THE EFFECTS OF AGE OF ACQUISITION AND PROFICIENCY ON THE NEURAL CORRELATES OF CATEGORICAL PERCPETION OF NON-NATIVE SPEECH

A Dissertation Proposal

Presented to

The Faculty of the Department

of Psychology

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In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

By

Victoria E. Wagner

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ABSTRACT

Age of Acquisition (AoA) and second language (L2) proficiency have been shown to influence bilingual neural recruitment and neuroanatomy, but previous literature shows inconsistencies. The current studies used multiple regression analyses to understand the influence of AoA and L2 proficiency on neural processing for categorical perception in Spanish-English bilinguals during a speech identification task. Functional data showed that AoA and L2 proficiency differentially recruited areas previously associated with speech processing. Increased L2 proficiency was associated with increased activity in bilateral inferior frontal gyrus and middle frontal gyrus as well as right superior temporal gyrus, middle temporal gyrus and angular gyrus. AoA was associated with a separate region of MFG. The data suggest that increased proficiency is associated with higher-level strategies such as attentional mechanisms and semantic processing to aid in a perceptual task. Study 2 focused on the influence of AoA and L2 proficiency on neuroanatomy. Structure based morphometry and multiple regression analyses were used to determine the relationship of AoA, L2 proficiency and L2 use and brain structure in speech processing areas. Significant relationships were found in left MTG, left supramarginal gyrus and right angular gyrus. The results suggest that L2 proficiency and AoA are associated with structural measures in speech processing areas, those associated with higher-level processing. The studies combine to provide a better understanding of the variability of AoA and L2 proficiency in bilinguals and how it impacts speech processing through recruitment of different neural regions that may underlie different strategies to complete a speech perception task.

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CHAPTER 1

General Introduction

Bilingualism is a topic that has garnered a plethora of research including its impact on cognitive processes such as speech perception, speech production and cognitive control. Research investigating differences in speech perception between monolinguals and bilinguals demonstrate the effects of various factors influencing final perceptual attainment, with many showing differences between bilingual groups and monolinguals, but the results of the bilingual literature are mixed. Through direct comparisons between groups, the studies show influences of age of acquisition, proficiency, amount of language use and the interaction of first and second language phonemic inventories (Archila-Suerte, Zevin, & Hernandez, 2015; Flege, Schirru, & MacKay, 2003; Mora & Nadeu, 2012; Tamminen, Peltola, Toivonen, Kujala, & Näätänen, 2013). Many of these studies separate bilinguals on a few dimensions with respect to age of acquisition (AoA) which still allows for some variability within these bilingual populations such as proficiency levels or language use. Understanding how bilinguals differ from each other, and how this variability plays a role in neural recruitment will allow a better appreciation and understanding of influences on neural recruitment in bilinguals.

Many studies use categorical perception to understand how bilingualism influences speech perception. Categorical Perception (CP) is a well-studied phenomenon that has shown a wealth of interesting findings, including the influence of multiple phonetic systems on speech perception(Casillas & Simonet, 2015; Hisagi, Shafer, Strange, & Sussman, 2010). These studies often show a variety of effects demonstrating how the characteristics of each language, as well as degrees of exposure and proficiency in the languages, influence the perception of L1 and L2 speech categories. Additionally, neuroimaging research focusing on bilingual speech perception also shows inconsistencies in brain areas recruited across studies. The overall objective of studies 1 and 2 is to investigate the influences of proficiency and age of acquisition among Spanish-English bilinguals on categorical perception of English vowels. Study 1 seeks to gain an understanding of how these variables influence the neural activity recruited to perceive and identify second language speech within the bilingual population. It is important to understand these differences in healthy bilinguals to provide additional background to understand clinical populations. Study 2 will address if and how brain structure is influenced by these variables. Understanding the relationship between experience and brain structure and function gives researchers a better understanding of healthy development and function in bilinguals.

Development of Speech Perception

As bilingualism increases in the world's population, it is important to understand the variability within this group and how they are related to cognitive processes. Research on how speech perception develops and how the age at which a second language is learned gives understanding to how bilinguals differ not just from monolinguals but also vary within the bilingual population.

Very young infants have universal discrimination of speech: the ability to perceive all phonemes represented throughout the world's languages, but begin to lose this ability within the first year of life with narrowing sensitivity to only phonemes that are in their native language (Werker & Hensch, 2014; Werker & Tees, 1984). Bilingual infants learn to perceive all phonemes present in their native languages and research shows they tend to experience perceptual narrowing at a later age (Maurer & Werker, 2014; Ramirez, Ramirez, Clarke, Taulu, & Kuhl, 2016; Werker & Hensch, 2014).

Research suggests that in early development, infants discriminate phonemes based on the acoustic cues present. They receive acoustic input from both perception and the exaggerated cues presented by infant directed speech as well as through their own production as infants learn to babble (Kuhl et al., 2008; Ramirez et al., 2016). Monolingual infants show a marked change in sensitivity to acoustic cues present in speech input, with increased sensitivity to native phonemes and decreased sensitivity to non-native cues (Kuhl et al., 2008; Maurer & Werker, 2014; Ramirez et al., 2016). Studies show decreased sensitivity for non-native speech occurs between 6-10 months of age but that these infants are still able to modify their speech categories with just a short period of exposure through about 10-11 months of age (Werker & Hensch, 2014). Bilingual infants show a decline in sensitivity at a later stage in development, as demonstrated by an MEG study of 11-month old Spanish-English bilingual infants who continued to process acoustic cues while monolingual infants had shifted from lower-level acoustic cue processing to phonetic level processing of speech at this age (Ramirez et al., 2016). This suggests that bilingual exposure allowed these infants to maintain the early strategies for processing non-native speech longer than monolingual infants.

In terms of neural recruitment, newborns show greater brain activity for speech than non-speech with studies showing a left-hemisphere dominance or specialization for speech within the first year (Peña et al., 2003; Perani et al., 2011; Werker & Hensch, 2014). Differences in activation between monolingual and bilinguals infants is often seen in prefrontal regions, with bilingual infants showing greater overall activation, though both groups recruit superior temporal regions for processing (Petitto et al., 2012; Ramirez et al., 2016).

Comparisons of monolingual and bilingual infants often focus on bilinguals with simultaneous acquisition of their two languages. These infant studies and adult studies support that this is the optimal time to learn a second language with minimal difference between monolingual and bilingual speakers in speech perception (Werker & Hensch, 2014). However, sequential bilingualism, or the learning of a second language after the establishment of the first, lead to differing results (Peltola, Tamminen, Toivonen, Kujala, & Näätänen, 2012).

A study comparing two groups of children found differences in neural recruitment based on current age in simultaneous bilinguals. Comparing younger (6-8 year old) and older (9-10 year old) bilinguals, researchers found that younger bilinguals recruited more lower level regions such as bilateral superior temporal gyrus (STG) compared to older bilingual children who recruited more higher order regions including inferior parietal lobule, middle temporal gyrus and middle frontal gyrus in additional to STG (Archila-Suerte, Zevin, Ramos, & Hernandez, 2013). As both groups of bilingual children were exposed to their second language at approximately 5 years of age, the difference in neural recruitment may represent changes in processing as a result of experience with their L2 with younger children relying on L1 phonemic categories to process L2 speech while older children used higher order strategies to process and discriminate between L2 speech sounds (Archila-Suerte et al., 2013). Archila-Suerte et al. (2013) results add to the literature on the effects of AoA on second language acquisition by giving evidence for changes in neural recruitment for speech acquisition outside infancy.

Adult L2 acquisition studies show clear effects of AoA on speech perception (Archila-Suerte et al., 2015; Piske, Flege, MacKay, & Meador, 2002). Most studies show that earlier acquisition is associated with L2 categories and performance on behavioral tasks that are most like native monolingual speakers. Adult acquisition models and the bilingual literature will be discussed further in the next sections.

Influence of Age of Acquisition and Second Language Proficiency

Age of acquisition also influences an individual's ability to discriminate difficult contrasts. Comparing early Spanish-English bilinguals with English monolinguals and Spanish monolinguals for discrimination of English vowels, Spanish monolinguals scored significantly lower than English monolinguals and early bilinguals (Højen & Flege, 2006). Early bilinguals performed similarly to monolingual English speakers. However, looking within the scores for early bilinguals and English monolinguals, the range for early bilinguals showed greater variability than the English monolinguals suggesting there was individual variability in perception despite similar age of acquisition(Højen & Flege, 2006). Other studies have shown similar results with early bilinguals performing most like monolinguals with later bilinguals performing worse on discrimination tasks than early bilinguals or native speaking monolinguals (Casillas & Simonet, 2015; Flege et al., 2003; Hisagi, Garrido-Nag, Datta, & Shafer, 2015; Peltola et al., 2012). Therefore, it is expected that AoA will have an influence on L2 speech processing.

Second language proficiency is another variable that has been shown to influence behavioral performance and neural recruitment. High proficiency bilinguals perform better than low proficiency bilinguals on L2 perceptual tasks (Archila-Suerte, Zevin, Bunta, & Hernandez, 2012; Borodkin & Faust, 2014; Díaz, Mitterer, Broersma, Escera, & Sebastián-Gallés, 2015; Morgan-short, Steinhauer, Sanz, & Ullman, Michael, 2012; Perani et al., 1998). Studies show that within AoA groups (late and early), proficiency varied more within the late acquisition group. Even though performance was similar on a behavioral task for early acquisition groups, neural recruitment differed based on proficiency (Perani et al., 1998). These studies suggest that AoA and L2 proficiency influence both behavioral performance and neural recruitment.

Neural Activity Supporting Speech Perception

The literature clearly shows influences of AoA and L2 proficiency on second language perception but the neuroimaging literature does not demonstrate consistent patterns across all bilinguals. Monolingual literature does provide a basis for understanding the neural substrates that support speech processing. Myers (2014) proposed a model for perception and learning of speech sound categories. The model includes both rapid and slow adapting regions that are interconnected. Slow adapting regions include the posterior superior temporal gyrus (STG) and superior temporal sulcus (STS) which are finely attuned to between category differences for native speech sounds (Myers, 2014). These areas are tuned during development and are more likely to be sensitive in early bilinguals compared to later bilinguals. The rapid adapting regions consists of middle frontal gyrus (MFG), posterior inferior frontal gyrus (IFG), specifically the opercularis region as well as left premotor and supplementary motor regions (Myers, 2014). Hickok and Poeppel (2007) also propose a model of auditory processing which includes dorsal and ventral pathways that is similar to the model proposed by Myers (2014). The dorsal pathway maps phonological representations onto sensory motor representations through the interaction of STG, IFG and parietal regions while the ventral pathway maps speech sound to meaning through STG and middle temporal gyrus (MTG) connections (Hickok & Poeppel, 2007). It would be expected that these regions would also be active in bilinguals but that they may not consistently show up when compared to monolingual groups due to the type of analyses used in neuroimaging data which only shows areas that differ between groups.

In the neuroimaging literature focused on bilingual speech perception and in particularly categorical speech perception, there are consistent differences between monolingual and bilinguals in ERP studies. Monolingual speakers show a clear automatic processing of their native language while early bilinguals show smaller responses to L2 stimulus than later bilinguals (Hisagi et al., 2015; Ortiz-Mantilla, Choudhury, Alvarez, & Benasich, 2010). ERP studies rely on the mismatch negativity (MMN) response that marks a change in neural activity in response to change in stimulus. Most studies present a series of stimuli with a stimulus that does not match. The MMN measures the neural response, if any, in processing to this change in stimulus. Within the bilingual speech perception literature, the MMN responses vary across studies with some finding greater activation in left hemisphere while others find it in right hemisphere regions specifically superior temporal gyrus (Nenonen, Shestakova, Huotilainen, & Näätänen, 2005; Shestakova et al., 2002). Other neuroimaging studies show clear patterns of processing for monolinguals but do not find a consistent pattern within bilinguals even though both groups performed similarly on behavioral tasks (Minagawa-Kawai, Mori, & Sato, 2005). The inconsistency across and within neuroimaging studies suggests that there is variability in the neural regions recruited by bilinguals. An early PET study comparing early and late high and low proficiency bilinguals showed that early bilinguals recruited greater activity when listening to stories in L1 and L2 but within AoA groups, high proficiency was associated with greater activity in bilateral STG and bilateral MTG (Perani et al., 1998). These studies suggest that for the bilingual population, AoA and L2 proficiency are related to different patterns of neural recruitment but the use of group comparisons and direct comparisons to monolinguals may obscure some of the result.

In a review of phonetic perception in bilinguals, studies of phonetic processing also see activity in STG, IFG and supplementary motor with additional studies finding activity in supramarginal and angular gyri in bilinguals for their L2 often for studies using post-lexical processing such as word or sentence reading (Golestani, 2015). The angular gyrus is also seen in several neural morphometry studies as an area impacted by bilingualism. Studies have also found increased inferior parietal lobule activation, which includes the angular and supramarginal gyri, with improved L2 performance after training for sentence reading (Barbeau et al., 2016). Other studies support these regions which frequently see activation in inferior frontal gyrus (opercularis, triangularis and orbital regions) (Archila-Suerte et al., 2013; Myers, 2014; Myers, Blumstein, Walsh, & Eliassen, 2009), middle frontal gyrus (Archila-Suerte et al., 2015, 2013; Myers, 2014), superior and middle temporal gyri (Archila-Suerte et al., 2015, 2013; Hisagi et al., 2015; Joanisse, Zevin, & McCandliss, 2007; Minagawa-Kawai et al., 2005), angular gyrus (Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015; Barbeau et al., 2016; Burgaleta, Baus, Díaz, & Sebastián-Gallés, 2014; Mechelli, Crinion, Noppeney, Frackowiak, & Price, 2004; Price, 2010; Seghier, 2012), supramarginal gyrus (Archila-Suerte et al., 2013; Barbeau et al., 2016), and putamen (Berken, Gracco, Chen, & Klein, 2015; Cherodath, Rao, Midha, T A, & Singh, 2016). These regions will be used in region of interest analyses to understand the patterns of activation associated with AoA and L2 proficiency in bilinguals.

The Current Studies

The overall goal of the current studies is to add to the body of literature on bilingual speech perception by investigating the possible effects of AoA and L2 proficiency on neural recruitment and structure. Previous literature provides some overlapping but inconsistent results for neural recruitment in bilingual speech processing. The current study will use multiple regression analyses and regions of interest to provide a clear picture of the brain regions recruited during a second language categorical perception task associated with AoA and L2 proficiency. A second study will use voxel-based morphometry to look at the relationship between AoA and L2 proficiency on neuroanatomy. These studies will provide an understanding of how AoA and L2 proficiency are related to neural recruitment and brain structure for speech processing.

CHAPTER 2

Study 1 Introduction

Research on speech perception has shown that there is variability across languages and individuals whether an individual speaks one or more languages. Understanding how this variability is dealt with is important. Speech perception requires the identification and interpretation of the perceptual space for comprehension. Perceiving speech is thought to involve categorical perception, the division of sounds into discrete categories based on relevant phonological information. This allows for quick and accurate discrimination of speech between category boundaries, e.g. " pat" to "bat", which in some cases are important for identifying separate words while being impervious to variance within a single category (Peltola et al., 2012). This task becomes more difficult for bilinguals whose languages may consist of different phoneme categories. How bilinguals handle their different speech sound inventories and how well they acquire their second language and what factors influence their final attainment has received considerable attention in the relevant literature (Best & Tyler, 2007; Flege, Schirru, & MacKay, 2003; Hisagi et al., 2015, 2010; McAllister, Flege, & Piske, 2002; Piske et al., 2002).

There is wide variability in speech perception with differences between monolingual and bilingual speakers as well as within bilingual speakers. Several studies have looked at the differences within bilingual populations by using group comparisons such as age of acquisition (AoA) in high proficiency bilinguals or first language usage within early and late bilinguals (Flege & MacKay, 2004; Flege et al., 2003). However, these comparisons do not control for the variability within these groups such as AoA or proficiency. The current study seeks to understand the influence of AoA and L2 proficiency on L2 categorical perception and the neural correlates supporting it while allowing for the differences within bilinguals.

The research on speech perception in bilinguals has shown the large amount of variability in responses as well as factors that influence final attainment. Age of Acquisition (AoA) is one of the largest factors in both behavioral and neuroimaging studies (Archila-Suerte et al., 2012, 2015; Flege & MacKay, 2004; Hisagi et al., 2015; Højen & Flege, 2006; Ortiz-Mantilla et al., 2010). These studies are consistent in the finding that bilinguals who have acquired their L2 at an early age perform closer to native speakers than later bilinguals. Other factors that influence L2 perception include proficiency and language dominance (Archila-Suerte et al., 2012, 2015; Borodkin & Faust, 2014; Díaz, Baus, Escera, Costa, & Sebastián-Gallés, 2008; Fox, Flege, & Munro, 1995; Peltola et al., 2012; Tamminen et al., 2013) as well as native language use (Flege & MacKay, 2004; Piske et al., 2002).

In addition, a bilingual's native language emphasizes the processing of acoustic cues that may interfere or assist in second language speech perception (Chládková, Escudero, & Lipski, 2013; Højen & Flege, 2006; Lipski, Escudero, & Benders, 2012; McAllister et al., 2002; Nenonen et al., 2005). Both the perceptual assimilation model (PAM) and speech learning model (SLM) predict similar relationships between L1 and L2 categories and behavioral responses in L2 learners through the formation and rigidity of L1 perceptual categories. These models suggest that L2 sounds that are most similar to native categories or can be assimilated into a single category, will be more difficult to learn (Best, 1994; Flege, Bohn, & Jang, 1997; Flege et al., 2003; Flege &

MacKay, 2004; Van Leussen & Escudero, 2015). If L2 sounds fall within separate L1 categories or are perceived as different from L1 categories, perception and final attainment will be improved (Best, 1994; Flege et al., 2003; Flege, Yeni-Komshian, & Liu, 1999; Peltola et al., 2012).

The current study uses three different phoneme categories to test how AoA and second language proficiency influences the behavioral and neural recruitment of L2 categories. Two categories, exemplified as "pen" and "pan", were manipulated with the main manipulation being duration of vowel and are expected to be more distinct than the categories centered on "pen" and "pin" which spectrally manipulates the vowels with slight durational differences. The "pen"-"pin" categories are expected to be more difficult for bilingual speakers as this category is often merged in the regional dialect of the study location (Labov, Ash, & Boberg, 2005). It is also expected that the neural recruitment for these phoneme pairings will differ with greater recruitment of language processing regions such as superior temporal gyrus and middle frontal gyrus for the pen-pan stimuli than pen-pin.

In the neuroimaging literature focused on bilingual speech perception and in particular categorical speech perception, there are consistent differences between monolingual and bilinguals in ERP studies. Monolingual speakers show a clear automatic processing of their native language while early bilinguals show smaller responses to L2 stimulus than later bilinguals (Hisagi et al., 2015; Ortiz-Mantilla et al., 2010). ERP studies rely on the mismatch negativity(MMN). The MMN measures the neural response, if any, in processing a change in stimulus. Within the bilingual speech perception literature, the MMN responses vary across studies with some finding greater activation in left hemisphere while others find it in right hemisphere regions specifically superior temporal gyrus (Nenonen et al., 2005; Shestakova et al., 2002). Other neuroimaging studies show clear patterns of processing for monolinguals but do not find a consistent pattern within bilinguals even though both groups performed similarly on behavioral tasks (Minagawa-Kawai et al., 2005). The inconsistency across and within neuroimaging studies suggests there is variability in the neural regions recruited by bilinguals. The current study will address this question by looking at AoA and L2 proficiency on neural recruitment in L2 speech perception.

The neuroimaging literature on monolingual speech perception gives clear neural regions to consider along with fMRI bilingual studies for bilingual L2 categorical perception. Combining a large number of studies on speech perception in monolingual and bilingual participants, several recent review articles have suggested brain regions that are associated with these tasks (Golestani, 2015; Myers, 2014). Myers (2014) proposed a model for perception and learning of speech sound categories. The model includes both rapid and slow adapting regions that are interconnected. Slow adapting regions include the posterior superior temporal gyrus(STG) and superior temporal sulcus(STS) which are finely attuned to between category differences for native speech sounds. These areas are tuned during development and are more likely to be sensitive in early bilinguals compared to later bilinguals. The rapid adapting regions consists of middle frontal gyrus (MFG), posterior inferior frontal gyrus (IFG), specifically the opercularis region as well as left premotor and supplementary motor regions (Myers, 2014).

In a review of phonetic perception in bilinguals, studies of phonetic processing also see activity in STG, IFG and supplementary motor with additional studies finding activity in supramarginal and angular gyri in bilinguals for their L2 often for studies using post-lexical processing such as word or sentence reading (Golestani, 2015). The angular gyrus is also seen in several neural morphometry studies as an area impacted by bilingualism. Studies have also found increased inferior parietal lobule activation, which includes the angular and supramarginal gyri, with improved L2 performance after training for sentence reading (Barbeau et al., 2016). Other studies support these regions which frequently see activation in inferior frontal gyrus (opercularis, triangularis and orbital regions) (Archila-Suerte et al., 2013; Myers, 2014; Myers et al., 2009), middle frontal gyrus (Archila-Suerte et al., 2015, 2013; Myers, 2014; Price, 2010), superior and middle temporal gyri (Archila-Suerte et al., 2015, 2013; Hisagi et al., 2015; Joanisse et al., 2007; Minagawa-Kawai et al., 2005), angular gyrus (Abutalebi et al., 2015; Barbeau et al., 2016; Burgaleta et al., 2014; Mechelli et al., 2004; Price, 2010; Seghier, 2012), supramarginal gyrus (Archila-Suerte et al., 2013; Barbeau et al., 2016), putamen (Berken et al., 2015; Cherodath et al., 2016) and caudate(Golestani & Zatorre, 2004; Price, 2010; Yi, Maddox, Mumford, & Chandrasekaran, 2016). See Figure 1 for cortical regions of interest.

For the current study, it can then be expected that bilinguals will use a variety of brain areas both those seen to support L1 processing as well as additional regions to support L2 categorical speech perception with possible bilateral recruitment or more right hemisphere recruitment for bilinguals that differ in language proficiency or language learning history.

Study 1

The current study used a two-forced-choice identification task to investigate how age of acquisition and L2 proficiency influenced behavioral and neural outcomes within Spanish-English bilinguals. Participants heard a single stimulus from either of two continua ("pen"-pan" or "pen"-"pin") after seeing images of the object representing the possible categories (pan or pen and pin or pen) and then identified which category they heard. Regression analyses were used to determine if and how AoA and L2 proficiency influenced performance and neural recruitment during these tasks. The following results were expected based on previous literature.

1. Age of Acquisition will be a significant predictor of behavioral performance with earlier AoA associated with steeper slopes and greater distance between category responses showing clearer more distinct categories.
2. As the two stimuli sets differ in their relationship to L1, it is expected that participants will show different patterns behaviorally and neurologically.
    a. It is expected that AoA and L2 proficiency will be predictors for behavioral results for pen-pan stimuli with early AoA and increased L2 proficiency improving category distinctions. AoA, on the other hand, would be the only predictor of pen-pin due to the amount of exposure needed to create a new category outside of their L1 category.
    b. It is expected that the amount of activation will be different with pen-pan categories recruiting more regions as it is a more easily perceived contrast and therefore, more likely to show effects of AoA and L2 proficiency across participants while pen-pin will show fewer differences

in analyses based on AoA and L2 proficiency.

3. For neuroimaging data, both AoA and L2 proficiency will recruit different regions.
    a. Early AoA will be associated with activity in left IFG and MFG indicating better discrimination through early exposure and development of categories as well as increased STG activity as it is tuned earlier and is slower to adapt (Alho et al., 2016; Myers, 2014; Myers et al., 2009; Shestakova et al., 2002). Right hemisphere activity is also possible as several studies have found that bilinguals may recruit right hemisphere regions for their second language (Golestani, 2015; Hernandez, 2009; Wei et al., 2015)
    b. Bilinguals with increased L2 proficiency will show greater recruitment of different areas of activation than those associated with AoA. It is expected that proficiency will be associated with activity in higher order areas such as those associated with memory, attention and semantic processing including frontal regions (IFG orbitalis) and angular gyrus (Burgaleta et al., 2014; Price, 2010; Seghier, 2012). Increased proficiency may lead participants to use a separate strategy for identifying the stimulus than processing only auditory cues, possibly recruiting motor commands or semantic information (Golestani, 2015).

Method

Participants

Twenty-four Spanish-English bilinguals (16 females, M_{Age}=24.04, SD=5.96) participated in the study. One participant was excluded from analyses investigating proficiency, as their scores were not recorded. None of the participants reported having language, speech or hearing disorders or taking psychoactive medication.

Participants acquired English on average at the age of 8.48 years (SD=5.53 years). Average proficiency scores for English and Spanish were 68.34 (SD= 8.26) and 70.44 (SD=10.03) out of 100 on the Woodcock-Muñoz language proficiency battery – Revised. To understand the relationship between AoA and proficiency in the bilingual population that participated in the study, several correlations were conducted investigating AoA, English proficiency, Spanish proficiency, and socio-economic status (SES). Pearson correlations were conducted with significance set to $p<.01$ (2-tailed). Significant correlation was found for AoA and Spanish proficiency (r=.697, p= 0.000) but was not significant for AoA and English proficiency. A lack of significant correlation between AoA and English proficiency suggests that when participants started learning English did not affect their proficiency. This may be due to a high level of proficiency obtained to attend an English-speaking university. There was no significant difference nor correlation between English and Spanish proficiency (t=0.38, r=.341). There were no correlations between SES and any other variable.

Behavioral Measures

Language history questionnaire*.* This online survey collected demographic, medical, academic, socioeconomic, and linguistic background information. Variables such as length of residency in the United States, age of acquisition, and amount of second language input were additionally collected for all participants.

Woodcock-Muñoz language proficiency battery – Revised (WLPB-R). This series of tests evaluates various linguistic skills in English and Spanish In order to assess overall expressive and receptive abilities in both languages, the tests of *picture vocabulary*, *verbal analogies* and *passage comprehension* were selected. Participants provided the label of different objects, animals, and professions for the picture vocabulary test and verbal analogies and filled in the blank to complete sentences for the listening comprehension test. Items in the tests gradually increased their level of difficulty, thereby resulting in higher scores for participants who answered more challenging items

Stimuli. Spanish has five vowels /i e a o u/ which occur in both stressed and unstressed syllables. American English phoneme inventories generally consist of eleven stressed vowel phonemes (/i, ɪ, e, ɛ, æ, ɑ, ɔ, o, ʊ, u, ʌ/), which utilize both durational (length of vowel) and spectral (frequency) cues for successful perception(Boomershine, 2013; Bradlow, 1995). The study used minimal pairs from American English with the vowel contrasts: /ɪ/ to/ɛ/ "pin"- "pen" and /ɛ/ to /æ/ "pen"-"pan". These contrasts were selected since they are specific to English phonemic contrasts. The frequency rank and frequency of the category stimuli, according to the Corpus of Contemporary American English, are as follows: pan (rank: 2501, frequency: 14148), pen (rank: 3618, frequency: 8117) and pin (rank: 4394, frequency: 6000) (Davies, 2008). An additional note about the stimuli, the study takes place in the American South linguistic region. The /ɪ/–/ɛ/ ["pin-pen"] categories are not always distinguished in the Texas dialect of

American English. This region is known for “merging” /I/ and /ɛ/ before nasal consonants as in the current stimuli “pin” and “pen” (Labov et al., 2005).

To create the stimuli a male native English speaker from the Northern region produced several instances of the words. Praat software (Boersma and Weenink, 2012) was used to create two 7-step re-synthesized vowel continua, one for each minimal pair (/ɪ/–/ɛ/ [*pin-pen*], and /ɛ/-/æ/ [*pen-pan*]). Each stimulus was then edited to eliminate background noise. Each stimulus was presented in isolation.

Procedure

Participants completed the study in two sessions. The first session consisted of completing several questionnaires to obtain information regarding language history, SES, handedness and claustrophobia. Language history questionnaires collected demographic, medical, academic, socioeconomic, and linguistic background information. Variables such as length of residency in the United States, age of acquisition, and amount of second language input were additionally collected for bilingual participants (Ravichandran, Archila-Suerte, & Hernandez, 2011).

Participants also completed three portions of the Woodcock-Muñoz Language Survey: Picture Vocabulary, Verbal Analogies and Passage Comprehension in both English and Spanish.

In the second session, participants completed an alternative forced choice task while undergoing fMRI scanning. Participants were placed in the MRI machine were given MRI compatible headphones and two-button response boxes, one for each hand. The anatomical and localizer sequences were run before the start of the task. The experiment was run on NEMO (Network Experiment Management Objects) an in-house presentation software that was compatible with fMRI data collection. Participants completed 5 runs of the task comprised of 143 trials with 56 test trials per run. Participants were allowed to rest between runs. For each trial, participants were first presented with two images representing the two categories (pen, pin or pan), which were presented side by side. Participants then heard the speech stimulus and selected which word they heard by using the handheld button box on the same side as the image representing the category. Test trials were randomly presented with rest trials presenting a fixation cross in the middle of the screen. Upon completion of the fifth and final run, participants were thanked for their participation and received either $50 or extra credit for compensation.

Neuroimaging Data Acquisition

Whole-brain MRI acquisition. High spatial resolution 3D T1-weighted images were acquired with a 3-Tesla magnetom TIM Trio scanner (Siemens AG, Germany) and a 12-channel head coil. A Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence was implemented (TR= 1.2s, TE= 2.66 ms, 256 X 224 matrix, 1 mm^3 isotropic voxel size). Anatomical scans lasted approximately 5 minutes.

fMRI Acquisition parameters. Whole-brain scans were performed with a 3.0 Tesla Magnetom Trio (Siemens, Germany) at the Core for Advanced Magnetic Resonance Imaging at Baylor College of Medicine in Houston, Texas. A total of 542 functional (T2*-weighted) images were acquired using a clustered volume acquisition (CVA) paradigm to quiet the scanner while the auditory stimuli were presented. An interleaved descending Echo Planar Imaging (EPI) sequence was employed with the following parameters: repetition time (TR)=3 s, TR delay (silent interval)=1.42 s, volume acquisition time (TA)=1.58 s, transversal slices per volume=26, TE=30 ms; 5 mm thickness, 3.4×3.4×5.0 mm resolution, flip angle=90°, with the centermost slice aligned with the anterior commissure and posterior cingulate (AC-PC). High-resolution anatomical images used a T1-weighted Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (TR=1.2 s, TE=2.66 ms, 1 mm^3 isotropic voxel size) reconstructed into 192 slices. Auditory stimuli were presented using the in-house software NEMO (Network Experiment Management Objects).

Neuroimaging Data Analyses

Whole-brain analyses were conducted with SPM12 (Wellcome Trust Center for Neuroimaging, London) using an event related design specification for our statistical model. Functional images were slice-time corrected, motion corrected, aligned to anatomical scans, and normalized to MNI stereotaxic space. Spatial smoothing was applied using an 8 mm full-width half maximum Gaussian Kernel. Participant data were further inspected for motion with the Artifact Detection toolbox (Whitfield-Gabrielli, 2010). Participant brain scans that exceeded 1 mm of linear movement and 0.5° of angular movement were dropped from analyses. Less than 1% of scans were excluded.

Each participant's preprocessed files were modeled at the individual level for two sound conditions ("pen"-"pan" continuum and "pen"-"pin" continuum) against rest. Event-Related design was modeled with event being model at the onset of the stimulus. At the group level, the "pen"-"pan" condition was entered into a multiple regression analysis with AoA and English proficiency entered as covariates. Region of Interest analyses were conducted by creating anatomical masks in WFU pickatlas (Maldjian, Laurienti, Kraft, & Burdette, 2003) for eight regions bilaterally: IFG, MFG, STG, MTG, angular gyrus, supramarginal gyrus, caudate and putamen resulting in 16 individual ROIs. These masks were then applied to the group-level activation maps.

Behavioral Data Analysis

Variables of interest included slope and difference in responses to the extreme stimuli. Both measures indicate how clearly or categorically the participants perceive the stimuli. Slope was calculated using linear regression as logistic regression was not appropriate for several participants whose responses cross the 50% response rate multiple times(Minagawa-Kawai et al., 2005). Category difference was calculated by averaging the response for the two stimuli on the extreme ends of continua (Mora & Nadeu, 2012). These stimuli were rated as unambiguous or clear category members by monolingual English speakers.

Results

Neuroimaging Results

Region of Interest analysie are reported for each location for p<.001 uncorrected with voxel threshold of k>20. All locations are reported using MNI coordinates.

Pen-pan contrast. For "pen"-"pan" stimuli, increased English proficiency was associated with activation in the following regions of the bilateral IFG pars orbitalis (left: k=22, T= 3.96, (-44, 32, -2), right: k=107, T=5.26, (48, 30, -6)) and MFG (left: k=26, T=3.97 (-20, 30, 38), right:k-67, T=4.53, (26, 22, 38)) . Increased English proficiency was also associated with the following right hemisphere activity: STG (k=29, T=3.54, (58, -10, 10)), MTG (k=71, T=4.49 (64, -40, 4)), and angular gyrus (k=21, T=4.10 (52, -56, 30)) See figure 2.

Early AoA was also associated with increased activity in right MFG (k=23, T=4.12, (32, 36, 42)) but this area did not overlap with the MFG cluster associated with increased English proficiency (See figure 3).

Pen-pin. Increased English proficiency was associated with increased activity in left IFG an area extending into triangular and orbital regions (k=124, T=5.86 (-48, 28, -2)). Early AoA was associated with activity in right STG (k=30, T=4.37, (44, -10, -6)) and right angular gyrus (k=21, T=4.28 (32, -58, 48)). See figure 4.

Behavioral results

Due to the possibility of training effects and the lack of a pre-fMRI perceptual test, the responses from the first run only were included in the regression analyses. Multiple regression analyses were conducted to determine if age of acquisition and L2 proficiency predicted slope and category differences for “pen”-“pan” and “pen”-“pin” continua.

Pen-pan behavioral results. Using multiple regression for pen-pan variables of interest, it was found that AoA and L2 proficiency explain a significant amount of the variance in slope (F(2, 20) = 5.268, p =0.014, R^2 = .345, $R^2_{Adjusted}$ = .279). The analysis shows that L2 proficiency did not significantly predict slope (Beta = 0.248, t(21) = -1.37, n.s), however, AoA did (Beta = -0.545, t(21) = 3.01, p =0.007)

For categorical differences of pen-pan, it was found that AoA and L2 proficiency explain a significant amount of variance (F(2,20)=5.472, p=0.012, R^2 = 0.353, $R^2_{Adjusted}$ = .289 Again, L2 proficiency did not significantly predict category differences (Beta = 0.129, t(21) =0.717, n.s.), but AoA did (Beta = 0.587, t(21) =-3.263, p=0.0039).

Pen-pin behavioral results. For pen-pin variables, the model did explain a significantly amount of the variance in slope ($F(2, 20) = 5.181$, $p = 0.015$, $R^2 = .341$, $R^2_{Adjusted} = .275$). AoA did predict slope (Beta=-0.572, $t(21)=-3.147$, $p=0.005$) while L2 proficiency was not significant (Beta=0.153, $t(21)=0.842$, $p=0.410$). For category difference, the model approached explaining a significant amount of the variance ($F(2,20)=3.242$, $p=0.060$, $R^2 = .245$, $R^2_{Adjusted} = .169$). AoA was a significant predictor (Beta=-0.484, $t(21)=-2.49$, $p=0.022$) while L2 proficiency was not significant (Beta=0.129,$t(21)=0.663$, $p=0.515$).

Comparisons were made using paired two-sample t-tests between first run responses and responses in all runs to check for possible change in individual responses across time. Results for run1 to all run comparisons led to the following findings. For "pen"-"pan" stimuli, significant differences were found for slope ($t(21)=-5.20$, $p<.001$) but not for category differences ($t(21)=1.14$, p=n.s.). For "pen"-"pin" stimuli, there were significant differences for first run responses compared to all responses for slope $t(21)= 3.34$, $p=0.001$) and CD ($t(21)=-11.13$, $p<.001$). Furthermore, changes in behavioral categorical perception across runs was not predicted by language proficiency or language history.

Discussion

Participants completed a two-forced-choice identification task for L2 phonemes that were manipulated for either length or frequency of vowel. In acquiring the L2 test stimuli, one continuum (pen-pan) required participants to extend the boundaries of their L1 categories while the second (pen-pin) presented a more difficult challenge as the contrast is not always present in the environment (Labov et al., 2005). The results show that the two continua did elicit differing activation patterns supporting the notion that different types of phonological processing and acquisition are needed for each type. The difference between categories may have also risen from the fact that one of the pairs (pen-pin) is frequently merged in the regional dialect (Labov et al., 2005). For all behavioral data, the significant model included AoA and L2 proficiency to explain a significant proportion of the variance while AoA was the only significant predictor. Altogether, the results followed a similar pattern to previous studies in which behavioral responses and neuroimaging data do not reflect the same influences (Hisagi et al., 2015; Minagawa-Kawai et al., 2005).

Pen-pan

For "pen"-"pan", L2 proficiency showed a large effect with bilateral activation in IFG and MFG for increased proficiency. These regions have been associated with differentiation of phonemes as well as compensatory "up-regulation" for speech perception (Du, Buchsbaum, Grady, & Alain, 2016; Myers, 2014; Myers et al., 2009). As participants may have adapted their L1 categories to perceive the "pen"-"pan" L2 contrasts, the use of up-regulation mechanisms from frontal regions help to create finer distinctions between these categories. Input from IFG and MFG into posterior regions help to improve their perception in the slower to adapt regions of STG (Myers, 2014).

In addition, the "pen"-"pan" continuum led to recruitment of right STG for participants with increased proficiency. These individuals may be more sensitive to categories in early levels of processing and may be influenced by how closely the stimuli fit in to categories as seen in previous studies (Myers, 2014). When combining this with recruitment of more posterior regions including angular gyrus, the data suggest these participants may be trying to break from their habitual L1 categories through multiple mechanisms. Superior parietal and inferior parietal regions are associated with selective attention and suggest that L2 proficiency may reflect a participant's ability to focus on the necessary phonemic distinctions to categorize speech (Archila-suerte et al., 2015). Participants may be using attention mechanisms to focus on the necessary speech contrasts while recruiting both low level processing regions along with up-regulation through frontal regions to select the correct category for each stimulus. An additional explanation involves the possible connections between angular gyrus with IFG orbital regions and middle temporal gyrus for semantic processing (Price, 2010; Seghier, 2012). As this is associated with increased L2 proficiency, it suggests that with increased proficiency comes possible different neural strategies to classify the phoneme into the correct category using all information available as well as using increased attentional mechanisms to aid this processing.

AoA played an independent role in perceiving and processing the pen-pan contrast, it appears that for this specific contrast, earlier acquisition leads to improved sensitivity difference in speech sound which was reflected in the behavioral results with increased difference between categories. Bilateral MFG is associated with increased sensitivity to learned speech contrasts independent from sensitivity in STG (Myers et al., 2009).

Pen-pin

For "pen"-"pin" which was a less frequent contrast in the dialect, neuroimaging results showed an influence of proficiency and AoA. The behavioral results did reveal significant effect of AoA on slope and category difference when L2 proficiency was included in the models. These results suggest that even though this is contrast is not very prevalent in the environment, earlier exposure to English leads to better performance on this contrast possibly due to accumulation of experience across time.

Similar to pen-pan, increased L2 proficiency was associated with activity in left IFG, as previously mentioned, this region has been implicated in up-regulation or compensatory mechanism for speech processing (Du et al., 2016). This suggests that for this low frequency contrast, additional information from frontal regions was necessary to complete the task. The fact that this region was once again associated with increased L2 proficiency suggests that successful L2 acquisition requires the use of top-down mechanisms. The influence of AoA was seen in younger bilinguals with activity in right STG right and angular gyrus. This suggests that for younger bilinguals, attentional mechanisms are used to selectively attend to low-level auditory information that aid in distinguishing and identifying the correct category (Myers, 2014).

Neuroimaging from both contrasts suggest individuals with increased L2 proficiency use a network of regions to attend to and identify speech stimuli. Using multiple regions (MFG and STG) that are sensitive to differences in speech categories, along with attentional mechanisms or possibly higher level processing such as semantic information through the angular gyrus (AG), these individuals may obtain improved speech perception which may have led to their higher L2 proficiency scores. This is in contrast to previous studies which have established the role of AoA with improved perception for L2 speech (Archila-Suerte et al., 2012, 2015; Casillas & Simonet, 2015). The current study further supports this while adding to the possible mechanisms used by early bilinguals to improve their perception through the recruitment of frontal regions that show sensitivity to differences in speech categories.

Study 1 focuses on only two variables that influence L2 speech perception. Future studies may want to include additional factors such as language use in analyses. This would require large numbers of participants to be recruited but would allow for additional variables to be included in both neuroimaging analyses as well as more complicated behavioral analyses with multiple variables and time points considered. Additionally, due to the low frequency of occurence of “pen”- “pin” in the regional dialect cross-language differences were not investigated. Future studies using other dialectical variations of English would help to replicate and expand upon the current results.

Conclusion

Study 1 gives a unique contribution to the literature as it looks within bilinguals for factors that influence L2 speech perception. This provides a clear picture in the differences and variability within the bilingual population demonstrating through neuroimaging the influences of both AoA and L2 proficiency on L2 speech perception. Future studies should further investigate if the neural patterns during speech perception in early stages of L2 learning change or how they influence final L2 proficiency attainment.

CHAPTER 3

Study 2 Introduction

In addition to understanding how age of acquisition (AoA) and second language (L2) proficiency influence behavioral and neural responses for L2 category speech perception, it is of interest to see if these variables influence brain structure.

Several neuroanatomical studies have investigated the influence of bilingualism on the structure of the inferior parietal lobule through measurements of age of acquisition, L2 proficiency and L2 exposure (Abutalebi et al., 2015; Mechelli et al., 2004; Wei et al., 2015). Compared to monolinguals, bilinguals show greater grey matter density in the bilateral inferior parietal cortex with significant regions found in the left hemisphere (Mechelli et al., 2004). AoA of L2 was negatively correlated with grey matter density while L2 proficiency was positively correlated with grey matter density in this region (Mechelli et al., 2004). However, a study with older bilinguals did not find that AoA predicted grey-matter density but that L2 proficiency and L2 use did influence structure; grey matter density in the left hemisphere was more influenced by L2 proficiency and grey matter density in the right hemisphere was more influenced by L2 use (Abutalebi et al., 2015).

Additional support for AoA effects on brain structure is provided by a study that investigated AoA, L2 proficiency and L2 use.(Wei et al., 2015) Their results found that in bilinguals, the right AG and right superior parietal lobule were most influenced by AoA while the right inferior frontal gyrus opercular region was related to AoA, L2 proficiency and L2 use. Earlier AoA was associated with larger volume for right AG and right superior parietal lobule. The authors suggest that the influence of AoA on right AG is due to the additional resources needed to process or switch between two languages during development. It has also been proposed that bilateral parietal regions are part of networks active for conflict resolution as well as shifting attention, which would be greater in bilinguals (Wei et al., 2015). Therefore, study 2 looked to replicate findings showing the influence of AoA, L2 proficiency and L2 use on inferior parietal regions.

Additionally, study 2 examined the possible influence of AoA and L2 proficiency on the structure of regions associated with L2 speech processing. These regions include inferior frontal gyrus (IFG), middle frontal gyrus (MFG), superior temporal gyrus (STG) as well as inferior parietal regions.

Studies have found a positive relationship between STG thickness and AoA (Chee, Zheng, Goh, Park, & Sutton, 2012; Wei et al., 2015). The opposite relationship was found between STG and angular gyrus measures and performance on a speech discrimination task (Burgaleta et al., 2014). A selective review of structural studies investigating bilinguals found that left inferior parietal cortices and left IFG were consistently influenced by bilingual status. Inferior parietal regions were negatively correlated with AoA while left IFG positively correlated with L2 proficiency (Stein, Winkler, Kaiser, & Dierks, 2014). Middle frontal gyrus thickness was positively correlated with L2 proficiency (Mårtensson et al., 2012). These studies provide support for investigating the influence of AoA, L2 proficiency and L2 use on these structural regions in bilinguals. The current study will look at the relationships between AoA, L2 proficiency and L2 use on grey-matter volume

Study 2

Study 2 collected structural as well as functional brain images of participants while they completed the two-forced-choice identification task for L2 speech in study 1. Regression analyses were used to determine the influence of AoA, L2 proficiency and L2 use on structural morphometry.

Hypothesis 1. It was expected that AoA and L2 proficiency would influence structural measures with AoA being negatively correlated with angular gyrus measures and positively correlated with STG measures. This means that we expected smaller angular gyrus grey-matter measures with increased AoA. Based on previous studies, L2 proficiency was expected to be positively correlated with grey matter volume in angular gyrus.

Hypothesis 2. It was expected that inferior frontal gyrus and middle frontal gyrus would be positively correlated with L2 proficiency, meaning they would be larger with increased proficiency as previously found (Mårtensson et al., 2012; Stein et al., 2014).

The results will provide us a better understanding of how AoA, L2 proficiency and L2 use influence brain structures associated with speech perception.

Method

Participants

The same participants from study 1 were used in study 2.

Stimuli

The same stimuli were used from study 1.

Procedure

The task procedure was the same as study 1. Imaging analyses were different and are described below.

Whole-brain MRI acquisition. High spatial resolution 3D T1-weighted images were acquired with a 3-Tesla magnetom TIM Trio scanner (Siemens AG, Germany) and a 12-channel head coil. A Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence was implemented (TR= 1.2s, TE= 2.66 ms, 256 X 224 matrix, 1 mm^3 isotropic voxel size). Anatomical scans lasted approximately 5 minutes.

Cortical parcellation and subcortical segmentation. FreeSurfer 5.3.0 software (http://surfer.nmr. mgh.harvard.edu/, Center for Biomedical Imaging, Charlestown, MA) was used to measure cortical thickness, cortical surface area, and subcortical volume. FreeSurfer automated processing stream corrects for motion and strips the skull of each T1-weighted image using a hybrid watershed/surface deformation procedure (Ségonne et al., 2004), transforms images into Talairach space, and segments cortical and subcortical tissue into cerebrospinal fluid (CSF), grey matter/subcortical nuclei, and white matter based on intensity gradients. During subcortical processing and segmentation, FreeSurfer yields an automatic labeling of subcortical structures. The cortex is displayed as a surface model with a mesh of triangles (i.e., vertices). After reconstruction, deformable procedures such as surface inflation are smoothed with a full-width-half-maximum Gaussian kernel of 30 mm and averaged across participants using a non-rigid high-dimensional spherical averaging method to align cortical folding patterns (Fischl & Dale, 2000; Fischl, Sereno, Tootell, & Dale, 1999). This is followed by the parcellation of the cerebral cortex into respective gyral and sulcal structure (Desikan et al., 2006; Fischl et al., 2004), along with the generation of curvature and sulcal maps. Intensity and continuity information is used from the entire 3D MR volume in segmentation and deformation procedures to produce representations of cortical thickness, calculated as the closest distance from the grey/white matter boundary to the grey/CSF boundary at each vertex on the tessellated surface (Fischl & Dale, 2000).

After automatic reconstruction of MR images, participants' brain images were visually checked in 2D using Freeview 1.0. Each of the volume's slices was scrolled through on the coronal, sagittal, and horizontal planes to ensure correct surface extraction and labeling of the white matter, pial surface, and subcortical regions. In case of defective labels, images were manually corrected and examined after a second reconstruction.

Regions of interest were extracted from FreeSurfer 2.0 Qdec and exported in to Excel. Volume, surface area and thickness measures were selected for the following regions: bilateral middle frontal gyrus, bilateral inferior frontal gyrus (orbital, triangularis and opercularis), superior temporal gyrus and sulcus (transverse, temporal, polar, and lateral), bilateral middle temporal gyrus, bilateral angular gyrus and supermarginal gyrus and bilateral caudate and putamen. The volume measures of each ROI were adjusted for total intracranial volume to account for head size. The adjustment was performed following a linear regression method (Buckner et al., 2004; Chee et al., 2012; Wei et al., 2015).

Structural Data Analyses. Regression analyses were performed in R CORE software (Team, 2013). Regression analyses were conducted for each measure using AoA, English Proficiency and English use as predictors. We performed multiple comparison corrections with a false discovery rate (FDR) of 0.05. Only models that were significant at $p<.05$ FDR are reported.

Results

Structural results

Four regions of interest survived FDR correction for multiple comparisons. In the left hemisphere, the model including AoA, L2 proficiency and L2 use explained a significant portion of the variance for middle temporal gyrus surface area ($R^2=0.499$, $F(3,20)=6.645$, $p=0.003$), MTG volume ($R^2=0.434$, $F(3,20)=5.12$, $p=0.006$) as well as supramarginal gyrus thickness ($R^2=0.427$, $F(3,20)=5.176$, $p=0.008$). For MTG area, only L2 proficiency was a significant predictor (Beta=0.552, p=0.001), while L2 proficiency(Beta=0.503, p=0.016). and AoA (Beta=0.409, p=0.028) significantly predicted L MTG volume. Supramarginal gyrus was predicted by L2 proficiency (Beta= -0.632, p=0.002) and L2 use (Beta= 0.428, p=0.039). In the right hemisphere, the model was significant for the angular gyrus thickness ($R^2=0.479$, $F(3,20)=6.119$, $p=0.004$). Right angular gyrus thickness was predicted by L2 proficiency (Beta=-0.508, p=0.006), L2 use (Beta=0.626, p=0.003) and AoA (Beta=0.504, p=0.012).

Discussion

Following up previous studies on the effects of AoA on brain structure in bilinguals, we looked at not only the structure of brain regions but the relationship between structure and neural activity associated with speech perception. We hypothesized that AoA and L2 proficiency would contribute to models explaining right angular gyrus as well as STG. It was also hypothesized that IFG and MFG measures would be positively correlated with L2 proficiency. Our model explained right angular gyrus thickness, but only L2 proficiency was a significant predictor. L2 proficiency was negatively correlated with AG thickness, meaning increased L2 proficiency was correlated with smaller AG thickness. This relationship differs from previous studies that found L2 proficiency was positively correlated with angular gyrus thickness (Wei et al., 2015). Left supramarginal gyrus thickness also showed the same relationship: thickness in this region was negatively correlated with L2 proficiency but was positively correlated with L2 use. The differences between the current results and previous studies may come from the type of analyses conducted. Previous studies used correlation analyses while the current study used multiple regression to control for the possible overlapping influence of variables.

Unexpectedly, left middle temporal gyrus surface area and volume were predicted by the regression models, though these regions were not discussed in previous neuroanatomical studies. Left MTG surface area was predicted by L2 proficiency; increased L2 proficiency was correlated with larger surface area. Left MTG volume was also positively associated with L2 proficiency as well as AoA. MTG has also been associated with both high-level linguistic processing as well as lower-level speech processing including being more sensitive to between-category differences (Joanisse et al., 2007; Liebenthal, Binder, Spitzer, Possing, & Medler, 2005; Poeppel et al., 2004).

L2 use did not predict any region of interest but was necessary for regression models to be significant. L2 use was included because several studies found it predicted structural outcomes and a study on older bilinguals found that L2 was a greater predictor of structure than AoA (Abutalebi et al., 2015). These results suggest that there are multiple variables that influence brain structure and that each factor does help explain the variability amongst bilinguals. Differences seen between studies may be due to the failure to account for correlations among their variables or maybe explained by differences in languages.

As the current study had a relatively low number of participants, future studies should examine larger data sets that include bilinguals whose first and second language differ in terms of relationships such as closeness in phonemic categories as these appear to also influence neuroanatomical changes (Abutalebi et al., 2015). It has been suggested that along with AoA, L2 proficiency and L2 use, language context and amount of time spent switching may also influence neuroanatomical differences within bilinguals (de Bruin & Della Sala, 2015).

Conclusion

The current study sought to replicate the relationship between AoA and L2 proficiency with brain structure, specifically in angular gyrus and other inferior parietal regions. The study did provide this evidence though the relationship did not necessarily match that of previous studies, which may be due to differences in methodology.

Chapter 4

General Discussion

The objective of the current studies was to understand how variability within bilinguals influences neural recruitment and brain structure associated with speech perception. Previous studies have shown the influence of several variables but with inconsistent results in terms of neural recruitment in bilinguals. The current studies contribute to the body of knowledge on bilinguals, which demonstrates that variability within bilinguals does in fact influence neural recruitment. With the use of regression analysis, we were able to tease apart the roles of age of acquisition and L2 proficiency on neural recruitment for an L2 speech identification task. The structural studies also showed that both AoA and L2 proficiency influence brain structure, most likely through maturational mechanisms and plasticity due to learning. Previous studies have used group comparisons or correlation analyses that did not control for the possible interaction of variables within the bilingual population which the current studies have addressed.

Experiment 1 found that both AoA and L2 proficiency influence neural recruitment but do so differentially, which may explain the variance seen in previous literature (Golestani, 2015; Myers, 2014). A few of the major findings include the recruitment of right hemisphere regions associated with both early AoA and increased proficiency in bilinguals. However, these variables were related to different regions that may not have been seen if multiple regression was not used. Early AoA was associated with improved behavioral performance and was associated with right middle frontal gyrus, superior temporal gyrus and angular gyrus activity. These results suggest that when L2 proficiency is controlled for, early AoA is associated with the recruitment of additional regions (beyond traditional left hemisphere regions) that leads to improved performance on behavioral perception tasks. While L2 proficiency was not a significant predictor of behavioral performance, it was necessary for the regression model to be significant. When looking at neural recruitment, there were several regions of interest that saw greater activation associated with increased L2 proficiency. These regions included bilateral IFG and MFG, right STG, right MTG and right angular gyrus. The increased activation in these regions, after controlling for AoA, suggests that L2 proficiency leads to use of different strategies for a perceptual identification task other than those associated with AoA.

Myers (2014) suggests that IFG and STG are sensitive to category-level differences between speech and that STG is established early on in development and is slow to adapt, while IFG and MFG regions are part of a rapidly adapting network. IFG orbital regions, MTG and angular gyrus are suggested to be part of a network for semantic processing (Price, 2010; Seghier, 2012). The finding of two types of processing, lower- and higher-level represented by AoA and L2 proficiency, actually mirrors results from a study on speech processing in older and younger children in which younger children recruited lower- level processing regions (STG) while older children recruited higher- level processing regions (MTG and parietal regions) (Archila-Suerte et al., 2013). Combining the results from experiment 1 and the child study, we posit that L2 processing may at first utilize low-level processing and shift to higher-order processing with increased L2 proficiency.

Combining the results from both experiments, the results show that neural recruitment and neuroanatomy are influenced by AoA, L2 proficiency and L2 use. Middle temporal gyrus and angular gyrus were significant regions in both functional and structural studies although the MTG was left lateralized while angular gyrus was significant in the right hemisphere in both studies. MTG area and volume were predicted by L2 proficiency and activity in right MTG was associated with increased L2 proficiency. The MTG has been found for higher-level linguistic processing including semantic processing which may related to L2 proficiency(Golestani, 2015; Liebenthal et al., 2005; Price, 2010; Seghier, 2012). The relationship between MTG changes and development of L2 proficiency should be further investigated.

The right angular gyrus has been consistently seen in studies of bilinguals. Angular gyrus has also been consistently seen in studies of neuroanatomy in bilinguals being related to AoA and L2 proficiency.   It has been suggested to play a role in several cognitive functions including attention as well as semantic processing (Seghier, 2012). These results further suggest that MTG and AG are further influenced by the bilingual experience. Longitudinal studies would provide useful insight into the development of these regions.

Limitations

The current study provides insight into how variability within bilinguals influences both neural recruitment and neuroanatomy in bilinguals. The results also provided another possible variable, which is that grey-matter volume may also influence neural activity seen in speech perception studies. The current studies were not able to include all possible variables to understand how they influence neural recruitment and possibly interact due to a small number of participants. Through multiple comparison corrections and region of interest analyses, the current study addressed its objectives with a limited number of variables. Future studies will want to recruit a larger number of participants to fully understand the relationship between additional variables and how they influence the bilingual brain.

Conclusion

The current studies provided insight into the influences of AoA and L2 proficiency on neural recruitment within the bilingual population. Previous studies have used group comparisons to investigate these influences, which may not have provided a clear picture due to variability within the bilingual participants. Multiple regression analyses showed that AoA and L2 proficiency influenced neural recruitment in bilinguals for an L2 perception task. This showed that early AoA was associated with lower-level strategies seen through activation in areas sensitive to phonemic discrimination, while increased L2 proficiency was associated with higher-level processing seen in as activation in areas associated with semantic processing .

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Figure 1. Regions of Interest. Regions of interest based on previous literature including inferior frontal gyrus, middle frontal gyrus, superior temporal gyrus, middle temporal gyrus, angular gyrus and Supramarginal gyrus.

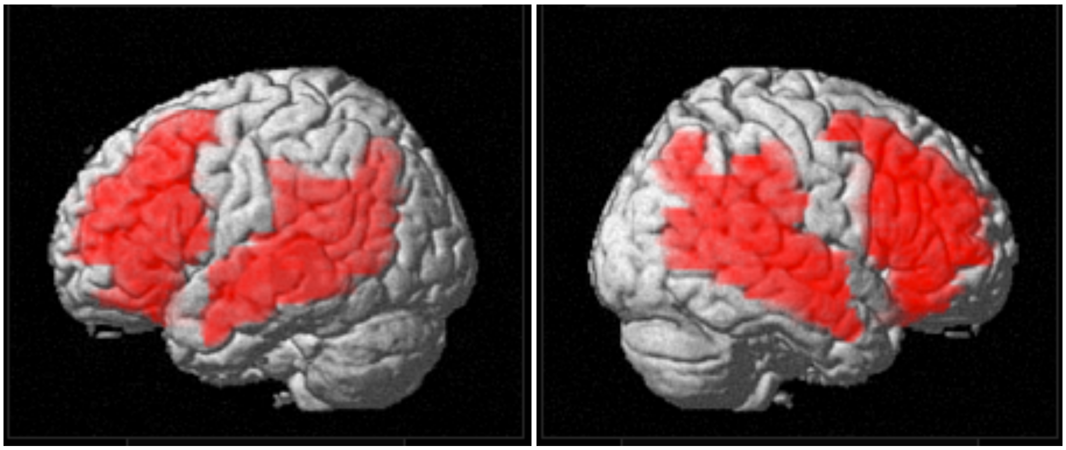

Figure 2. Pan-Pen Increased Proficiency Results. Neural activity associated with increased L2 proficiency including bilateral IFG pars orbitalis (left: k=22, T= 3.96, (-44, 32, -2), right: k=107, T=5.26, (48, 30, -6)) and MFG (left: k=26, T=3.97 (-20, 30, 38), right:k-67, T=4.53, (26, 22, 38)) .Increased English proficiency was also associated with the following right hemisphere activity: STG (k=29, T=3.54, (58, -10, 10)), MTG (k=71, T=4.49 (64, -40, 4)), and angular gyrus (k=21, T=4.10 (52, -56, 30))

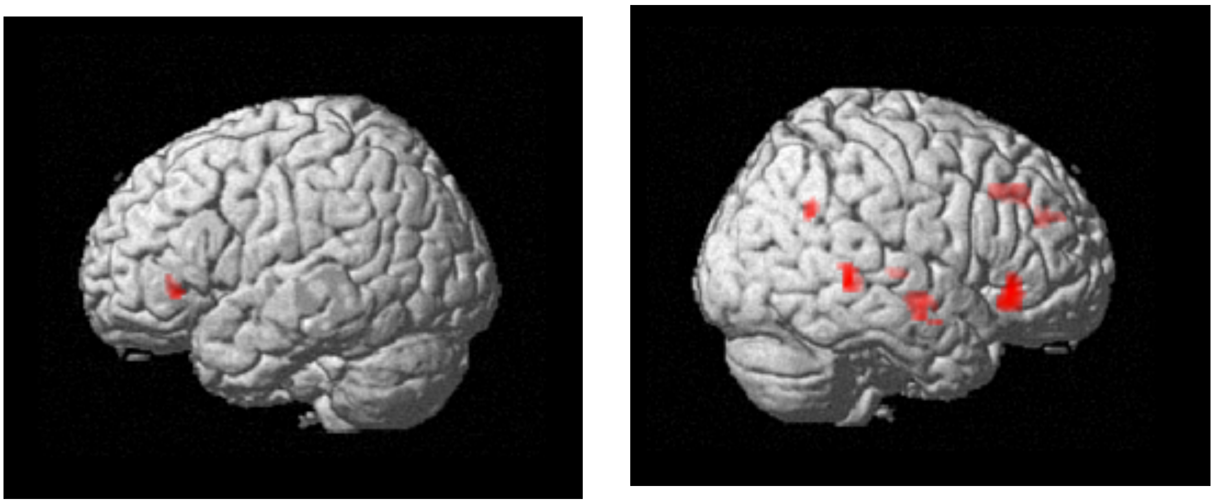

Figure 3. Pan-pen Early AoA Results. Early AoA was also associated with increased activity in right MFG (k=23, T=4.12, (32, 36, 42)).

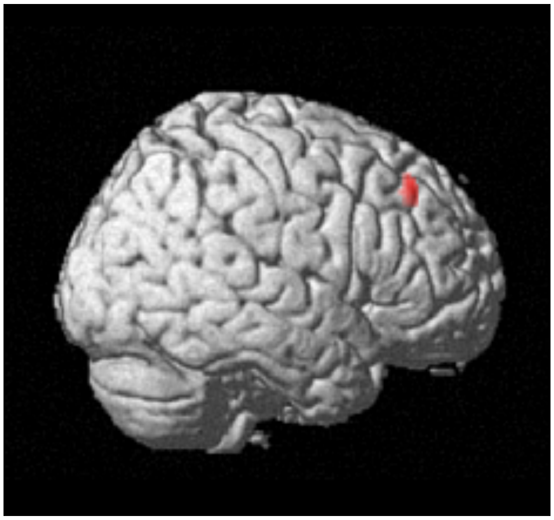

Figure 4. Pin-Pen fMRI results. Figure 4A shows activation associated with increased L2 proficiency centered in the left IFG triangular and orbital regions (k=124, T=5.86 (-48, 28, -2)). Figure 4B. shows activation associated with early AoA in right STG (k=30, T=4.37, (44, -10, -6)) and right angular gyrus (k=21, T=4.28 (32, -58, 48)).