THE RELATIONSHIP AMONG GRAY MATTER CORTICAL THICKNESS, ACTIVITY, AND BILINGUAL BACKGROUND VARIABLES

A Dissertation

Presented to

The Faculty of the Department

of Psychology

University of Houston

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

By

Aurora I. Ramos Nuñez

December 2015

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ABSTRACT

A bilingual person's brain has to manage two languages. According to psycholinguistic models, lexical representations of the two languages are always active and to select the correct language, the other has to be inhibited (Green, 1998). This includes cognitive control processes (e.g. language planning, response inhibition, maintenance of representation) that might require additional brain networks beyond those classically involved in language processing. Regions such as prefrontal, anterior cingulate cortices, inferior parietal lobule, and caudate have been found to be involved in cognitive control processes (Abutalebi & Green, 2007). The present study examined whether or not bilingual experience shapes the structure and function of the brain by examining relationships among language proficiency, second language age of acquisition, and structural and functional correlates. Participants were 49 Spanish-English bilinguals who learned English between the ages of 0 and 17 years. Cortical thickness measures as well as functional activity during a picture-naming task requiring switching between the two languages on a trial-by-trial basis were acquired using a functional Magnetic Resonance Imaging scanner. The results indicate that age of acquisition of the second language but not proficiency is related to gray matter structure in the right dorsolateral prefrontal cortex, a cognitive control region and that gray matter cortical thickness is related to functional activity during a condition that requires switching in naming pictures between two languages. These results carry implications for the understanding of how language experience shapes the functional and neural correlates of the bilingual brain.

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The relationship among gray matter cortical thickness, activity, and bilingual background variables

Bilingualism, the ability to use two languages effectively, requires the individual to frequently manage the interplay between their two languages. To carry out this task, various processes have to be in place in the brain so that bilinguals do not mistakenly use their languages in the wrong context (e.g. speaking in Spanish to someone who only speaks English). How might this occur? The inhibition model suggests that the lexical representation of two languages is always active in the bilingual brain and that in order to select the correct language, the other has to be inhibited (Costa, Caramazza, & Sebastian-Galles, 2000; Costa & Santesteban, 2004; Costa, Santesteban, & Ivanova, 2006; Green, 1998; Green, Crinion, & Price, 2006). In order to resolve the conflict of having to select between two languages that are active, bilinguals use considerable cognitive effort. The question could therefore be asked, what functional and structural networks are involved in the management and representation of two languages? Are bilingualism factors such as language experience and ability associated with the functional and structural networks involved in bilingualism? Is the relationship between language experience (i.e. age of acquisition (AoA)) and ability (i.e. proficiency) with brain development dissociable? How are structure and function related in the bilingual brain? Previous research has addressed some of these questions, but there is still much debate about the interplay among language variables, brain structure and function associated with bilingualism. The present study will attempt to address some of these questions by examining whether or not bilingual experience has an influence on structural and functional developmental trajectories.

The Neural Basis of Cognitive Control

Bilingualism research has advanced our understanding of the neural and cognitive processes involved in the representation and management of two or more languages. A compilation of previous imaging and language impairment research presented by Abutalebi and Green (2007) has shown evidence of a cognitive control mechanism needed for switching between two languages that does not necessarily involve classical language areas (Green, 1998). Cognitive control, in the context of language, involves processes such as task switching, language planning, response inhibition, maintenance of representation, conflict monitoring, and error detection, to achieve the desired goal of selecting the correct language (Abutalebi & Green, 2007). That is, producing the correct word in the correct language may require additional areas beyond those that are classically identified with language processing (Green, 1998).

According to cognitive control models, language switching demands extra cognitive processes to resolve conflict caused by lexical representation in both languages (Green, 1998). Therefore, cognitive control processes are needed for managing task-relevant information in order to perform the function at hand, while ignoring irrelevant information (Abutalebi & Green, 2007; Green, 1998). Functionally speaking, cognitive control mechanisms involve brain regions including the prefrontal cortex (PFC), inferior parietal lobule (IPL), anterior cingulate cortex (ACC), and caudate nucleus (Abutalebi & Green, 2007, 2008; Crinion et al., 2006; Hernandez, 2009; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Price, Green, & von Studnitz, 1999; Rodriguez-Fornells et al., 2005; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008; Y. Wang, G. Xue, C. Chen, F. Xue, & Q. Dong, 2007). According to

Abutalebi and Green model of cognitive control (2007, 2008), the prefrontal and bilateral inferior parietal cortices are associated with attention, while the anterior cingulate cortex (ACC) is related to error detection and conflict monitoring. These cognitive control regions were further examined in a meta-analysis study and were indeed found to be associated with language switching relative to nonswitching during language production in bilinguals (Luk, Green, Abutalebi, & Grady, 2011).

Recent studies have since supported the hypothesis that regions involved in cognitive control processes are involved in the management of two languages (Abutalebi et al., 2012; Garbin et al., 2011; Guo, Liu, Misra, & Kroll, 2011; Hernandez, 2009; Luk et al., 2011; Wattendorf et al., 2014). Garbin et al. (2011) measured brain activity of early, high proficient Spanish-Catalan bilinguals during a language-switching picture naming task. They found greater activation during the language switching compared to the non-switching condition in regions related to cognitive control processes such as the head of caudate and the pre-supplementary motor area (pre-SMA)/anterior cingulate cortex (ACC) during the language switching relative to the non-switching trials. Guo et al. (2011) had two groups of Chinese-English bilinguals perform a language-switching picture naming task. They set out to examine the neural correlates related to the 'local inhibition' effect (switching between languages on a trial by trial basis) and 'global inhibition' effect (switching between blocks of naming in English or Chinese only). They found increased activity in the dorsal bilateral ACC and the SMA in the local switching condition (switching between languages on a trial by trial basis) and increased activity in the left dorsal frontal gyrus and left parietal cortex in the global inhibition condition (switching between blocks of naming in English or Chinese only). The authors concluded that bilinguals utilize these neural correlates in order to resolve conflict between competing responses. While these studies implicate a very specific brain network that is active in resolving conflict between two competing responses, AoA and proficiency differences may impact the specific patters of activation within this network. This brings into mind the following question: Are the neural mechanisms required for resolving conflict between two competing responses influenced by second language AoA and language proficiency?

Individual Differences: AoA and Language Proficiency

Bilingualism research has shown that individual differences in second language age of acquisition or language proficiency may play a role in the neural mechanisms necessary for resolving conflict (Abutalebi et al., 2012; Archila-Suerte, Zevin, Ramos, & Hernandez, 2013; Fabbro, 2001; Golestani & Zatorre, 2004; Greene, Ramos-Nuñez, Vaughn, & Hernandez, 2015; Hernandez, 2013; Mechelli et al., 2004; Perani et al., 1996; Wattendorf et al., 2014), and that AoA and proficiency may have dissociable relationships with neural mechanisms (Greene et al., 2015; Wartenburger et al., 2003). However, the dissociable relationship between AoA and proficiency with the bilingual brain has not been fully explored and most research either examines one variable or the other. While dissociating AoA and proficiency has proven challenging, bilingualism research has attempted to make this distinction. This has been done previously by controlling proficiency and varying AoA. For example, Waternburger et al (2003) examined the effects of AoA and proficiency on neural activity during grammatical and semantic judgment tasks. They examined three groups of Italian-German adult bilinguals according to different AoA and proficiency level. One group was composed of early and high proficient bilinguals (EAHP), the second group included late and high proficient bilinguals (LAHP), and the third group consisted of late, low proficient bilinguals (LALP). They discovered that proficiency level was related to brain activity in the left middle frontal gyrus (BA 46) and the right fusiform gyrus (BA 37) during semantic judgment while AoA was mainly related with brain activity in bilateral IFG (BA 44 and 44/6) during grammatical processes (Wartenburger et al., 2003). However, this study was not able to provide with a fourth group, that is an early, low proficient group of bilinguals. Despite its limitations, this early study suggests that AoA and proficiency might have a dissociative effect on brain regions related to language processes in bilingualism. Along the same lines, preliminary data in our laboratory has found dissociable relationships among AoA (time as a bilingual), language ability (the summation of proficiency scores from the two languages indicating underlying language skill), and brain activity in cognitive control regions during performance of a task of inhibition. It was found that later AoA of a second language was associated with an increase in activity in the left IPL and lower proficiency was associated with increased activity in the right ACC and DLPFC during a difficult condition. These results not only highlight possible dissociable contributions of AoA and proficiency to neural activity, but also show that such contributions are seen in seemingly nonverbal tasks. That is, having the bilingual experience and language skill level may lead to a more efficient neural processing of a nonverbal task (Greene et al., 2015).

Recently Wattendorf et al. (2014) examined how learning a second language early or late in life is associated with the neural correlates sub-serving language control of a third language. In this study, trilingual participants had learned a second language either before or after the age of three, and a third language after the age of nine. They covertly produced sentences in their first (L1), second (L2) and third (L3) languages while lying inside the fMRI scanner. The researchers found that during sentence production in the L1 and L3, early bilinguals (who had learned the L2 before the age of three) preferentially activated a fronto-striatal network including the superior, middle and inferior frontal gyri, anterior cingulate gyrus, and the striatum of the left hemisphere compared to late bilinguals (who had learned the L2 between three and nine years of age). In contrast, late bilinguals presented with activity only in the left posterior superior temporal gyrus (pSTG) during sentence production in the L1 and L3. This study reported two important findings. The first finding was that similar patterns of activity were seen when early but not late bilinguals produced language in the L1 and L3. The second finding was that the conditions in which two languages were acquired in childhood (early vs. late) might exert an influence on the recruitment of language control regions in trilingual adults (Wattendorf et al., 2014). That is, early neural patterns set the tone for later neural patterns when acquiring a third language.

Abutalebi et al. (2012) examined trilingual persons whose language proficiency varied within their three languages. Participants performed a picture-naming task while lying in the scanner. The authors found that when trilingual persons switched between their languages, they presented with increased activity in the pre-SMA/ACC regardless of language proficiency differences. When switching from the most proficient language to the least proficient language, participants presented with increased caudate activity. The authors concluded that the ACC and caudate play different roles in language switching, with the first having a more general role and the latter being affected by proficiency level.

While significant strides have been made in the search for the mechanisms that underlie bilingualism, there is still much that is unknown. The studies discussed in this section have provided functional information of the neural correlates involved in bilingualism. However, studies examining the structural correlates of bilingualism are scarce. Given the interplay between brain structure and function, where function arises from structure (Kandel, Schwartz, & Jessell, 2000), an examination of the neural structure of the bilingual brain is a fundamental step in understanding how bilingualism affects brain and behavior.

Brain Morphometry

Examining the relationships between brain morphology of healthy humans and language has proven challenging due to the fact that most of the methods used in animal brain studies are invasive in nature. Additionally, since spoken language is unique to humans, animal models cannot be used to understand language processes. The invention of neuroimaging methods such as MRI has made possible the examination of healthy brains *in vivo*. One such advantage of using MRI data is for the study of brain structure using voxel-based morphometry (VBM). VBM is the systematic study of brain structure on a voxel-by-voxel basis of high-resolution MRI scans in an unbiased whole-brain approach. It allows for the study of different brain tissue types such as gray and white matter and cerebrospinal fluid by using a semi-automated segmentation method (Ashburner & Friston, 2000). Additionally, advancement in brain morphometry methods such as surface-based morphometry approaches (SBM) allows for the examination of characteristics of gray matter volume such as cortical thickness (Fischl & Dale, 2000; Hutton, Draganski, Ashburner, & Weiskopf, 2009). In a comparison between voxel-based morphometry and surface-based morphometry, Hutton and colleagues (2009) demonstrated that cortical thickness was a more sensitive measure of age-related changes in gray matter relative to gray matter volume measures obtained from VBM. The present study's main focus was to examine relationships between changes in gray matter and age of acquisition of the second language; therefore, the method of choice was cortical thickness SBM.

Brain Morphometry: Learning influences brain structure. Research examining the structure of human brains using MRI anatomical scans has shown that acquiring special abilities such as playing a musical instrument, navigating through the streets of London, juggling, or studying for an important medical exam can lead to structural changes that are evidence for brain plasticity (Abdul-Kareem, Stancak, Parkes, & Sluming, 2011; Bermudez, Lerch, Evans, & Zatorre, 2009; Draganski et al., 2006; Gaser & Schlaug, 2003a, 2003b; Hanggi, Brutsch, Siegel, & Jancke, 2014; Maguire et al., 2000; Morosan et al., 2001; Schneider et al., 2002). Maguire et al. (2000) compared the brain structure of a group of London taxi drivers with non-taxi drivers. They found that the posterior portion of the hippocampi was larger in taxi drivers compared to non-taxi drivers and that this difference correlated positively with the amount of time spent driving (Maguire et al., 2000). Another prominent study by Gaser and Schlaug (2003a) investigated whether practice of a skill leads to differences in brain morphometric characteristics in keyboard professional, amateur, and non-musicians. They found that professional musicians presented with greater gray matter volume in regions associated with motor, auditory, and visual-spatial processes compared to amateur and non-musicians (Gaser & Schlaug, 2003a). These two results suggest that having the experience of continuously performing a difficult task such as navigating the streets of London or practicing a musical instrument is related to structural changes in the brain. A longitudinal study measured brain structure in German medical students who were preparing to take a preliminary medical exam. They found continuous gray matter expansion of the hippocampus and parahippocampus and the posterior parietal cortex during the three time points in which they acquired structural scans. The authors concluded that learning large amounts of new information as well as retrieving it lead to changes in structural gray matter of medial temporal and posterior parietal regions (Draganski et al., 2006). While these studies found an increase of brain gray matter associated with experience, other studies have found the opposite association. A recent study examining the brains of chess players found that expert chess players presented with a decrease in gray matter volume and cortical thickness of the occipito-temporal junction compared to the control group (Hanggi et al., 2014). The studies discussed here have a common theme: learning a new skill appears to influence anatomical changes in the developing brain. The question that arises is whether or not learning a new language could also be related to structural changes in the bilingual brain.

Second language learning influences brain structure. Indeed, language research has demonstrated that learning a second language is a unique experience (Grosjean, 1982) and could therefore potentially lead to brain plasticity as well. Voxel-based and surface-based morphometry (VBM) (Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015; Abutalebi et al., 2014; Abutalebi et al., 2012; Della Rosa et al., 2013; Grogan et al., 2012; Klein, Mok, Chen, & Watkins, 2014; Li, 2014; Li, Legault, & Litcofsky, 2014; Mårtensson et al., 2012; Mechelli et al., 2004; Stein et al., 2012; Zou, Ding, Abutalebi, Shu, & Peng, 2012) have been used to study the effects of learning two or more languages on brain regions that have been associated with cognitive control and language.

Mechelli et al. (2004) were the first to compare the brain structure of monolinguals and bilinguals. The group of bilinguals was composed of two types, 'early' (learning the second language before age 5) and 'late' (learning the second language between the ages of 10 and 15) bilinguals. They showed that gray matter density in the inferior parietal cortex was greater in bilinguals than monolinguals and that this increased gray matter density was more pronounced in the early relative to late bilinguals. They also reported an association between gray matter density and two bilingualism variables (e.g. proficiency and second language AoA). This association indicated that earlier AoA and higher language proficiency increased gray matter density in the left inferior parietal cortex. That is, both lifelong language experience and language proficiency seemed to have an effect on gray matter density. The authors concluded that the left inferior parietal cortex's association with second language AoA and proficiency implicates an important role of this area in vocabulary learning (Mechelli et al., 2004). Along this line of research, Grogan and colleagues (2012) demonstrated a similar association between language background and a different brain region, the left pars opercularis. They reported that both the second language age of acquisition and language efficiency (or proficiency) correlated negatively and positively (respectively) with gray matter of the left pars opercularis. However, the association between brain structure and second language age of acquisition has only been shown in young adults. Abutalebi and colleagues (2015) found that older adult bilinguals showed greater gray matter volume in the left inferior parietal lobule relative to older adult monolinguals, but found no relationship between age of acquisition of the second language and gray matter volume in the inferior parietal lobule. While no second language age of acquisition and brain structure was found, they did find a differential association between language proficiency and exposure and gray matter of the left and right inferior parietal region (respectively) in the bilinguals. These studies suggest that learning a second language has implications for cortical structural changes in the bilingual brain.

A recent article compared a group of monolinguals with three subgroups of bilinguals (simultaneous, early and late bilinguals) to see whether there were structural differences among the groups (Klein et al., 2014). They found that early and late bilinguals presented with thicker cortex in the left inferior frontal gyrus (IFG) compared to monolinguals and simultaneous bilinguals. Simultaneous bilinguals presented with similar patterns as those of the monolinguals. Additionally, their correlation analyses showed that AoA was positively correlated with cortical thickness in the left IFG and negatively correlated with cortical thickness in the right IFG. That is, late bilinguals presented with thicker cortex in the left IFG and thinner cortex in the right IFG (Klein et al., 2014). The authors concluded that learning a second language after proficiency has been established in the first language may exert an influence on brain structure and that such modification seems to be age-dependent. This study also suggests that the experience of learning a second language has the potential to influence the development of brain structures that are associated with language.

Studies have also reported a change in brain structure after a short period of learning a second language. A longitudinal study of adult Native-English speakers learning German in Switzerland measured structural brain changes using VBM during two time points, before and after learning the second language (Stein et al., 2012). They observed an increase in gray matter of the left inferior frontal gyrus (IFG) and left anterior temporal lobe (ATL) as second language proficiency increased. The authors concluded that gray matter changes could be observed after only five months of learning a second language and that these results are related to studies that have found decreases in brain activation in the IFG as proficiency of the second language increased (Stein et al., 2012).

Research in our laboratory in collaboration with Dr. Chiarello and colleagues from the University of California in Riverside examined cortical thickness asymmetry and corpus callosum volume in bilinguals and monolinguals. It was found that the group of bilinguals presented with thicker right than left cortex of the anterior cingulate and the reverse was seen in the monolinguals. Additionally, two regions of the corpus callosum including the mid-anterior and central portion showed greater volume in bilinguals compared to monolinguals (Vazquez, Ramos, Felton, Greene, McDowell, Hernandez, & Chiarello, submitted). Most of the studies examining bilingual brain structure have used voxel-based morphometry, which only examines gray matter volume (a combination of cortical thickness and surface area). More research is necessary to individually investigate gray matter characteristics (e.g cortical thickness, surface, area and folding of the gyri) (Hutton et al., 2009). Nonetheless, the results discussed in this section suggest that bilingualism may be related to structural changes in the brain. Learning a second language, either earlier or later in life, could exert an influence on the structure of cognitive control and language related regions. The question that arises is how are structure and function in the bilingual brain related?

Brain Structure and Function Relationship

The number of studies examining the relationship between gray matter structure and functional activity is limited (Abutalebi et al., 2012; Hegarty et al., 2012; Ilg et al., 2008; Lu et al., 2009; Rasser et al., 2005; Woolgar, Bor, & Duncan, 2013). Moreover, this number shrinks further when bilinguals are included in the sample pool (Abutalebi et al., 2012). These few studies have reported positive or negative relationships between gray matter structure and functional activity depending on the region of interest and the population under study. Abutalebi et al. (2012) examined a region that has previously been associated with conflict resolution, the anterior cingulate cortex (ACC). They compared the relationship between gray matter density and brain activity of the ACC during a verbal and nonverbal task that measured language switching and conflict monitoring, respectively. In their correlational analyses, the authors found greater gray matter density of the ACC was related to greater activity during language switching and conflict monitoring tasks. Moreover, the positive correlation between activity in the ACC and its gray matter density was significantly greater in the bilingual compared to the monolingual group. The authors concluded that learning a second language early in life as well as the experience of lifelong bilingualism has an impact on the developing human neocortex (Abutalebi et al., 2012).

Another study examining gray matter structural and functional relationship in healthy monolingual adults during a Go/NoGo task, a response inhibition task, found that thicker cortex in the ACC was related to greater brain activity (Hegarty et al., 2012). This positive relationship between structure and function of the ACC in these two studies may suggest an efficient use of this region to resolve conflict caused by demanding tasks. Contrary to the previous studies, two other studies found that thicker cortex was associated with lesser activity in fronto-parietal networks during high cognitive demand tasks (e.g. fast naming, Tower of London) (Lu et al., 2009; Rasser et al., 2005). However, these two studies examined schizophrenia patients and typically developing children, suggesting that the cerebral cortex was either damaged or still developing and that these results may not parallel those expected in the present study. Results from these studies lead to the conclusion that under normal circumstances, thicker cortex is related to greater brain activity during tasks of inhibition, switching, planning, and maintenance of representation.

The research looking into associations between structural characteristics of gray matter and functional activity is at its infancy, more research is needed to uncover the effects of lifelong bilingualism on the brain. The structure-function relationship between prefrontal and parietal regions and activity during verbal tasks in bilinguals has not been examined. The current study attempts to answer these questions by examining how structural characteristics relate to functional activity during a language-switching picture naming task.

Present Study

In the present surfaced-based morphometry was used to examine cortical thickness of regions involved in cognitive control in two experiments. In experiment one the relationship among AoA, language ability, and cortical thickness in cognitive and language control regions of the bilingual brain was investigated. This relationship has been previously examined in IFG and IPL and this current examination attempts to replicate these findings. Additionally, this examination adds to the existing literature by focusing on the ACC and DLPFC that have not been previously considered. In experiment two the relationship between structural gray matter and brain activity during a language-switching picture-naming task in language and cognitive control regions was examined for the first time in a group of bilinguals. This relationship has only been examined by looking at the association between gray matter density and brain activity in ACC during a nonverbal switching task (Abutalebi et al., 2012) but has not been studied during a language-switching task.

Experiment 1 Objective 1: to examine how second language age of acquisition (AoA) and language ability (combined proficiency scores from the first and the second langauges) are related to structural gray matter in the bilingual brain and whether or not this relationship is dissociable. Objective 1 was motivated by previous findings of a relationship between gray matter and language variables in cognitive control regions (Abutalebi et al., 2012; Klein et al., 2014; Mechelli et al., 2004) and by preliminary findings in our laboratory, in which Spanish and English proficiency scores were summed to create a composite score thought to reflect language ability in general, independent of the specific language (Greene et al., 2015). In order to create a composite score representing language ability, in the present study, scores from the first and second language proficiency tests were combined following what was done in our preliminary study. This has not previously been done; therefore our study will be the first to examine cortical thickness and combined proficiency relationships in order to measure general language ability. Our preliminary findings showed that later AoA was related to increase left IPL activity while lower language ability was associated with increased right ACC and DLPFC activity. The results from this study suggest that AoA and combined language proficiency are differentially related to activity in different parts of the brain during a test of inhibition. This dissociation may be in part due to differences in what AoA and language ability represent. AoA may indicate a training effect, that is, years in a bilingual setting may lead to a more efficient processing of a nonverbal task. Language ability, on the other hand, may reflect language skills, which in turn lead to a more efficient processing in cognitive control regions. The present study extended these findings by examining whether AoA and language ability are differentially related to anatomical structures of the brain.

Experiment 1 Predictions: *Hypothesis 1a* sought to replicate previous studies in that earlier AoA and high language ability (underlying language skill) would be related to thicker gray matter of the left IPL and right IFG. *Hypothesis 1b* is the first investigation looking at the relationship between gray matter of ACC and DLPFC with language history variables. It was predicted that gray matter of these areas would decrease as AoA increased and increase as language ability increased. High language ability and early acquisition of a second language would indicate a more effective way of recruiting cognitive control and language regions when managing two languages. The continuous recruitment of these regions during management of two languages by early bilinguals could be considered a way of having continuous practice of a skill. These hypotheses are consistent with the studies discussed in the introduction, which found that both AoA and proficiency were related to structural gray matter of the IPL but in opposite directions.

Experiment 2 objective: To examine the relationship between structural gray matter and functional brain activity in cognitive control and language regions during a language-switching picture-naming task. Objective 2 originated from the necessity to address the gap in the literature about brain structure and function. As stated previously, studies examining the relationship between anatomical and functional correlates of the bilingual brain are scarce and have not examined all the brain regions that have previously been associated with bilingualism (Abutalebi et al., 2012; Hegarty et al., 2012; Lu et al., 2009; Rasser et al., 2005; Woolgar et al., 2013). Thus a clear link between brain structure and function has not been established. An examination of the relationship of gray matter and functional activity in the bilingual brain is therefore warranted, focusing on questions such as how is gray matter related to functional activity during verbal tasks in bilinguals? Does this relationship vary depending on task difficulty or region of interest? Is greater gray matter related to more or less brain activity? Does this relationship change depending on the brain area of focus? The current study examined structural gray matter characteristics and functional activity in the following *a priori* selected regions that have been previously associated with cognitive and language control: inferior parietal lobule (IPL), anterior cingulate cortex (ACC), caudate, dorsolateral prefrontal cortex (DLPFC), and inferior frontal gyrus (IFG).

Experiment 2: Predictions. The goal of this experiment was to examine the relationship between structural gray matter and functional brain activity in cognitive control and language regions during a picture-naming task. Previous literature examining structure and function relationships found positive or negative relationships between structural gray matter and functional activity varying from region to region. However, these mixed results appear to have been linked to the type of population under study (i.e. patients with schizophrenia, children, adults). For example, in the two studies that examined adults, thicker cortex in the ACC was related to greater activity during tasks of switching and inhibition (Abutalebi et al., 2012; Hegarty et al., 2012). In contrast, in the other two studies that included patients with schizophrenia and children, thicker cortex was related to lesser activity in fronto-parietal regions (Rasser et al., 2005). The present study examined healthy adult bilinguals during a picture-naming task, therefore it was hypothesized that greater gray matter of cognitive and language control regions would be related to greater activation during a picture-naming task.

General Methods

Participants

The present two experiments involved 49 neurologically intact right-handed Spanish-English bilinguals (as shown by their language proficiency scores) between the ages of 18 and 34 (M= 23.7, SD = 4.3) who learned Spanish at birth and English around the age of seven years old (M = 7.02. SD = 3.5) (Table 1). Participants were University of Houston students and members of the greater Houston community who received a gift card as compensation for their time.

Imaging

Prior to acquiring functional MRI scans, two T1-weighted high-resolution images were obtained from Siemens Magnetom Trio 3-T MRI scanner at the Center for Advanced MR Imaging (CAMRI) at Baylor School of Medicine. The T1-weighted image were obtained with the following parameters: 192 slices, 1.0 x 1.0 x 0.48 mm^3 voxel size, and a 4.30 min TR. Functional scans to detect brain areas involved in the management and representation of two languages were acquired. During fMRI data acquisition, 3D functional images were obtained using a Siemens 3-T MRI scanner. Functional activation was acquired in a block design using a gradient-echo planer imaging (EPI) pulse sequence with the following parameters: TR = 2 s, TE = 30 ms, a flip angle of 90 degrees, and slice thickness = 4 mm. Off-line reconstruction algorithms (SMP8 software) were used to reconstruct the echo-planar images.

Experiment 1

Objective 1: To examine the effects of second language age of acquisition (AoA) and language ability on structural gray matter of cognitive control regions.

Screening questionnaires Before participation, subjects were screened with a language history questionnaire to make sure they qualified as Spanish-English bilinguals and to examine language proficiency. The language history questionnaire included questions about age of second language acquisition, daily language usage, knowledge of additional languages, etc. To ensure fMRI compatibility, bilinguals were also screened with a questionnaire to thoroughly assess whether or not there is metal in their bodies. In order to measure participants' language proficiency, the Woodcock Language Proficiency Battery-Revised test was used (Woodcock & Muñoz-Johnson, 2005). This is a comprehensive test battery that includes various tests measuring different language abilities. This assessment included picture vocabulary in which a picture was shown and participants had to name it in both languages and reading comprehension tests where participants read sentences and questions related to the sentences and had to give the correct answer that goes with the sentence. The scores from the Spanish and English proficiency subtests were combined to create a composite score representing general language ability. These scores were then entered in the regressions model to examine the association between cortical thickness of cognitive and language areas and language ability.

Surface-Based Morphometry (SBM) Analyses The present study examined cortical thickness as research has shown that it is a more sensitive measure of age-related changes on gray matter (Hutton et al., 2009). Structural gray matter thickness was measured using two high-resolution T1-weighted images from each participant. The two T1s were preprocessed using the freely available FreeSurfer v 4.5 analysis software **(http://surfer.nmr.mgh.harvard.edu/).** The T1-weighted images underwent co-registration, motion correction and averaging of the two T1 images, non-brain tissue removal using an automated transformation, deep gray and subcortical white matter segmentation, intensity normalization, tessellation of gray and white matter boundaries, automated Talairach transformation, and automatic topology correction. These standard steps have been described and validated in numerous published studies (Dale, Fischl, & Sereno, 1999; Fischl & Dale, 2000; Fischl, Salat, et al., 2004; Fischl, Sereno, & Dale, 1999; Fischl, van der Kouwe, et al., 2004). After the preprocessing steps were performed, cortical thickness measures were automatically extracted for the dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), inferior frontal gyrus (IFG), and inferior parietal lobule (IPL) using the freely available FreeSurfer software ((http://surfer.nmr.mgh.harvard.edu/). Cortical thickness is defined as the distance between white matter and pial matter layers (Figure 1). Linear multiple regression analyses were performed using SAS 9.2 to predict gray matter structure using second language age of acquisition, language proficiency, and age as covariates.

Experiment 1: Results

Cortical Thickness, AOA, and Language Ability Multiple regression analyses were performed in SAS 9.2 (SAS Institute Inc., Cary, NC, USA) to examine whether bilinguals' background variables would predict cortical thickness in language and cognitive control regions. The variables in question were second language age of acquisition (AoA) and language ability as well as cortical thickness of the left and right inferior frontal gyri (IFG), dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), and inferior parietal lobule (IPL).

Multiple regressions analyses showed that after controlling for age, AoA significantly predicted cortical thickness of the right DLPFC ($\beta =$ -0.01319, $p <0.035$). This relationship was negative in that earlier second language age of acquisition was related to thicker right DLPFC (Figure 2). AoA did not predict cortical thickness of any other language or cognitive control regions examined in the present study. Language ability did not predict cortical thickness of any of the regions of interest (table 2)

Experiment 1: Discussion

In experiment 1 two hypotheses were tested. Hypothesis 1a sought to replicate previous studies by predicting that later age of acquisition (AoA) of the second language would be related to a decrease in gray matter of the left IPL and right IFG and that higher language ability would be related to an increase in gray matter in those same brain regions. Hypothesis 1a was not supported by the current results. There was no association between left IPL and right IFG with AoA and language ability. The fact that there was no association between IPL, AoA, and proficiency as seen by Mechelli et al., (2004) could be due to the fact that the present study examined cortical thickness, while the Mechelli et al., (2004) examined volume/density. These two ways of measuring gray matter involve slightly different steps (Hutton et al., 2009). The lack of replication could also be due to difference in age range at which the groups learned the second language. In the present study the AoA range was between zero and seventeen and in the Mechelli study was between two and thirty-four. This difference in AoA between the Mechelli et al 2004 and the present study could be related to the findings about gray matter maturation trajectory going from posterior to anterior regions (Sowell et al., 2003; Sowell, Trauner, Gamst, & Jernigan, 2002). The Mechelli et al (2004) study includes bilinguals who learned the second language way past the age in which areas of the brain continue to develop, while the present study involves bilinguals who learned the second language during development. Additionally, the lack of association between language ability and cortical thickness of the IPL in the present study could be due to the way in which proficiency was defined.. In the Mechelli et al (2004) study, proficiency was measured using a standardized neuropsychological test including English vocabulary, reading and semantics subtests of the Psycholinguistic Assessments of Language Assessments in Aphasia, an object and action naming battery the test of reception of English grammar, the national adult reading test, and the graded naming test. Additionally, these tests measured proficiency in the second language only. The present study measured proficiency in the two languages and used the Woodcock and Muñoz-Johnson test, which included vocabulary and reading comprehension subtests. Additionally, the scores from the Spanish and English tests were combined together as to create a test of language ability.

The lack of association between AoA and cortical thickness of the IFG as see in Klein et al., (2014) could be explained by the difference in the second language AoA and age range of the bilingual groups. The Klein et al., (2014) study examined bilinguals who ranged in age between 18 and 48 and whose AoA of the second language was between zero and thirteen years of age. In the present study participants were between the ages of 18 and 34 and acquired the second language between the ages of 0 and 17 years of age. The lack of replication between the present study and the studies discussed here could also be due to the fact that the present study controlled for age, a variable that has previously been associated with structural changes (Salat et al., 2004; Salat et al., 2005), as well as other variables not examined in the present study. Thus, more research needs to be done in this area.

Hypothesis 1b predicted that gray matter of DLPFC and ACC would be thinner as AoA increased and thicker as language ability increased. This hypothesis was supported in that there was a negative relationship between AoA and thickness of the right DLPFC. That is, earlier second language acquisition was related to thicker cortex of the right DLPFC. There was no association between gray matter of the ACC and any of the language variables. There was not a relationship between any of the areas of interest and language proficiency. One major finding that has been shown in the present study, and to our knowledge has not been demonstrated before, is the association between AOA and right DLPFC. The present study is the very first to show that the earlier a second language is acquired the greater the effect it might have on gray matter structure of the right DLPFC. This result adds to the findings that other studies have shown in with cognitive and language control regions (Abutalebi et al., 2015; Klein et al., 2014;

Mechelli et al., 2004), but more importantly, it demonstrate the pivotal role that the prefrontal cortex has in the management of two languages.

Experiment 2

Stimuli Experiment 2 used a picture-naming paradigm with 80 black and white line drawings from the UCSD Center for Research in Language International Picture Naming Project normalized database (Bates et al., 2003). The picture-naming items included only concrete objects (Appendix A), which participants were instructed to name them as quickly and accurately as possible in either English or Spanish as they appear on the screen. The task was divided into three conditions: switching, naming switched from Spanish to English or vice versa and was randomized, English, naming in English only, and Spanish, naming in Spanish only.

Experimental procedures Participants performed a picture-naming task during image acquisition for brain activation measures. Brain activation measures were obtained using a Siemens Magnetom Trio 3-T MRI scanner from the Center for Advanced MR Imaging (CAMRI) at Baylor School of Medicine. The picture-naming task was presented using Eprime (Version 2.0). The fMRI session lasted 20 minutes with two runs lasting 10 minutes each. Each of the runs contained four blocks (one Spanish, one English, and two mixed conditions) each lasting two minutes and a one minute rest period separating the blocks, where participants only saw the following message: “Rest. Keep your eyes open”. Block types and pictures within blocks were presented to each participant in a randomized order (Figure 3). A given trial was as follows: First a fixation cross appeared and remained on the screen for 1000 ms, then the fixation cross disappeared and a cue to indicate in which language to respond (“diga” for Spanish and “say” for English) appeared and stayed on the screen for 200 ms, and finally after the cue disappeared, the picture was presented for 800 ms (Figure 4). Participants' task was to overtly name the picture in the cued language as quickly and accurately as possible. Participants' responses to naming the pictures were recorded but due to the high scanner noise and technical difficulties response times and accuracy scores are not reported.

fMRI Analyses

Objective*:* To examine the relationship between cortical thickness and brain activity during a verbal task. FMRI analyses were carried out with the following pre-statistics processing: motion correction; spatial smoothing using a Gaussian kernel of FWHM 8mm; mean-based intensity normalization of all volumes by the same factor; high pass temporal filtering using a Gaussian-weighted least-squares straight line fitting, with a high pass filter of = 240s; and time-series statistical analysis with local autocorrelation correction (Frinston et al., 1995). Voxel wise activation patterns during English, Spanish, and mixed conditions during the picture-naming task were determined using a general linear model (GLM). Higher-level statistical maps were thresholded at a significance level of $p < 0.05$ FWE corrected according to the theory of Gaussian random fields (Frinston, Jezzard, & Turner, 1994).

Regression analyses: The present study had a sample size of 49 participants, therefore, multiple regressions using AoA and language proficiency as well as cortical thickness from the cognitive control regions as predictors of brain activity during the picture naming were not carried out. Thus, individual gray matter cortical thickness measures from the DLPFC, ACC, IFG, and IPL in the left and right hemispheres were used as variables to predict brain activity in those regions during the picture-naming task. As stated in the stimuli section, the picture-naming task was presented to participants in blocks of mixed, English, and Spanish conditions. However, since the main focus of this study was to examine the relationship between activity and cortical thickness during the switching and nonswitching trials, the English and Spanish trials were collapsed across in order to create a nonswitching condition. These statistical analyses were performed using the publicly available package SPM8 (http://www.fil.ion.ucl.ac.uk/spm/).

Experiment 2: Results

Brain structure and function Regression analyses were carried out using SPM8 and small voxel correction (SVC) regions of interest (ROI) analyses using a priori MNI coordinate of regions that are associated with language and cognitive control (Abutalebi & Green, 2008; Archila-Suerte et al., 2013; De Bleser et al., 2003; Garbin et al., 2010; Hernandez, 2009). Cortical thickness measures of the DLPFC, ACC, IFG, and IPL of the left and right hemisphere were used to predict brain activity during a picture-naming task required to name pictures during the nonswitching (naming in one language only) and switching (naming alternated between the two languages on every other trial) conditions.

ROI results indicated that cortical thickness of left and right DLPFC, ACC, and IFG, positively predicted brain activity during naming in the mixed condition at a $p > .0001$, FWE-corrected. That is, thicker cortex was related to greater activity in these regions while participants performed the picture-naming task during the condition that required language switching. Naming in the single nonswitching conditions did not yield any relationships between brain activity and cortical thickness. Cortical thickness of the IPL did not predict activity during any of the three conditions.

Experiment 2: Discussion

The purpose of experiment 2 was to investigate the relationship between cortical thickness and brain activity in regions related to language and cognitive control in a group of Spanish-English bilinguals. It was predicted that greater gray matter of cognitive and language control regions would be related to greater activation during a picture-naming task. This prediction was supported by the present study showing that thicker cortex of the DLPFC, ACC, and IFG in both hemispheres predicted greater brain activity during naming in the mixed/language switching condition but not in the non-switching condition. This relationship might be related to the fact that the switching condition, a process that required participants to switch between naming in their two languages on a trial-by-trial basis, was more difficult than the non-switching condition. This created an environment of intense competition between the two languages, calling upon control mechanisms that are beyond classical language networks. The intense competition created by the switching condition has been shown in previous studies in which functionally and behaviorally, the switching condition leads to increased brain activity and response times (Guo et al., 2011; Hernandez, 2009, 2013; Hernandez et al., 2001; Hernandez et al., 2000; Yapeng Wang, Gui Xue, Chuansheng Chen, Feng Xue, & Qi Dong, 2007). In fact, the difficulty caused by the language switching condition in the present study compares to the difficulty caused by tasks of inhibition reported by two other studies involving healthy adults. Such studies revealed a positive relationship between gray matter and activity in the ACC similar to the present results. That is, greater gray matter volume and thickness were related to increased activity during tasks of inhibition (Abutalebi et al., 2012; Hegarty et al., 2012). Thus it seems that during tasks of difficulty, thicker cortex leads to an increase in activity. Two other studies found a negative relationship between cognitive control tasks and fronto-parietal regions. That is, thinner cortex was related to greater activity in cognitive control areas (Lu et al., 2009; Rasser et al., 2005). However, these two studies examined patients with schizophrenia and child populations, with the first suffering from damage to prefrontal regions that are involved in cognitive control and the latter still in development (Callicott et al., 2000; Sowell et al., 2003; Sowell et al., 2002). Therefore, a negative relationship between gray matter and activity might not be representative of the healthy population. Thus it appears that thicker cortex leads to greater activity in cognitive control regions during demanding tasks such as language and task switching.

The present study did not find a relationship between cortical thickness and activity of the inferior parietal lobule (IPL). This might in part be due to the nature of the picture-naming task in which switching between the two languages on a trial-by-trial basis was required. Instead, IPL has been associated with cognitive control processes that involve maintenance of representation (Abutalebi & Green, 2007). This study is the very first to demonstrate a relationship between activity in cognitive control regions during a language-switching task and cortical thickness in healthy bilinguals.

General Discussion

The present study used a multimodal neuroimaging and individual differences approach to examine the effects of language experience on structural and functional correlates of cognitive control processes. The purpose of the current study was twofold:

1) to examine the association among language proficiency, second language age of acquisition, age, and a measure of structural gray matter; 2) to examine the relationship between cortical thickness of cognitive and language control regions and brain activity during a picture naming task. There are two major findings in this study. The first is the relationship between AoA and cortical thickness of the right DLPFC. This study is the first to show that learning a second language early leads to thicker cortex of the right DLPFC. That is, time as a bilingual is related to anatomical changes in a region associated with cognitive control. This relationship can be explained by theories of inhibition (Green, 1998) and theories of left versus right prefrontal cortex function (Aron, Robbins, & Poldrack, 2014; Erika-Florence, Leech, & Hampshire, 2014; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Mostofsky & Simmonds, 2008).

The Inhibitory Control model proposed by Green in 1998 supposes that as a bilingual person is confronted with naming an item in one language, the lexical representation of the two languages becomes active. In order to name the correct item in the correct language, the bilingual must inhibit the lexical representation of the item from the non-target language. This process of inhibition has been shown to be a function of the right prefrontal cortex (Aron et al., 2014; Erika-Florence et al., 2014; Hampshire et al., 2010; Mostofsky & Simmonds, 2008), and neuroimaging studies have shown that the DLPFC activates during tasks that require managing two languages (e.g. switching) (Hernandez, 2009; Hernandez et al., 2001; Hernandez et al., 2000; Nardone et al., 2011; Prior & Gollan, 2011; Y. Wang et al., 2007). The relationship between age of acquisition of the second language and cortical thickness of the right DLPFC found in the present study demonstrates evidence for an inhibitory process that might consistently be in use when two languages need to be managed. The consistent use of the inhibitory mechanism might have lead to an increase in cortical thickness of the right DLPFC shown by the current study.

The second finding of the current study is demonstrating for the first time the association between cortical thickness and brain activity of cognitive and language control regions seen during bilinguals' performance of a language switching picture naming task. Creating an environment of intense language competition lead to a unique relationship between cortical thickness and brain activity in language and cognitive control regions. That is, greater cortical thickness of the DLPFC, IFC, and ACC was associated with greater activity during the language switching relative to the non-switching condition. The difficulty caused by the language switching condition in the present study compares to the difficulty caused by tasks of inhibition reported by two other studies, which revealed a positive relationship between gray matter and activity in the ACC similar to the present results. That is, greater gray matter volume and thickness were related to increased activity during tasks of inhibition (Abutalebi et al., 2012; Hegarty et al., 2012). This relationship was not seen in the single-language naming conditions where language switching was not a requirement. Nor was it seen during language switching and the inferior parietal lobule. Thus it seems like during tasks of increasing difficulty such as switching between two languages on a consistent basis, the relationship between structure and function in regions associated with inhibition and selection processes rather than maintenance of representation appear to be indispensable. The fact that the relationship between cortical thickness of cognitive control regions and brain activity during the nonswitching condition was not shown in the present study might suggest that during this condition, inhibition or suppression of the other language might not have been necessary. Thus the results from the current study might not provide enough evidence for the inhibition theory, which states that a bilingual's two languages are always active in the brain and that one must constantly be suppressed or inhibited. Examining the relationship between thickness and brain activity during one language as compared to the other, as long as language proficiency differs between the two languages, could provide with a better examination of language inhibition.

The results from the first and second experiment might seem parallel at first but in actuality they might involve similar mechanisms affecting the brain, but with different developmental trajectories. The fact that AoA showed an association with cortical thickness indicates a lifelong experience that shapes gray matter structure specifically in the right DLPFC, a region known to play a critical role in control processes such as inhibition. In contrast, the association between cortical thickness and brain activity seen during the language switching condition but not during the non-switching condition could be thought of as the immediate outcome that results from submitting the cognitive control system to an environment of intense language competition which could have lead to the necessity of recruiting regions related to inhibition processes. This could be seen as a sneak preview of how bilingualism exerts an effect over the cognitive control system. In fact, various fMRI studies on bilingualism have shown increased activity during tasks that require high cognitive demands as compared to task with lesser cognitive control demands or baseline (Abutalebi & Green, 2007, 2008; Bialystok, Craik, & Luk, 2012; de Bruin, Roelofs, Dijkstra, & Fitzpatrick, 2014; Grant, Fang, & Li, 2015; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015), indicating training mechanisms related to task difficulty.

Due to the small sample size, the present study did not examine the nature of the relationship among cortical thickness and brain activity in combination with AoA, and language proficiency. Future studies should focus on increasing the sample size to examine these variables in conjunction. The present study used an individual differences approach to study the effects of bilingualism variables such as AoA and language proficiency on gray matter structural characteristics as well as to study brain function and structure relationships. It would beneficial to compare bilinguals to monolinguals in order to further examine the effects of bilingualism on brain structure and function relationships. Therefore, future studies should investigate the nature of these relationships in monolinguals and bilinguals in language switching tasks. Additionally, the present study found associations between AoA and cortical thickness. However, it is difficult to say whether learning a second language early in life lead to thicker gray matter of the right DLPFC or having a thicker right DLPFC lead to learning a second language. It would be interesting to examine these variables using longitudinal studies while monolinguals embark on a second language learning experience. At present, only a couple of studies have examined such relationships by investigating second language acquisition and brain activity (Grant et al., 2015) and second language acquisition and gray matter (Stein et al., 2012). More future studies should attempt to examine this relationship using longitudinal studies.

In conclusion, the first set of results demonstrates a clear association between the age at which a second language is learned and cortical thickness of the right prefrontal cortex. Learning the second language earlier in life leads to structural changes in a region that has been previously strongly associated with the management of two languages. Additionally, the second set of results from the present study showing a relationship between activity and structure of cognitive control regions during a language-switching task suggests a training mechanism that can be seen as the brain is subjected to demanding tasks. In general, language experience seems to play a pivotal role in the structural mechanisms associated with the management of two languages, thus submitting these brain structures to demanding tasks might serve as a training process.

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Table 1

Participants' Characteristics

Measure	M	SD
Gender (35 F; 14 M)		
Age	23.67	4.38
AoA	7.02	3.50
English Proficiency	75.61	6.92
Spanish Proficiency	76	10.5
Combined Proficiency	151.6	13.32

Note: The English and Spanish proficiency scores were composed of a comprehension and vocabulary score. These two scores were first weighted equally, and then added together so that the maximum possible score was 100. The combined proficiency score was a summation of the English and Spanish scores in order to create a language ability variable that was used to run the regression analysis to predict gray matter thickness. Age of acquisition (AoA) and age were obtained via a language history questionnaire.

Table 2

Regression analysis using language background variables as predictors of gray matter cortical thickness in cognitive control regions

		HEMISPHERE			
		LEFT		RIGHT	
Region	**Variables**	**β**	**p value**	**β**	**p value**
DLPFC	AOA	-0.060	0.675	**-0.311**	**0.035**
	CProf	0.006	0.966	-0.120	0.394
	Age	-0.383	0.009	-.127	0.374
ACC	AOA	-0.098	0.524	0.004	0.978
	CProf	-0.022	0.885	-0.233	0.114
	Age	-0.143	0.351	-0.205	0.167
OpIFG	AOA	-0.235	0.108	-0.126	0.417
	CProf	0.042	0.769	0.179	0.238
	Age	**-0.290**	**0.046**	-0.101	0.506
IPL	AOA	-0.112	0.467	-0.164	0.264
	CProf	-0.187	0.218	-0.136	0.345
	Age	0.120	0.427	-0.248	0.09

Note: Age of Acquisition (AoA) significantly predicted cortical thickness of the right dorsolateral prefrontal cortex (DLPFC) (In blue font). This relationship was negative in that earlier AoA of the second language was related to thicker cortex in the right DLPFC. Age significantly predicted cortical thickness of the left opercular inferior frontal gyrus (OpIFG) (In blue font). Combined proficiency (Cprof), that is, language ability did not predict cortical thickness of any of the cognitive and language regions.

Figure 1. Cortical Thickness Measure

Figure 3 illustrates an MRI T1-weighted image demonstrating the division between gray and white matter surface. Cortical thickness (red delineation) is a measure of gray matter defined as the distance between pial (outside of red delineation) and white matter surface (yellow delineation). The green arrows in the figure on the right demonstrate cortical thickness.

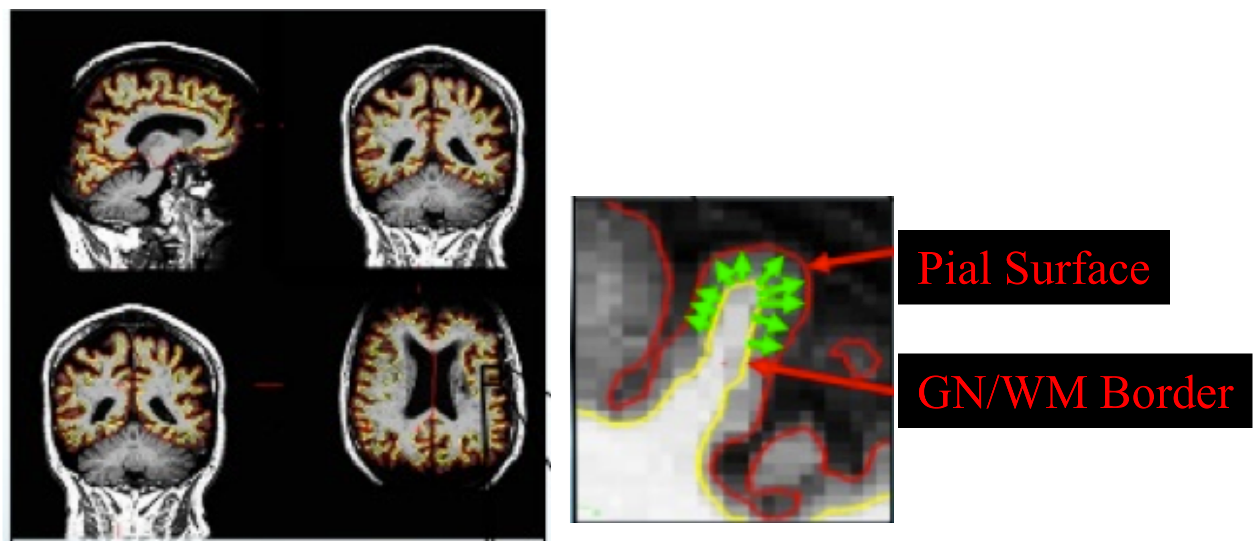


Figure 2. AOA and Right DLPFC Relationship

This graph shows the relationship between second language age of acquisition (AoA) and cortical thickness of the right dorsolateral prefrontal cortex (DLPFC). The regression analyses performed after controlling for age indicated that AoA of the second language significantly predicted cortical thickness of the right DLPFC (β = -0.01319, p <0.035).

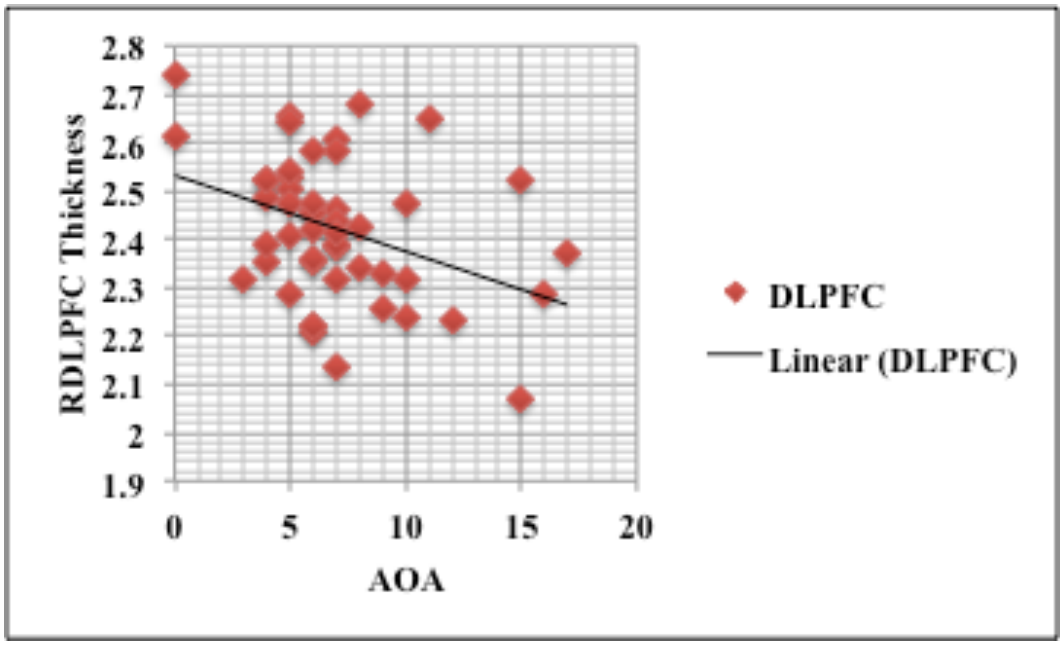


Figure 3. Picture-Naming Runs

The fMRI session lasted 20 minutes and 40 seconds with two runs lasting around 10 minutes each. Once inside the scanner participants were required to complete a short practice run that included 15 pictures (5 pictures per condition) in order to get familiar with the task. After completing the short practice session the first run began. Each run contained four blocks (one Spanish, one English, and two mixed conditions) lasting one minute and 20 seconds and five one minute rest periods where participants only saw the following message: “Rest. Keep your eyes open”. Blocks and pictures were presented to each participant in a randomized order to prevent order effects.

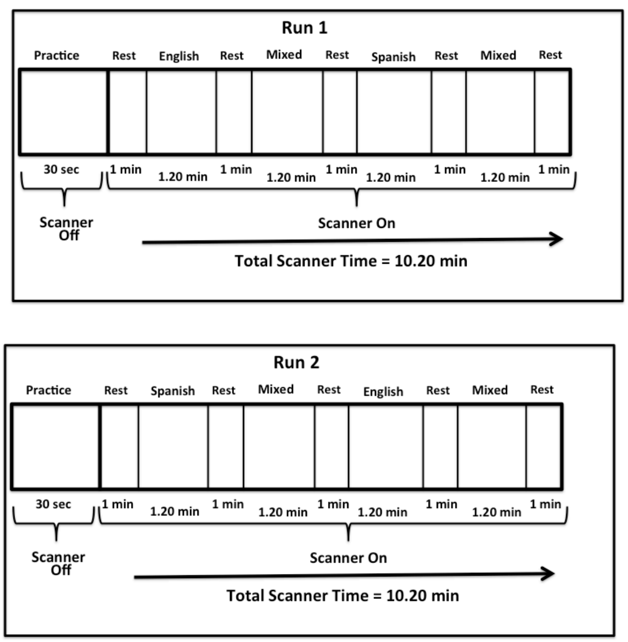
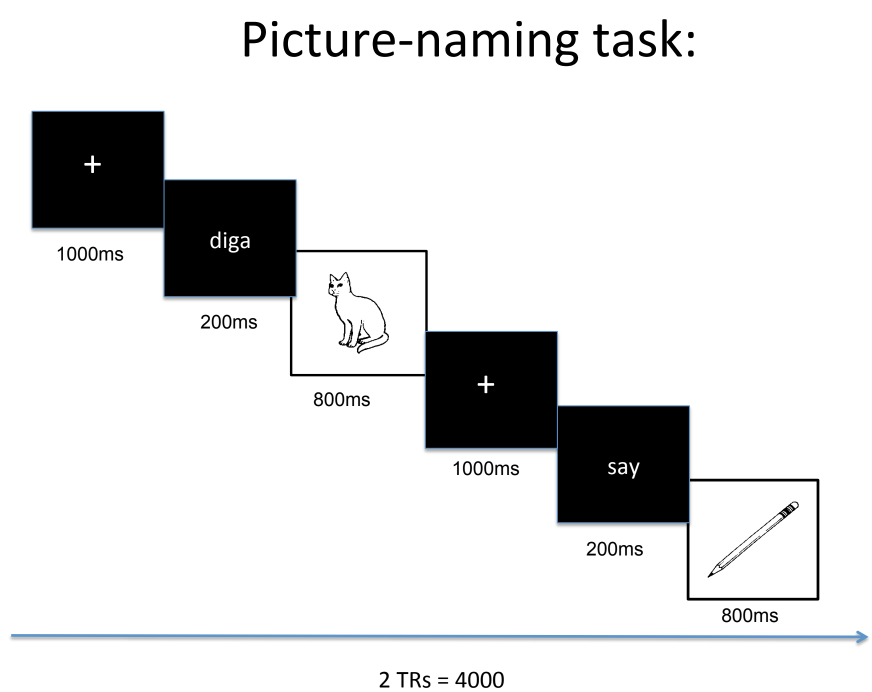


Figure 4. Picture-Naming Task

A given trial was as follows: First a fixation cross appeared and remained on the screen for 1000 ms, then the fixation cross disappeared and a cue to indicate in which language to respond ("diga" for Spanish and "say" for English) appeared and stayed on the screen for 200 ms, and finally after the cue disappeared, the picture was presented for 800 ms



Appendix A: Picture-Naming Items

Appendix A: Picture-Naming Items

English		Spanish	
arrow	king	flecha	rey
banana	kite	platano	papalote
bed	leaf	cama	hoja
belt	mirror	cinturon	espejo
bench	monkey	banca	chango
bird	mouse	pajaro	raton
bone	nail	hueso	clavo
bottle	needle	biberon	aguja
box	octopus	caja	pulpo
bricks	onion	tabiques	cebolla
bride	pillow	novia	almohada
bridge	pool	puente	alberca
broom	present	escoba	regalo
brush	puzzle	cepillo	rompecabezas
butter	queen	mantequilla	reina
cane	rain	baston	lluvia
canoe	rug	bote	tapete
cat	scarf	gato	bufanda
cheese	shark	queso	tiburon
chest	shirt	pecho	camisa
church	snail	iglesia	caracol
clock	spider	reloj	araña
comb	squirrel	peine	ardilla
cookie	swing	galleta	columpio
crab	tail	cangrejo	cola
crib	tear	cuna	lagrima
door	teeth	puerta	dientes
dress	tie	vestido	corbata
drum	trash	tambor	basura
egg	turkey	huevo	pavo
fan	umbrella	ventilador	paraguas
feather	vacuum	pluma	aspiradora
fireman	wallet	bombero	billetera
fish	whale	pescado	ballena
foot	window	pie	ventana
fork	witch	tenedor	bruja
ghost	wolf	fantasma	lobo
girl	woman	niña	mujer
gun	worm	pistola	gusano
hair		pelo	
helmet		casco	