisition. The authors from this study attributed their findings to poor premorbid language proficiency in bilinguals compared to monolinguals and suggested that poor premorbid language proficiency makes bilinguals more sensitive to lesion-deficit associations to the brain (Hope et al., 2015).

It appears that while bilinguals may demonstrate less severe cognitive symptoms following a stroke, it may be moderated by the type of bilingual experience (i.e., premorbid proficiency). Next, we discuss the types of language recovery patterns seen following injury to the bilingual brain and then discuss moderating variables that have been suggested to influence the trajectory of language recovery.

Recovery of Translation Skills in Bilingual Aphasia

Language deficits in bilinguals are unique, as translation disorders may affect either language, compromising translation from L1 to L2 and vice versa. The skill of translating is a cognitive task that involves not only language skills but also implements the skill of switching that is usually controlled voluntarily. Paradis et al. (1982) identified four types of translation deficits in bilinguals with aphasia: the inability to translate, paradoxical translation, translation without comprehension, and spontaneous translation. The translation deficit that involves the inability to translate refers to its obvious characteristics. Following an injury to the brain that affects regions involved in language, the individual is unable to translate from either language to the other. Paradoxical translation involves the ability to translate in one language but not the other. Translation without comprehension is the ability to translate language promptly but the inability to understand its meaning. Last, spontaneous translation refers to the inability to inhibit translating, therefore, producing involuntary translations.

Language control appears to be a role in the type and severity of language deficits seen in bilinguals. Green and Abutalebi (2008) noted that acquiring a second language entails the need to continually coordinate language use by inhibiting the nontargeted language and activating the language of choice (Green & Abutalebi, 2008). This language control process entails the constant recruitment of cognitive control functions and cognitive flexibility to properly and efficiently shift from one language to the other (Green & Abutalebi, 2008). Therefore, impairment in the ability to translate can result from deficits in the integrity of the circuits normally involved in language control in bilinguals. Deficits in the language control system are discussed further in the last section of this chapter. Cross-linguistic effects of therapy are focused on language recovery patterns by understanding how therapy implemented in one language transfers or fails to transfer to the other. It provides further insight into variables that influence the trajectory of recovery.

Implications for Cognitive Rehabilitation with Bilinguals

Cross-linguistic transfer of therapy effects focuses on understanding how implementing an intervention to one language transfers or neglects to transfer to the untreated language (Ansaldo & Saidi, 2014). Cross-linguistic transfer of therapy effects is further utilized to aid in identifying the most efficient procedures for triggering language recovery in bilinguals with aphasia (Ansaldo & Saidi, 2014). Providing therapy in both languages is often not an option, and thus, understanding how therapeutic interventions provided in one language transfer to the untreated language can help implement effective treatments. In reviewing the bilingual aphasia literature, some of the identified potential influencers in greater cross-linguistic transfer of therapy effects depend on language similarity (i.e., word type; Kohnert, 2004; Kurland & Falcon, 2011; Roberts & Deslauriers, 1999) pre- and postmorbid language proficiency profiles (Kiran & Iakupova, 2011), and the status of the cognitive control circuit (Green, & Abutalebi, 2013). These will be discussed further individually.

First, word type refers to cognates, clangs, and noncognates (Ansaldo & Saidi, 2014). Bilingual aphasia research has provided evidence for the effects of cross-linguistic therapy in studies with cognates and noncognates. Cognates are equivalent words, the meaning of which may be identical or almost identical. An example of a cognate may include "tiger" or "tigre." Noncognates are translation equivalents that share semantics but not phonology, such as "butterfly" in English and its Spanish equivalent "mariposa" (Ansaldo & Saidi, 2014).

Roberts and Deslauriers (1999) demonstrated that highly proficient bilinguals with aphasia were able to name cognates better than noncognates. Kohnert (2004) also demonstrated cross-linguistic generalization of therapy effects when therapy was administered to the L1 (Spanish) to the untreated L2 (English) for cognates only. Language treatment consisted of lexical-semantic retrieval strategies such as word recognition, semantic association, and cueing.

Conversely, Kurland and Falcon (2011) found an interference effect with cognates, resulting in the language errors with the nontarget language, following intensive language therapy with a semantic approach, with Spanish-English bilinguals having chronic and severe expressive aphasia. However, it is important to note that the patient had a lesion in the basal ganglia, a component of the subcortical control network (Green & Abutalebi, 2013). Green and Abutalebi (2013) hypothesized that the basal ganglia, the left precentral cortex, the anterior cingulate, and the inferior and parietal lobule are all part of the language control network in bilinguals. Therefore, damage in any portion of the language control network, such as the basal ganglia, can result in language control skills in bilinguals and make it more difficult for therapy effects to transfer to the untreated language.

As evidenced by Roberts and Deslauriers (1999), level of proficiency also appears to moderate the effects of cross-linguistic therapy. Roberts and Deslauriers found that highly proficient bilinguals with aphasia were better able to name cognates than noncognates. Kiran and Iakupova (2011) further investigated the relationships among language proficiency, language impairment, and rehabilitation in a case study with two late-learner Russian-English bilinguals with a history of aphasia. Both participants were reported to be more proficient in Russian than English before their stroke. However, patient one demonstrated more impairment in L2 relative to L1 than patient two. Therefore, treatment was only given to patient one, as patient two demonstrated more uniform deficits in both languages. Treatment was provided in the less proficient language. A baseline measure was performed before treatment, and the patient participated in a 10-week program. There were eight treatment sessions. The sessions consisted of seven-step semantic feature-based treatments where the patient attempted to name the picture and was told if the answer was correct, the clinician named the object, the clinician placed the printed name of the object below the picture, the patient read a short sentence or phrase describing the 12 semantic features of the object, the patient sorted the pictures into piles/groups of correct/incorrect features, the patient was asked 12 questions regarding the features of the picture and the patient named the picture again. Kiran and Iakupova (2011) administered semantic therapy in L2 (English) to measure lexical-semantic naming difficulties. Naming was then measured on trained and untrained words both in L2 and L1.

Following therapy, the participant demonstrated 100% accuracy in both treated and untreated items, reflecting effective cross-linguistic therapy effects. The authors suggest that cross-linguistic therapy effects reflect strengthened connections between the weaker (English) language and the stronger (Russian) language. The post-treatment performance revealed that participant one performed stronger in Russian than in English. A *t*-test indicated that the pre-treatment and post-treatment scores in the English subtests were significantly different (t (25) = −3.8, p = 0.001), suggesting improvement in the participant's overall English auditory comprehension and verbal expressive abilities subsequent to treatment. Results further demonstrated significant differences in the participant's Russian post-treatment scores compared with his Russian pre-treatment scores on the BAT (t (25) = 3.18, p = 0.004). The authors took this to suggest that the semantic-based treatment in English may have generalized to the patient's Russian lexical-semantic abilities. It also appears that training the non-dominant language in an individual with bilingual aphasia may be beneficial in facilitating cross-linguistic generalization (Kiran & Iakupova, 2011).

Growing evidence has also demonstrated that the language control system plays a crucial role in language recovery in bilingual aphasia following a stroke. Healthy bilinguals have demonstrated increased involvement of the control system in language production due to the continual manipulation and motoring of both languages (Abutalebi & Green, 2007). Bilinguals' control system involves the constant process of selecting the appropriate vocabulary and syntax and inhibiting the nontarget language. Concerning bilingual individuals with aphasia, Abutalebi and Green (2007) proposed a dynamic view among bilingual language recovery that involves the control system. Abutalebi and Green (2007) suggested that the pattern of language recovery in bilinguals with aphasia depends on the patient's ability to select and control language activation, a necessary skill in healthy bilinguals. When the language control system is damaged, bilinguals may experience various language impairments and recovery processes (Abutalebi et al., 2009; Abutalebi & Green, 2007). Parallel language recovery is one such recovery process in which both languages are impaired and improve to a similar extent. An antagonistic language recovery occurs when one language recovers to a certain extent first and then begins to regress when the other language begins to recover. Selective recovery of language is when one language remains impaired while the other recovers. Pathological language mixing occurs when the elements of the two languages are involuntarily mixed during language production and when languages can no longer be selectively inhibited (Abutalebi et al., 2009; Abutalebi & Green, 2007).

In a more recent study, Abutalebi and Green (2016) proposed various brain regions are involved in language control and that lesions in a specific brain region might cause different control deficits. Brain regions reported to be involved in the language control network include both cortical (i.e., prefrontal cortex, dorsal anterior cingulate cortex/presupplementary motor area, and inferior parietal cortex, with the involvement of both hemispheres) and subcortical regions (i.e., left basal ganglia and thalamus and right cerebellum). Among the various brain regions involved in language control, the basal ganglia and the left head of the caudate and putamen have been highlighted as playing a curial role in appropriate language selection (García-Caballero et al., 2007).

Overall, bilinguals' recovery patterns are diverse, with patterns of recovery mediated by various bilingual experiences (i.e., language modality, premorbid proficiency, and damage to the language control network). However, damage to the language control network appears to be the most detrimental, as it leaves bilingual individuals with language and non-language deficits and impedes recovery. The language network is comprised of several executive function skills that are critical for performing routine activities (i.e., the frontal lobe's involvement in thinking and attention for performing a sequence of tasks). Executive function skills are essential components for successful cognitive recovery and lay the foundation for successful cross-linguistic therapy effects.

CHAPTER V: IMPLICATIONS FOR REHABILITATION: CLINICAL PEARLS FOR WORKING WITH BILINGUAL CLINICAL POPULATIONS

As indicated in the previous chapters, a combination of knowledge of the structural and functional patterns of bilinguals' cognitive processes through neuroimaging data and neuropsychological assessments aids in creating appropriate rehabilitation treatments. Clinicians are better equipped to identify differences in the language processes in bilinguals, adequately identify deficits, predict patterns of recovery, and implement more appropriate treatment for successful recovery. This final chapter serves as a point of reference for the essential information noted in this literature review regarding bilingual individuals.

To begin, the utilization of imaging data is a critical piece of the foundation for establishing correlations among lesion site and the impact on cognitive recovery patterns. The tables developed for the previous chapter (i.e., 2, 3, and 4) provide clinicians with information on identified region utilization and networks created as a result of acquiring a second language. Easy access to this information can further provide clinicians with possible avenues for future exploration. Predictions for recovery patterns can be hypothesized to gain greater knowledge on the bilingual language system, the areas recruited to best manage the language system, and potential moderating factors that may influence brain development and cognitive recovery (i.e., language modality and second-language acquisition across the lifespan). For example, imaging data have demonstrated that the caudate nucleus in bilinguals shows increased gray matter, brain volume (Zou et al., 2012), and activation (Crinion et al., 2006). Therefore, the brain's plasticity effects in the caudate nucleus demonstrate essential involvement in managing L1 and L2. In bilinguals, the caudate nucleus has shown to be critical for language selection (García-Caballero et al., 2007) switching in bimodal bilinguals (Zou et al., 2012) and monitoring and controlling language output in proficient bilinguals (Crinion et al., 2006). Concerning the profile following brain injury to this region, studies investigating deficits to the caudate nucleus with monolinguals have typically seen deficits in confrontational naming and word-finding difficulties (Pickett et al., 1998). Given that bilinguals utilize the caudate nucleus for language selection while inhibiting the nontarget language (i.e., switching) for adequate language output, injury to this region may result in deficits in language control and language interference in bilingual populations.

In reviewing the literature, a crucial cognitive network in bilinguals that has demonstrated a significant impact in bilingual brain region utilization pre- and post-brain-injury is the language control network. Regions that have been identified to be a part of the language control network include both cortical (i.e., prefrontal cortex, dorsal anterior cingulate cortex/presupplementary motor area, and inferior parietal cortex, with the involvement of both hemispheres) and subcortical regions (i.e., left basal ganglia and thalamus and right cerebellum). Another essential point to highlight is that bilinguals' language control network has demonstrated a positive impact on executive function skills. The enhancement of executive functions appears to result from the continual activation of bilinguals' language control system (Abutalebi et al., 2009; Abutalebi & Green, 2007). Managing two languages results in the use of two executive function skills (i.e., inhibition and switching), suggesting continual practice using executive function skills. However, while continual activation has been shown to promote increased executive function skills in normal healthy bilinguals, executive functions appear to take on the greatest impact following a TBI. More severe deficits in executive functions among bilinguals following a TBI may be due to the critical involvement of executive functions in even the most routine activities (i.e., the frontal lobes involvement in thinking and attention for performing a sequence of tasks) and the additional cognitive load on executive functions for the management of two language systems (i.e., inhibition and shifting between languages and translating) for effective communication.

Another essential piece for providing adequate treatment to bilingual individuals is a thorough evaluation of background information on bilingual patients' language experience. More detailed information will allow clinicians to control for various language experiences (i.e., age of acquisition and language modality) and determine the level of impact on healthy cognitive functioning and dysfunction following a brain injury in bilingual populations. However, despite the increasing bilingual demographic and the apparent need for treatment protocols designed to meet the unique characteristics and needs of bilingual patients in clinical settings, there has been limited development of a consistent means to evaluate this population. For example, as Lorenzen and Murray (2008) mentioned, there are no consistent means to evaluate pre- and postmorbid language abilities in bilingual clients or regular use of specific interview and/or rating tools and/or linguistic and cognitive tests to assess bilingual clinical populations. Below are recommendations and potential questions clinicians can ask the patient, family member, or caretaker during a clinical evaluation with bilingual patients.

Collecting Premorbid History

- Family members who know the patient well can serve as valuable historians that can provide more accurate information about the patient's premorbid language use.
- Collecting history on premorbid level of proficiency, age of acquisition, usage, etc. can allow the clinician to establish a more accurate level of impairment.
- Use interpreter services if needed. Family members can only be used as a last resort, as it can impair the family members' objectivity in the assessment process.

Assessment of Language Use History

- Each language should be thoroughly assessed, regardless of its level of use.
- Determine types of language modalities (i.e., verbal versus nonverbal).
- Relying on the patient's report may cause one to miss language impairments due to the patient's poor awareness that can influence making poor life choices.
- A complete assessment ensures an accurate picture of the strengths and weaknesses within each language. Reveal language deficits that are only detectable in one of the languages due to structural differences of the languages.

Proper Evaluation of Deficits

- The clinician's goal is to understand and identify deficits across languages to select the most appropriate treatment for successful recovery.
- Clinicians should be careful not to assume the level of bilingualism (i.e., languages are equally developed), as doing so can cause under- or over-reporting of symptoms.
- Clinicians are encouraged to administer tests designed and normed for the bilingual population when available, while being careful not to simply use tests that have been translated and not adequately normed.

Modifications

- Making appropriate modifications should be considered to increase the accuracy of the assessment.
- When assessing reading and writing abilities, clinicians should consider cultural differences in learning academic skills. Some patients may read from opposite directions, which can affect an accurate assessment of severity and visual field neglects.

Cross-Linguistic Therapy

- There is evidence to support that treating the premorbid weaker language can promote CLTE.
- Cognates appear to have better CLT potential than noncognates. However, the cognate advantage is hindered when cognitive circuits in the language control model are damaged. This may be due to the reduced excitatory and inhibitory resources secondary to the damage in the cognitive network.

Limitations and Future Directions

While this review focused on identifying clinical pearls/considerations for clinicians working with bilingual populations, there is a considerable need for further empirical investigation. First, the debate persists regarding how best to quantify and qualify bilingualism and other linguistic concepts unique to bilingual speakers (e.g., early versus late; simultaneous versus sequential). The unique characteristics among bilingual speakers are important to consider when defining bilingualism and exploring differences in language development. Therefore, adopting a definition that accounts for the diverse backgrounds is still in need of development. Collecting background data on the unique characteristics, such as style of acquisition (i.e., simultaneous versus sequential) and age of acquisition (i.e., early versus late), among bilingual populations allows clinicians to rule out confounding variables that influence significant findings, identify patterns of brain and cognitive development, and identify potential influencers in cognitive recovery following a TBI or stroke. However, while stroke and TBI are among the most prevalent acquired brain injuries, they are not the only brain injures bilinguals can experience. Given that the type of brain injury can impact recovery trajectories, there is a need for further research exploring recovery profiles in bilinguals who experience other types of acquired brain injuries.

Identifying and establishing more demographically appropriate neuropsychological tests to measure bilingual cognitive performance pre- and post-brain-injury is also an area lacking research. A large portion of neuropsychological tests are normed toward measuring monolingual brain function and dysfunction. Therefore, they are not appropriate measures to use on bilingual populations.

It is evident from a limited number of published bilingual aphasia treatment studies that research on bilingual cognitive recovery is still in its infancy and in need of considerable systematic research. Investigations of bilingual aphasia and TBI treatment outcomes are of clinical importance to gain further insights into cognitive and language representation. For example, lesion-deficit correlations hold the potential for refining neuroanatomical models of bilingual language representation. Associations between language recovery and lesion characteristics can contribute to the understanding of rehabilitation-dependent neural plasticity.

There have also been mixed results in the literature regarding the length of recovery and cognitive areas most often affected. Potential contributors to the mixed results could result from relatively weak study designs (e.g., case descriptions, small group designs) and not controlling for potential confounding variables. Variables that have been identified as significant mediating or moderating factors have not always been consistently controlled for in studies across the literature. Such factors include but are not limited to early versus late bilingualism, differing levels of premorbid levels of proficiency, and simultaneous versus sequential language learning.

Few bilingual studies with children were also identified. This may be due to children's sensitive developmental phase compared to adults and older adults, making this population more complex to evaluate. Therefore, researchers are encouraged to include how aspects of children's developmental phase impact the acquisition of a second language while performing longitudinal studies that follow children's changing and developing cognitive processes along with the language development of acquiring a second language.

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