Exploring the Resting State Neural Activity of Monolinguals and Late and Early Bilinguals

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Exploring the Resting State Neural Activity
of Monolinguals and Late and
Early Bilinguals

Carrie Elizabeth Gold

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Arts

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ABSTRACT

Exploring the Resting State Neural Activity of Monolinguals and Late and Early Bilinguals

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Master of Arts

Individuals who speak more than one language have been found to enjoy a number of benefits not directly associated with the use of the languages themselves. One of these benefits is that bilingual individuals appear to develop symptoms of dementia 4-5 years later than comparable individuals who speak just one language. Studies on this topic, however, do not consistently account for factors including if the individual learned their second language as a child or later in life, or their language proficiency. In an attempt to more carefully examine these variables, this study looks at structural and resting-state functional MRI scans of the default mode network, English and Spanish (where applicable) proficiency, language background, and demographics of young healthy adults who fall into one of three groups: early bilinguals, late bilinguals, and monolinguals. Of the three groups, late bilinguals were found to have a small but statistically significantly higher level of connectivity compared with early bilinguals in the region of the medial prefrontal cortex; patterns found examining number of languages and language proficiency in relation to functional connectivity and research group also supported this finding. These results indicate studying a language after adolescence could provide neuroprotective benefits of a nature that could potentially help delay symptoms of dementia. Age, gender, ethnicity, level of education, English language proficiency, and Spanish language use did not result in statistically significant findings, the latter of which challenges using frequency of language use to define bilingualism.

Keywords: bilingualism, multilingualism, memory, cognition, dementia, cognitive reserve, language, default mode network
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Introduction

As our modern world shrinks, it is becoming more and more common for individuals to interact with those from other cultures as well as those who speak a different language. Many individuals have experience with more than one language—experience which ranges, of course, from knowing a few words in Spanish from *Sesame Street* to growing up speaking different languages inside and outside of the home.

Many have also heard reasons that support multilingualism and foreign language education, be it improving professional prospects or getting more out of travel (Committee for Economic Development, 2006). Studies have, in addition, produced findings that those who study a language have higher scores on assessments that measure reading skills in their native language (Carr, 1994), greater creativity (Al Saud, 2016), better math performance (Stewart, 2005), and higher ACT and SAT scores (Olsen & Brown, 1992).

The effects of multilingualism, however, are deeper than broader communication and improved test scores. Research is showing that speaking more than one language actually changes your brain and affects your cognitive health: Bilingualism (the term “bilingualism” is used in this paper to refer to the speaking of two or more languages, including speaking three or more, even though the latter is generally referred to as “multilingualism”) has been associated with a variety of cognitive benefits, including better executive function, auditory attention, cognitive and sensory processing, and working memory (Bialystok, Poarch, Luo, & Craik, 2014; Marian & Shook, 2012) and even a delay in developing dementia (Bialystok et al., 2016; Bialystok, Craik, & Freedman, 2007). It is these cognitive changes and benefits that are the focus of this study.
Looking at dementia specifically, the various kinds that exist are a concern for the modern, developed United States of a magnitude that did not exist in our country a century or even a generation ago. Particularly as American baby boomers grow older, issues surrounding aging are an important public health concern for the country, presenting a pressing need for new knowledge and creative solutions. Currently, approximately 5.2 million Americans have Alzheimer’s disease (AD); though the disease is not a normal function of aging, this number includes one in nine Americans over 65 and one in three over 85 (Alzheimer’s Association, 2014, p. 16). This trend creates not just health concerns, but also economic ones. In 2014, approximately $214 billion was spent caring for individuals with AD and other dementias in the United States, and in 2013 caregivers gave approximately 17.7 billion unpaid hours to their care (Alzheimer’s Association, 2014, pp. 29, 43). Dementia presents a major public health issue for the aging population as well as caregivers and the healthcare system.

A better understanding of Alzheimer’s is key to confronting the disease. In addition to family history, pathophysiological indicators, and overall health, various lifestyle factors appear to correlate with incidence of the disease, one of which may be an individual’s experience with foreign language. Among these, research has indicated that bilingualism may delay the onset of symptoms of AD for four to five years, likely in accordance with the idea of bilingualism helping to create a “cognitive reserve” that allows the brain to better handle tasks even when the biological processes of AD are present (Alladi et al., 2014; Bialystok et al., 2016; Craik, Bialystok, & Freedman, 2010). The implications of this kind of effect are significant—one article explains the 4-5 year delay in symptoms constitutes a “more powerful impact [against dementia] than any known drug,” and notes, “delaying the average onset of the disease by just five years
would reduce the number of Americans with Alzheimer’s in 2050 by 42%, and cuts costs by a third” (Bialystok et al., 2016, p. 59).

Knowing more than one language is an exciting prospect for confronting the challenge of AD and dementia. It is one that invites further investigation and better understanding, particularly as research on the topic is not always consistent in measurements or terminology. Studies that have examined the topic, for example, use a variety of definitions of bilingualism and use a range of techniques to assess language proficiency. In addition, much of the research focuses on “lifelong bilinguals” at the same time being a “lifelong bilingual” is generally out of an individual’s control. Studying a foreign language later in life, however, is well within one’s own sphere of influence, which means if doing so has the potential, like being a “lifelong bilingual,” of delaying dementia, it would be possible for individuals to make lifestyle choices that could help protect their memory.

In an effort to more carefully parse out these variables in a way that other studies have not always done, and in order to better understand their relationships, this study looks at the linguistic background, language proficiency, and demographics of three groups of individuals ages 18-30, namely early bilinguals (or “lifelong bilinguals”), late bilinguals, and monolinguals, and then examines the connectivity of the default mode network (DMN) of these three groups, specifically of the medial prefrontal cortex, retrosplenial cortex, precuneus, and left and right angular gyri. These regions have sometimes been classified as "network hubs" that are consistently co-activated during both task and resting state conditions (Buckner et al., 2009). Further, these regions greatly overlap with regions that have increased neuropathology in AD, leading some to theorize that the high resting-state activity in these regions may accelerate pathology seen in AD (Buckner et al., 2005; Buckner, Andrews-Hanna, & Schacter, 2008). Thus, changes in DMN connectivity may reflect metabolic changes that may help protect against AD.
Research Questions

Accordingly, this examination is done with the intention of understanding differences in DMN connectivity in the three research group as well as the relationship between DMN connectivity and proficiency, demographics, and linguistic background. This research will help build a better understanding of bilingualism and cognition, particularly in connection with its implications for memory and for preventing or delaying AD and dementias. In order to do so, the study will examine the following research questions:

1. What is the relationship between bilingual status, namely as early bilingual, late bilingual, or monolingual, and DMN connectivity?

2. What is the relationship between first- and second-language proficiency and DMN connectivity?

3. What is the relationship between demographic and linguistic background, including the number of languages one has experience with, and DMN connectivity?
Review of Literature

What Effect Does Bilingualism Have on Dementia?

AD and associated dementias are frightening, little-understood diseases. As there is no cure for these conditions, it is compelling when research reveals information about how one might stave them off, and so, therefore, is information about the relationship between dementia and bilingualism.

Dementia is, of course, a complex disease, a fact reflected in the many variables examined by those researching the condition. Alladi et al. (2014), in looking at some 600 individuals in India, gathered information on a variety of variables including age, education status, occupation, family medical history, age of onset of dementia, and language history in addition to using various tools to measure memory, cognition, and dementia. In their observations, the researchers found their monolingual participants had more severe instances of dementia. They also found, when comparing bilingual and monolingual participants, that bilinguals were an average of 4.5 years older when their symptoms of dementia first appeared. These findings held up even after controlling for variables such as age and education status.

Bialystok, Craik, and Freedman (2007) found similar results. The Canadian study looked at 184 individuals who were diagnosed with dementia, 51% of whom were bilingual. The researchers interviewed the participants’ medical providers, families, and caregivers to gather information on when their symptoms of dementia began, as well as their languages spoken and English fluency, age, place of birth, and year of immigration to Canada. The researchers discovered the bilingual individuals’ symptoms of dementia began an average of four years later than the monolingual participants, a finding remarkably similar to the Alladi study.
Other studies draw similar conclusions. Craik, Bialystok and Freedman (2010) again found the age of onset of symptoms of AD was significantly later in bilingual individuals than monolinguals, regardless of immigration status. Work by Gollan, Salmon, Montoya, and Galasko (2011) concluded a higher degree of bilingualism correlated with a later diagnosis of AD, though a higher degree of bilingualism was only beneficial for individuals with a lower amount of education. Woumans et al. (2015) saw that bilingual study participants experienced their first symptoms of AD 4.6 years later and were diagnosed with AD 4.8 years later than monolingual participants after they controlled for demographics. These studies demonstrate a significant connection between bilingualism and a delay in the onset of AD and dementia. A better understanding of this connection, then, could have important implications for these diseases.

There is also, of course, additional evidence from studies that indicate the relationship between bilingualism and dementia is not always straightforward. Zahodne et al. (2004) found those who self-reported higher proficiency in their second language (English) had a lower chance of having received a diagnosis of dementia, but this effect was not present after controlling for demographic information. Research by Lawton, Gasquoine, and Weimer (2015) found similar conclusions, namely that in a group of individuals diagnosed with AD or vascular dementia, bilinguals had been diagnosed later than monolinguals, but this difference was not statistically significant. Chertkow et al. (2010) suggest studies looking at bilingualism and dementia do not always produce common results because researchers do not always consider potential confounding factors, such as not specifying or limiting the types of dementia being examined, not using reliable methods to measure the age of onset of symptoms, and failing to consider immigration status or other lifestyle differences which may or may not be associated with
dementia, such as education, community participation or isolation, socioeconomic status, diet, stress, and life history.

Some inconsistencies in research on the relationship between dementia and bilingualism, however, should not lead one to the conclusion that this area is not worth studying or dedicating resources to. Instead, it points to the need for more investigation. It is this compelling connection between bilingualism and dementia and memory that is the focus of this study, as there are significant implications for health and lifestyle if there is indeed a significant relationship.

**What is the difference between the bilingual and monolingual brain? Why is there a difference when it comes to dementia?**

The previously cited studies show different cognitive implications for individuals who speak more than one language versus those who speak just one. What, exactly, is different between the brains of these two groups is a complex question, and while researchers are still trying to understand the differences, there are some studies with results that are beginning to shape an answer.

**White and gray matter.** One difference between the monolingual and bilingual brain appears to be in the white matter and gray matter that is present. White matter consists of neurons with long axons extending from them, coated with and protected by an outer myelin sheath, whose function is to pass information along from the cell. These cells are responsible for much of the connectivity between the brain and body as well as between different parts of the brain (Filley, 2012, pp. 24, 29). Disruption in these connections are associated with disruption in normal mental functioning, and patterns of white matter disruptions are found in conditions including schizophrenia (Di Biase et al., 2017), Tourette syndrome (Plessen et al., 2006), autism (Barnea-Goraly et al., 2004), bipolar disorder (Brambilla, Bellani, Yeh, Soares, & Tansella,
2009), and fragile X syndrome (Barnea-Goraly et al., 2003), as well as AD (Andrews-Hanna et al., 2007). Gray matter, in turn, is unmyelinated, and is largely responsible for the processing (versus the transfer) of information (Filley, 2012, p. 23). The brain continues to form gray matter into puberty, at which time it begins to “prune” these cells as part of the brain becoming more efficient (Dryden, 2015). White matter volume increases until the mid-forties, then naturally begins to decline (Bartzokis et al., 2001).

Mechelli et al. (2004) looked at 25 monolingual individuals, 25 individuals who learned a second language before age 5 and who “had practiced regularly since,” and 33 individuals who had learned a second language between ages 10-15 and who had “practiced it regularly for at least 5 years” (p. 757). The researchers found greater gray matter density in both bilingual groups when compared with the monolingual controls. Similar results were found by Olsen et al. (2015) who looked at three comparable groups of participants. They found their bilingual groups had more white matter in the frontal lobe than their monolingual group. These researchers also asked participants to complete a Stroop task, where individuals look at the written names of colors in text that appears in a variety of colors, the two of which do not necessarily correspond. Participants are then asked to either name the text color or read the written word. They found performance on this task had a positive correlation with the density of frontal lobe white matter—findings which, they report, demonstrate that greater white matter is associated with better executive function performance.

**Executive function.** Other significant differences between the monolingual and bilingual brain have to do with executive function or control. Executive function is an individual’s mental control and self-regulation, especially the skills of inhibition (such as in stopping inappropriate behavior), shifting from one situation to another, emotional control, initiation (such as starting a
task independently), working memory (holding information needed to complete a task in mind), planning and organization, and self-monitoring one’s own behavior (Cooper-Kahn & Dietzel, 2008). There have been findings concerning executive function in aging individuals. Voss and Bullock (2004), for example, looked at three groups of participants: One with AD, one with vascular dementia (VaD), and a control group. When they tested their participants’ executive function, they found participants in the control group performed significantly better than those in other groups. The group with AD also performed more poorly than the VaD group on 11 of the 18 cognitive tests, but these two groups performed similarly on tests of episodic memory, executive control, and face recognition. Albert, Moss, Tanzi, and Jones (2001), in turn, found assessments of memory and executive function were able to discriminate between those with mild memory difficulty whose disease developed into AD during a three-year span, again showing a connection between executive function and dementia.

Executive function also appears to be a useful paradigm for understanding the bilingual brain, as researchers have found evidence that bilingualism is associated with greater executive control. Looking at the task of using more than one language, Hernandez, Martinez, and Kohnert (2000) had English-Spanish bilinguals name pictures in both of their languages during an fMRI. The researchers found the task of switching between languages activated the dorsolateral prefrontal cortex, an area involved with the general executive control system, evidence that using more than one language involves and strengthens areas of the brain associated with executive function.

Bilingual children have also demonstrated superior performance in tasks that involve executive control when compared with monolingual peers. Bialystok (2007) cites a task designed by Zelazo and Frye (1997) to measure executive control where individuals sort colored images
by shape and then subsequently by color, an assignment that requires them to suppress irrelevant information about the image during each phase in addition to requiring their attention. She goes on to name findings in Bialystok (1999) and Bialystok & Martin (2004) of bilingual children completing this said task more easily than comparable monolingual children doing so. She then suggests that this kind of result does not indicate greater intelligence or knowledge on the part of the bilingual children versus monolingual children. Rather, it demonstrates the former group has strengthened their cognitive ability to suppress distracting or competing information (i.e., one of their languages), a component of executive control.

**Activated brain regions.** It is important to note that these differences are not necessarily always apparent in bilingual adults—they are, rather, more pronounced in children and the elderly, though differences may be present for young and middle-aged adults when performing more demanding tasks (Bialystok, 2006, 2007; Bialystok, Craik, & Ryan, 2006). It has also been observed, though, that even when mono- and bilingual adults did not have significantly different reaction times on tasks that require executive control, the groups have shown activation in different brain regions for such tasks. One study (Bialystok, Craik, et al., 2005) used magnetoencephalography to discover that when asked to perform a Simon task, monolingual participants showed increased activity in an area near the dorsolateral prefrontal cortex, associated with conflict resolution. On the other hand, bilingual participants also showed activation in regions including Broca’s area, associated with language, for the same task. The authors conclude these results demonstrate that the bilingual brain has connected tasks that require conflict resolution (such as those that use executive control) with language and cognitive function associated with language.
These findings could help explain why bilingual individuals can show superiority in executive function tasks, namely that they are using executive control when they use their languages, thus practicing and strengthening associated skills. These functions include inhibiting the language not being used and selecting words in the correct language, as well as sustaining attention and utilizing their working memory, tasks that strengthen mental flexibility and neuroplasticity (Bialystok, Craik, & Luk, 2012).

**Other ideas.** There is, of course, also evidence against and limitations to this research. Paap, Johnson, and Sawi (2015) take issue with findings that bilingualism is connected to executive function. They identify several problematic areas with this kind of research finding, namely the “file drawer problem,” where researchers are more likely to lay aside null results that contradict previous publications than they are hypothesis- affirming evidence; that other factors including socioeconomic status, immigrant status, and cultural differences can become confounding variables in such research due to potential patterns in the differences between bilingual and monolingual populations; and the fact that study design and/or statistical analyses are sometimes inadequate or lead to biased results (for example, when researchers publish multiple studies with small samples rather than a single study with a large sample group), a concern also brought up by Chertkow et al. (2010). Such concerns point to the importance of carefully considering results and claims of research on the topic, as well as the need for more research.

Still, the concept of how a bilingual individual has more than one language at the ready in the brain, but is generally required to only use one at a time, is an important one. It means there is constantly a greater cognitive demand on the bilingual person as they balance these languages when compared to someone who only speaks one language. It also means this individual is
consistently exercising their executive control by constantly choosing which language to use and then suppressing the other(s) (Abutalebi & Green, 2007; Luk, De Sa, & Bialystok, 2011). Referring to this idea, Bialystok (2007) writes, “The process necessary to control the two language systems for a bilingual—attention, inhibition, monitoring and switching—are all components of the executive function” (p. 212). Evidence for this idea comes from studies with designs such as asking participants to switch between their languages and then looking for any pattern of inappropriate language switches, imaging studies that show neural activation for both the participant’s languages when just one is being used, and linguistic tasks that include distractor words that share phonology or some other aspect of the participant’s other language and observation of how bilingual participants are distracted by them (Bialystok et al., 2012). This idea of being able to suppress one language when both of a bilingual’s languages are always present and active is an important difference between mono- and bilingual individuals.

**What is the default mode network? What does it have to do with memory?**

In addition to indicators of executive function, information about the default mode network (DMN) is also important for understanding the bilingual brain as well as aging. Research on the DMN began a few decades ago, and is beginning to uncover information on where it is located as well as its purpose. The DMN is a part of the brain that is working when an individual is not engaged in any particular task. Buckner, Andrews-Hanna, and Schacter (2008) explain that it is associated with the stream of consciousness, namely the thoughts that occur when not thinking about anything in particular. It also includes the tasks of remembering, thinking about the future, imagining different scenarios for present events, external monitoring, and theory of mind (or thinking about the perspectives of other people).
**Anatomy of the default mode network.** Research on the DMN is still new, and as of yet its makeup does not have a single set definition. Buckner, Andrews-Hanna, and Schacter (2008) list components of the brain that are involved with the DMN as the ventral medial prefrontal cortex, posterior cingulate cortex, retrosplenial cortex, inferior parietal lobule, dorsal medial prefrontal cortex, and hippocampal formation. In their study examining resting state connectivity and the DMN, Greicius, Supekar, Menon, & Dougherty (2008) focus on the medial prefrontal cortex, medial temporal lobes, and “posterior cingulate cortex/retrosplenial cortex” (p. 72). For this study, a data-driven approach was used to identify the DMN. First, a seed was placed in the retrosplenial cortex (region 5 in Figure 1). Brain regions whose time course significantly correlated with that of the retrosplenial cortex over the course of the resting-state scan were then selected. This approach yielded five regions, which are labeled in this study as follows: the retrosplenial cortex, the medial prefrontal cortex (though it is sometimes labeled in research as the ventral medial prefrontal cortex), the precuneus (sometimes labeled as the posterior cingulate cortex), and the left and right angular gyri (sometimes called the left and right inferior parietal lobules). These five regions are illustrated in Figure 1.

*Figure 1.* The five areas of the default mode network examined in this study. 1. Left angular gyrus 2. Precuneus 3. Right angular gyrus 4. Medial prefrontal cortex 5. Retrosplenial cortex
The retrosplenial cortex is involved in episodic memory, navigation, imagination, and planning for the future. It is associated with disorders that impair memory and pathological changes including decreased metabolic activity in individuals with mild cognitive impairment and AD (Vann, Aggleton, & Maguire, 2009).

The medial prefrontal cortex is a region associated with processing risk and fear, inhibition of emotional responses, planning, personality, decision making, and moderating social behavior as well as with executive function in general (J. Anderson, 2010). The area connects motivation from working memory to action from motor areas of the cortex—a process of deciding actions and sequencing behavior (P. Mason, 2011).

The precuneus is an area in the brain that is involved in “visuo-spatial imagery, episodic memory retrieval…and first-person perspective taking,” as well as self-awareness and self-consciousness (Cavanna & Trimble, 2006, p. 564). These activities, as well as the region’s activation during rest, indicate its part in the DMN.

The left and right angular gyri are associated with tasks including processing language and numbers, retrieving memories, solving problems, paying attention, reasoning, and making sense of events (Bemis & Pylkkänen, 2013; Seghier, 2013). Abnormalities in their white and gray matter have been associated with major depressive disorder and schizophrenia (Ma et al., 2007; Nierenberg et al., 2005), and reduced blood flow in the gyri has been found to be an indicator of the progression of mild cognitive impairment to Alzheimer disease (Hirao et al., 2005).

The default mode network and memory and dementia. Studies have found connections between the state of the DMN and dementia. As mentioned, abnormalities in the retrosplenial cortex and left and right gyri have been found to be associated with dementia or
AD. Reduced activity in the posterior cingulate cortex (or precuneus) is a common finding when examining the early stages of AD (Johnson et al., 1998; Matsuda, 2001; Minoshima et al., 1997). Greicius et al. (2004) examined fMRI data of the DMN from subjects age 68-83 with mild AD and compared them to similar scans of healthy subjects ages 66-89. The researchers found a significant difference between the groups, with the healthy group demonstrating better connectivity. They even suggest that this kind of test “shows promise as a clinical marker of AD” (p. 4640-4641). Koch et al. (2012) conducted a similar study looking at coactivations in DMN regions in three research groups, namely individuals with mild cognitive impairment, with AD, and a healthy control group. Their results are similar, showing the mild cognitive impairment group demonstrated lower coactivation in the anterior cingulate cortex and the parietal lobule (or angular gyrus) than the control group. Comparing the group of participants with AD and the healthy control group, lower activity in the DMN did not reach significance, but lower interconnectivity between most of the regions of the DMN did.

This study’s participants are young, healthy adults, however, so it must be recognized that findings such as those cited above from studies that examine the DMN in older adults may not necessarily apply directly to this sample. There have, however, been some studies on young and healthy individuals and the DMN, some of which have found differences that are likely connected with AD. Specifically, research has shown hypometabolism in the posterior cingulate cortex (or precuneus) in subjects with genetics that show a susceptibility to AD (Greicius et al., 2004; Reiman et al., 2001; Small et al., 2000).

The DMN also seems to be associated with working memory in general. Yakushev et al. (2013) write that a stronger connection between the medial prefrontal cortex and the posterior cingulate cortex (or precuneus) when individuals are at rest is associated with better working
memory performance, though they caution the superior connectivity may be a product of better working memory performance rather than better connectivity causing better working memory (Esposito et al., 2009; Hampson, Driesen, Skudlarski, Gore, & Constable, 2006; Sambataro et al., 2010). Yakushev et al., in turn, looked at 35 healthy subjects ages 20-40. They had the subjects complete a digit span backwards task, where a researcher gives a multi-digit number to the subject that he or she then has to repeat backwards (the researchers continue to give the participant numbers with more and more digits until the participant makes a mistake in reciting them backwards), a test designed to measure working memory. The researchers then looked at the metabolic and structural connectivity between the posterior cingulate (or precuneus) and medial prefrontal cortex, components of the default mode network, using fluorodeoxyglucose positron emission tomography. The researchers found “…both metabolic and structural connectivity was found to be greater in individuals with higher performance in a standard verbal WM [working memory] test,” illustrating that better DMN connectivity is associated with better working memory (p. 187).

This present study focuses on finding out how age of second language acquisition, language proficiency, linguistic background, and demographics are connected to DMN connectivity. As illustrated with the above findings, DMN connectivity can serve as an indicator of working memory that may ultimately related to the development of dementia and AD. While DMN connectivity is not synonymous with memory nor is it a perfectly correlated indicator of the development of dementia, the findings of this study from looking at DMN connectivity could be helpful for better understanding the relationship between language background, memory, and perhaps even the development of dementia.
Does language background matter?

Whether they speak one language or many, everyone has unique linguistic backgrounds. These individual backgrounds include how well a person knows each of their languages, referred to as proficiency, as well as their age of acquisition (AoA) of the language. AoA is a somewhat nebulous concept: When a baby first hears their native language from their parents, they are not able to immediately form words and sentences and participate in long conversations. At the same time, it does not make sense to say that the same child’s AoA is not until several years later when they are finally able to participate in all of these tasks. Language development is a continuum, not an on-off switch, which it turn makes it difficult to declare AoA. This study will define this variable as the age of first contact with a language, as this is a clear and consistent measure.

Still, the fact remains that AoA does not have one set definition. Some have defined it as when an individual first started hearing or studying a language (as it was defined here), while others consider it the age at which the individual started using it on a daily basis, and some studies that use the term do not offer a definition for it at all. Specific studies and their different definitions are shown in Table 1.

**Proficiency, Age of Acquisition, and Cognition.** Various studies have demonstrated the importance of considering AoA and proficiency when drawing conclusions about cognition. Archila-Suerte, Zevin, and Hernandez (2015) studied the neural processing of second language (L2) speech sounds in 82 participants divided into three research groups: English monolinguals, early English-Spanish bilinguals (with AoA younger than 9 years old), and late English-Spanish bilinguals (with AoA older than 10 years old). The participants listened to English-language sounds during an fMRI scan while the researchers examined activity in eight regions of interest in the brain chosen due to their involvement in speech perception and executive processes. The
researchers also gathered data on the participants’ AoA, socioeducational status, and second language proficiency. They found some effect from socioeducational status and proficiency on the measured brain activity, though they report that AoA was “the main variable affecting the neural response in L2 speech processing” (p.35), demonstrating how it is an important piece of understanding language and cognition.

Luk, De Sa, and Bialystok (2011) also found AoA had an important effect in a similar study looking at early and late bilinguals (based on if they became “actively bilingual” before or after the age of ten) and monolinguals, with AoA defined as the age at which the individual started using two languages on a daily basis. All participants spoke English, and bilingual participants spoke one of 26 other languages. The researchers gathered data on participants’ self-assessed proficiency and language background, and had them perform a flanker task, where researchers presented a row of chevron shapes to participants who were asked to signal the direction of the center chevron. This task was used to measure participants’ executive control. From the data they gathered, the researchers found a few results that have implications for AoA. First, early bilinguals and monolinguals had similar levels of English proficiency that were significantly better than the late bilingual group. Next, AoA was negatively correlated with proficiency. Finally, early bilinguals performed the best on the flanker task with late bilinguals and monolinguals performing similarly. These results show suggest longer experience being bilingual correlates with greater cognitive advantages as well as proficiency and certainly indicate the need for measuring AoA.

Yang, Hartanto, and Yang (2016) repeated the flanker task and found the same result, namely early bilinguals performing significantly better than late bilinguals. Like Archila-Suerte, Zevin, and Hernandez’ study, these findings demonstrate there are cognitive differences present
with different AoA, which also shows the importance of considering AoA when looking at bilingualism and cognition.

_Age of Acquisition in Relation to the Critical Period Hypothesis._ In considering AoA, there are indeed observable differences between learning a language in either stage in life. As the previously mentioned studies demonstrate, proficiency has been correlated with AoA. Accent can be another difference—individuals who grew up speaking two languages generally do not, by adulthood, have a foreign-sounding accent in either language, while such an accent is generally detectable in someone who learned their second language after their youth. These differences between early and late bilingualism are often summarized with “The Critical Period Hypothesis,” which states that there are cognitive differences in children that allow them to learn a second language as a native speaker would (or “acquire” the language). After around age ten (Thompson, 1991) or twelve (Bongaerts, Planken, & Schils, 1995, p.31), the hypothesis states, the brain begins to trim unused neural pathways, essentially closing off the capacity to acquire new languages as a native speaker (Hoff-Ginsberg, 1998; Long, 1990; Scovel, 1999; Shrum & Glisan, 2005).

The Critical Period Hypothesis is yet a _hypothesis_, however, and it is not a complete model for how AoA effects language learning, nor can it offer exact age cutoffs or precise predictions of certain outcomes from learning a language at a certain age. Patkowski (1990), for example, found that age fifteen (versus ten) was a more accurate cut-off for acquiring native-like grammar and syntax (versus just looking at pronunciation). Age in general, though, is not a perfect indication of language proficiency. A young learner of a second language may have a perfect accent, for example, but still make syntactical mistakes. In addition, research has also found that individuals who grew up bilingual demonstrate overall weaker verbal skills in each of
their individual languages when compared to monolingual speakers of the same languages, a finding that demonstrates gaps in linguistic knowledge even while supposedly knowing the language well because of growing up speaking it (Bialystok et al., 2012). Research has also found that there are adult language learners (e.g., late bilinguals) who reach a native-like level (in, for example, accent, grammar, and syntax) in a non-native language (Ellis, 1994; Ioup, Boustagui, El Tigi, & Moselle, 1994). There are, as well, other factors involved in creating a bilingual individual’s portrait—how exactly they learned the language, how and how often they use it, dominant language in the area of residence, immigration status, personal identity and interests, and social network are some of many pieces of the overall picture.

**Proficiency.** Besides AoA, language proficiency is another product of this variety of circumstances and factors, and, like AoA, is an important component of understanding bilingualism and cognition. One example of this is found in the previously mentioned study by Mechelli et al. (2004) examining gray matter in early and late bilinguals and monolinguals. In the study, the researchers found gray matter density correlated not just with bilingualism, but found it had a negative correlation with AoA and a positive one with proficiency. In another previously mentioned study, Archila-Suerte, Zevin, and Hernandez (2015) found differences in the neural processing of second-language speech sounds based on participants’ L2 proficiency. Again, these findings show both AoA as well as proficiency matter when examining language and cognition.

As these findings demonstrate, AoA and proficiency are important components of language processing, and automatic conclusions cannot be drawn from AoA nor proficiency. Studies that have examined language and the brain, however, have not always carefully accounted for them. Many studies looking at this topic have made assumptions that do not
adequately reflect the variety of these variables in bilingual individuals, or whose study design lacks enough structure to account for them. It is for this reason that this study attempts to quantify proficiency as well as AoA.

**Monolingualism Versus Bilingualism.** It appears that one significant problem with many articles on the topic of language and cognition is when authors consider monolingualism versus bilingualism as a binary state. A continuum, however, is a much more accurate model, as speaking a language or not falls along a whole spectrum of proficiency based on, as noted above, a huge variety of factors. Bialystok et al. (2012) touch on this theme, explaining, “Individuals can never be perfectly monolingual or bilingual: Even the most monolingual people have had some experience with another language…and all bilinguals have preferred languages or…contexts” (pp. 12-13). Simply quantifying language experience in terms of a yes or no question is a poor way to represent the reality of this spectrum or the factors that contribute to it.

A classic example of this continuum of bilingualism is the heritage language speaker, that is, an individual who grows up speaking a minority language at home. These speakers may appear quite fluent in their language, even participating in rapid conversations. When confronted with a linguistic task in their heritage language such as addressing a topic outside of the day-to-day or that requires technical language, hypothesizing or defending an opinion, or reading or writing, this individual may suddenly encounter significant difficulties and demonstrate much more limited proficiency, as such tasks have often not been a part of their (heritage) language acquisition (Valdés, 2001). These individuals do not all have the same formative experiences, however, and a heritage speaker might only be able to recognize some words in their heritage language or show wonderful fluency and literacy. Like any individual, there are many factors that contribute to their linguistic background. Indeed, Bateman and Wilkinson (2010) write that
heritage speakers “…exhibit widely varying characteristics in terms of [their heritage] language proficiency” (p. 325). The example of the heritage speaker helps illustrate not just how individuals speak a second (or even first) language to different degrees, but also how simply labeling a study participant as bilingual or not based on self-identification does not capture the complexity of the spectrum of bilingualism.

**Defining and Quantifying Language Background.** Still, as noted, many of the published studies that look at bilingualism and cognition do little to quantify or even identify the range of linguistic diversity that exists among bilingual—and even monolingual—participants. Table 1 presents a summary of several such studies, and helps demonstrate the difficulty and inconsistency that exists in defining, identifying, and quantifying these important components of an individual’s linguistic background.
Table 1

Variables in Research on Bilingualism and Cognition

<table>
<thead>
<tr>
<th>Study</th>
<th>How is bilingualism defined?</th>
<th>How is late vs. early bilingualism defined?</th>
<th>How is age of acquisition determined?</th>
<th>How is proficiency assessed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Bilingualism as a protection against the onset of symptoms of dementia” (Bialystok et al., 2007)</td>
<td>The researchers used “the following information about language history: languages spoken, English fluency, place of birth, date of birth, and year of immigration to Canada. This information, without any other details, was given to 11 judges experienced in conducting behavioral research with bilinguals who classified each patient as monolingual or bilingual. The criterion for bilingualism was that the patients had spent the majority of their lives, at least from early adulthood, regularly using at least two languages” (p. 460).</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>“Delaying the onset of Alzheimer disease” (Craik et al., 2010)</td>
<td>“Information was…collected about…language history, [and] fluency in English and other languages….The criterion for classification as bilingual was having spent the majority of life, at least from early adulthood, regularly using at least 2 languages” (p. 1727).</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>“Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: Evidence from a bilingual community” (Chertkow et al., 2010)</td>
<td>“Language history was obtained from patient and caregiver interviews…Bilingualism and multilingualism was defined according to the criterion [in] Bialystok et al. [2007] (‘…patients had spent the majority of their lives, at least from early adulthood, regularly using at least two languages’ [p. 460])” (p. 119).</td>
<td>N/A</td>
<td>“We did not control specifically for the age at which the second language was learned” (p. 119).</td>
<td>N/A</td>
</tr>
<tr>
<td>Study</td>
<td>How is bilingualism defined?</td>
<td>How is late vs. early bilingualism defined?</td>
<td>How is age of acquisition determined?</td>
<td>How is proficiency assessed?</td>
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</table>
| “Structural plasticity in the bilingual brain” (Mechelli et al., 2004) | - Monolinguals “had little or no exposure to a second language”  
- Bilinguals “had learned a second…language” (p. 757)                                                                                                                                                                                                                                           | Early bilinguals learned a second language before the age of 5 “and practiced it regularly since”; late bilinguals between 10 and 15 “and practiced it regularly for at least 5 years” (p. 757) | N/A                                                                                                                                                                                                                                                                                                                                                                         | N/A                      |
| “Lifelong bilingualism maintains neural efficiency for cognitive control in aging” (Gold et al., 2013) | Participants were given a questionnaire about their language background “similar to that used in…Bialystok et al., 2006” (p. 388)                                                                                                                                                                                                                              | Lifelong bilinguals spoke English and their L2 “on a daily basis since…10 or younger” and rated “themselves as completely proficient in their two languages”  
Lifelong monolinguals “spoke only English and had no significant exposure to a second language” (p. 388) | The questionnaire asked for information on AoA  
The Peabody Picture Test to assess English proficiency: Participants are shown four pictures, then read a word and “asked to choose the picture on…that best corresponds to the word” (p. 388) | The questionnaire asked participants to compare their language proficiency to that of a native speaker (for all their languages) |
<table>
<thead>
<tr>
<th>Study</th>
<th>How is bilingualism defined?</th>
<th>How is late vs. early bilingualism defined?</th>
<th>How is age of acquisition determined?</th>
<th>How is proficiency assessed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Effects of bilingualism and aging on executive function and working memory” (Bialystok et al., 2014)</td>
<td>Participants completed the Language and Social Background Questionnaire (LSBQ) (Anderson, et al., 2017), which collects extensive information on which language is used in different situations and with different individuals; a self-assessment of speaking, understanding, reading, and writing proficiency of each language; and information on where the language was learned and at what age</td>
<td>N/A</td>
<td>LSBQ</td>
<td>LSBQ</td>
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<td></td>
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<td></td>
<td>Shipley Vocabulary Test (participants read a word, then select a synonym out of four other words) (Zachary, 1986)</td>
</tr>
<tr>
<td>“Is there a relation between onset age of bilingualism and enhancement of cognitive control?” (Luk, De Sa, &amp; Bialystok, 2011)</td>
<td>A “detailed language history questionnaire” where participants were “asked to report the age at which they began using both languages actively and regularly on a daily basis” (p. 590). Language questionnaire. “Early bilinguals reported they started active bilingualism before the age of 10…late bilinguals…after the age of 10” (p. 590). Participants who reported active bilingualism at the age of 10 were excluded, as were individuals who spoke more than one language but “had never used both languages actively in their daily lives” (p. 590).</td>
<td>Self-reported on questionnaire</td>
<td>“…the bilingual participants were asked to rate their language proficiency relative to a native speaker in their first language (L1) and L2, respectively” (p. 591)</td>
<td>The Peabody Picture Vocabulary Task</td>
</tr>
<tr>
<td>Study</td>
<td>How is bilingualism defined?</td>
<td>How is late vs. early bilingualism defined?</td>
<td>How is age of acquisition determined?</td>
<td>How is proficiency assessed?</td>
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<td>“Lifelong bilingualism maintains white matter integrity in older adults” (Luk et al., 2011)</td>
<td>“…bilingual older adults reported that they had used both English and another alphabetic language regularly since childhood (before age 11)” p. 16809</td>
<td>Participants self-reported they used their two languages regularly since before age 11</td>
<td>Self-reported</td>
<td>Participants self-rated their proficiency</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>The Shipley Vocabulary Test</td>
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<td></td>
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<td></td>
<td></td>
<td>To assess verbal fluency, “participants were asked to produce words that either begin with a specific letter…or belong to a semantic category within 1 min” (p. 16809)</td>
</tr>
<tr>
<td>“Age of second language acquisition in multilinguals has an impact on gray matter volume in language-associated brain areas” (Kaiser et al., 2015)</td>
<td>N/A (Though this study focused on individuals with experience with three languages, not two or more)</td>
<td>Simultaneous multilinguals (SiM) grew up speaking their L1 and L2 due to growing up in a bilingual or minority language family. Successive multilinguals (SuM) acquired their L2 between ages 2-5 or at school at 9 or after. L3 for both groups was acquired at school at 9 or after.</td>
<td>“…age of second language acquisition was defined after analyzing each individual’s language biography,” which was created “through oral interviews lasting 2-3 hours.”</td>
<td>The study uses proficiency scores from the Council of Europe’s Common European Framework of Reference for Languages, but does not state how the scores were obtained.</td>
</tr>
</tbody>
</table>

**Defining and Quantifying Bilingualism.** As Table 1 demonstrates, current research utilizes a variety of methods to quantify and describe participants’ linguistic background in studies that examine language experience and cognition. First, there are a variety of definitions
of bilingualism. The word itself simply means that one can use two languages. Examining the studies in Table 1, several define it as an individual spending the majority of their life regularly using two languages, a definition that again does not effectively encompass the spectrum of bilingualism (Bialystok et al., 2007, p. 460; Chertkow et al., 2010; Craik et al., 2010; Luk, Bialystok, et al., 2011).

While “bilingual” does imply fluency in both languages, drawing a line for when fluency is achieved is relatively arbitrary. Again, when considering a child’s natural language development, a two-year-old does not speak their native language with fluency, but would it be appropriate then to count the child for that reason as not speaking their language at all? What about a tourist who is easily able to use their destination’s foreign language to interpret train schedules and explain what they want on their sandwich, but who is not necessarily able to use the technical language required to explain what they do for a living? Similarly, the argument that bilingualism is not achieved until the individual regularly uses the language is also arbitrary. It does not even account for much of their language background (before they were “proficient”). In addition, it likely results in inconsistent responses, especially considering this point in time was determined by asking participants to look back and estimate (with little to no criteria). This kind of definition of bilingualism also discounts individuals who use more than one language but not necessarily on a daily basis—though would they not also be bilingual?

**Defining and Quantifying Age of Acquisition.** In addition to attention to defining bilingualism, it is important to consider AoA, as evidenced from previously-discussed studies. Table 1 shows, however, that several of these studies did not attempt to determine AoA, nor to define what constitutes early vs. late bilingualism. As previously mentioned, research has found cognitive differences between these two groups. Though it is just a hypothesis, there is some
evidence that the “critical period” for acquiring a language like a native speaker may close around puberty (Lightbrown & Spada, 2003), and that the window for acquiring a native-sounding accent is between ages six and ten (Thompson, 1991). There is no definitive age that has been established for defining early vs. late acquisition, however—establishing one fixed age would likely not be appropriate anyway, considering how individuals develop at different rates both physically and cognitively. For this reason, this study uses an age range in attempt to respect developmental differences, defining early bilinguals as those whose experience with a second language began at or before the age of ten, and late bilinguals as those whose experience started after age 14. Ages eleven through thirteen were purposely excluded: The Critical Period Hypothesis does not necessarily have a certain age attached to it, but, as noted, it has long been associated with puberty (Arshavsky, 2009; Friedmann & Rusou, 2015; Grimshaw, Adelstein, Bryden, & MacKinnon, 1998; Snow & Hoefnagel-Höhle, 1978), and puberty certainly does not have a set age: One source reported it usually takes place between ages 10-15 (“Puberty,” 2017); another’s authors followed over 1,500 boys and girls and reported various stages of puberty were met at a mean age of 11.5-11.8 years for boys and 9.9-12.9 for girls (Wohlfahrt-Veje et al., 2016). The age thresholds for this study were chosen with the hope of allowing a clear pre- and post-puberty distinction between the EB and LB groups.

**Defining and Quantifying Language Proficiency.** Finally, proficiency is an important aspect of understanding an individual’s experience with a language. It is also a complex, multi-faceted concept, which makes measuring proficiency complex as well. Indeed, as demonstrated in Table 1, there are many ways to assess proficiency. The gold standard in the United States, however, is known as the Oral Proficiency Interview (OPI) from the American Council on the Teaching of Foreign Languages (ACTFL). Though ACTFL’s guidelines include provisions to
assess writing, listening, and reading, the OPI focuses on spoken proficiency and is often considered an assessment of global proficiency.

ACTFL’s Proficiency Guidelines (2012) outline the organization’s scale for assessing proficiency. It focuses on global speaking tasks, which are made up of vocabulary, grammar, and cultural competency, and that illustrate how an individual can express themselves in real contexts rather than focusing one small component of speaking. The guidelines of the OPI themselves state that they are “descriptions of what individuals can do with language…in real-world situations in spontaneous and non-rehearsed context” (p. 3). This is in contrast with some studies’ attempts to measure proficiency: Consider, for example, the Shipley Vocabulary Test, which (as its name implies) only looks at vocabulary, just one component of proficiency and real-world language use.

ACTFL’s Proficiency Guidelines outline levels that can be conceived as an inverse triangle, with the “Distinguished” rating at the top representing a wide range of skill in linguistic structures, vocabulary, and fluency—though, due to the specific scoring system of the language assessments used for this study, the highest level used for these tests was “Superior” (meaning “Distinguished” was implicitly included); this is also the highest level depicted in Figure 2. The “Novice” category forms the bottom point of the triangle, showing little functional knowledge of the language. Each progressive category represents broader skills and depth of knowledge. The triangle shape is also appropriate, then, when considering one can master new skills and progress relatively quickly through the Novice levels, but that progress is much slower through the upper levels. The progression of these levels is illustrated in Figure 2.
Though there are many ways to measure proficiency, this study uses a tool that is based on ACTFL’s proficiency scale, and that has been evaluated for consistency and reliability: a tool called elicited imitation (EI). As its name suggests, EI asks individuals to repeat back phrases in the target language that are played out loud to them. Items increase in length and complexity with the idea that individuals need to be able to understand the prompt in order to remember it, and then have enough linguistic knowledge to reproduce it. As described later in the “Methods” section of this paper, the results of this kind of test have a high correlation with the results of an OPI.

Taken in sum, there are a range of factors involved in cognition and language learning, including the components and anatomy of cognition and their effect, an individual’s language
background, and how these elements are measured, quantified, and analyzed. The goal of this research is to help illuminate how cognition, AoA, proficiency, and demographics connect, and to help understand their implications.
**Methods**

**Participants**

One hundred and two individuals participated in the study, of whom 57 were female and 45 were male. Participants were ages 18-29, from specific linguistic backgrounds, and were eligible to participate in an MRI scan. Due to various incidental circumstances, not all data points were collected from every participant, so a participant was not included in an analysis if they lacked any of the specific data being considered. The following describes the recruitment process and participant compensation; a table summarizing participant information is found in Table 2.

**Recruitment.** Participants were recruited primarily through fliers that were posted around the Brigham Young University (BYU) campus as well as the wider Provo, Utah area. These fliers are included in Appendix A. The study was also posted on social media. These methods yielded over 1,200 interested individuals.

Recruitment focused on locating individuals for each of the three research groups, namely individuals who were early bilinguals, late bilinguals, and monolinguals. Finding late bilinguals was particularly easy, likely in part because of the large number of BYU students who have served as volunteer missionaries abroad. Finding monolingual participants was slightly more difficult; BYU’s admission policies recommend potential students to have taken at least two years of secondary foreign language classes to even apply to the school ("Acceptance Criteria," n.d.), which may have contributed to this fact. Because there were simply not enough potential participants who had no foreign language experience to reach the target number (n=30) for this research group, individuals who reported some foreign language experience but estimated their proficiency in the language or languages in the “Novice” range when referring to
short proficiency descriptions based on the ACTFL scale were accepted for this participant group. When it was necessary in this way to recruit individuals with some foreign language experience, those with experience with the Spanish language specifically were prioritized, as the study’s design permitted measuring Spanish proficiency (as well as that of English), but not the proficiency of other languages. In addition, despite the large number of potential participants, finding early bilinguals was relatively difficult. In order to find the needed number early bilinguals, participant referrals were used as an additional recruitment tool. As previously alluded to, potential participants with English or English and Spanish experience exclusively were prioritized for the recruitment of all three research groups; however, those who also had experience with other languages were not systematically excluded from the study, nor were those with experience with more than two languages.

Subject selection and exclusionary criteria. Individuals who saw recruitment material and were interested in participating were first referred to the study’s website. There, they could read about the study’s design and purpose, and they could take a survey to see if they qualified for the study. This survey was designed to uphold the study’s exclusionary criteria, namely disqualifying anyone younger than 18 or older than 30, left-handed, color blind or color deficient, who has had a traumatic brain injury, who has been diagnosed with a mood or psychiatric disorder (such as ADHD or depression), who has been diagnosed with a neurological condition (such as a stroke or multiple sclerosis), who was or could have been pregnant, who has had complications with a previous MRI, who has any possible non-MRI compatible metal in their body (such as from being injured while working with metal or having a pacemaker), with tattoos or permanent makeup (which may have metallic ink), who weighed more than 300 pounds (due to the MRI machine’s capacity), or who was claustrophobic.
These criteria were designed with three purposes. First, they insured participants’ safety—having ferromagnetic material in the body could cause serious injury to an individual in an MRI machine’s strong magnetic field. Second, these criteria helped insure accurate scanning, as magnetic material on the participant’s person can cause visual gapping or blurring in the imaging, and an issue such as claustrophobia could result in an incomplete scan if the individual needs to be taken out of the scanner prematurely. Finally, the criteria were designed to foster the homogeneity of the research sample by excluding factors that could cause deviation in the MRI results that were not related to the variables under investigation. Factors such as right- vs. left-handedness or depression have cognitive underpinnings that could result in confounding variables for the study. Potential participants were also asked if they had a permanent retainer or similar dental device, though having one did not exclude them from the study. This initial questionnaire is included in Appendix B.

If individuals completed this survey and were not disqualified, they were then asked if they would like to participate in the study. Those who responded “yes” were asked to provide their contact information, and then to read through the study’s consent document containing its procedures, possible risks and benefits, and information about incidental findings, confidentiality, compensation, and participation. Individuals then signed the document electronically; they were later emailed a copy of the consent form. This information is included in Appendix C.

After this stage of recruitment, the potential participants were emailed a link to a second survey, this one asking about the individual’s language background. It asked for information on what languages they had experience with, at what age this experience began, how they learned (or are learning) the language, how they currently use the language, their self-assessment of their
gobal proficiency of the language based on a summary of the ACTFL scale, and what country they have lived in for three months or longer, which languages they used there, and for what percentage of the time. The survey also asked about potential participants’ demographic information, specifically the individual’s gender, age, occupation, ethnicity, and education level. These questions were designed to, along with the study’s proficiency testing, more carefully quantify participants’ language experience in a way that previous studies on this topic have not, though not all of the data included in this survey was used in the project’s analysis. Nearly 500 individuals completed this survey, a copy of which is included in Appendix D.

Individuals were invited to participate based on their survey responses, specifically whether they showed the individual would fit into one of the three research groups. The early bilingual group was composed of individuals proficient in English and Spanish whose experience with both began before the age of ten. The late bilingual group consisted of individuals proficient in English and Spanish and who started learning their second language at age fourteen or later. The monolingual group included individuals who had experience with only English, or who, in addition to English, also had experience with other languages that began at any age but that resulted in a level of proficiency that was self-assessed at the “Novice” level. Finally, concerning gender, an effort was made to have an equal number of males and females in the study, though a perfect balance was not achieved. Please refer to Table 2 for a summary of information on the study’s participants.

**Participant Characteristics.** The afore mentioned survey collected information that gave a more complete picture of the study’s participants, the results of which are described here. First, the group’s ethnic composition is notable: The majority of the early bilingual (EB) group is Hispanic or Latino/a, including those who are Hispanic or Latino/a and White, at 29 of the 31
participants, or 93%. The remaining two participants (6%) were White. The late bilingual (LB) group, on the other hand, is 94% non-Hispanic White individuals, and the monolingual control (MC) group is entirely composed (100%) of this ethnicity. This shows a contrast between the EB group when compared with the LB and MC groups, also dividing participants’ ethnicity into two rather homogenous groups.

Table 2
Survey findings

<table>
<thead>
<tr>
<th></th>
<th>Whole Group</th>
<th>Early Bilinguals (EB)</th>
<th>Late Bilinguals (LB)</th>
<th>Monolingual Controls (MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n</strong></td>
<td>102</td>
<td>31</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>57 (56%)</td>
<td>21 (68%)</td>
<td>15 (44%)</td>
<td>21 (57%)</td>
</tr>
<tr>
<td>Male</td>
<td>45 (44%)</td>
<td>10 (32%)</td>
<td>19 (56%)</td>
<td>16 (43%)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
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<td></td>
</tr>
<tr>
<td>Range</td>
<td>18-29</td>
<td>18-29</td>
<td>20-28</td>
<td>18-26</td>
</tr>
<tr>
<td>Mean</td>
<td>22</td>
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<td>22</td>
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<tr>
<td>Mode</td>
<td>21</td>
<td>22</td>
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<td>21</td>
</tr>
<tr>
<td><strong>Ethnicity</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Asian</td>
<td>1 (1%)</td>
<td>1 (3%)</td>
<td>1 (3%)</td>
<td>White: 37 (100%)</td>
</tr>
<tr>
<td>Hispanic or Latino/a: 22 (21%)</td>
<td>Hispanic or Latino/a: 21 (68%)</td>
<td>Hispanic or Latino/a and White: 8 (26%)</td>
<td>Hispanic or Latino/a and White: 8 (26%)</td>
<td></td>
</tr>
<tr>
<td>Hispanic or Latino/a and White: 8 (8%)</td>
<td>White: 2 (6%)</td>
<td>White: 2 (6%)</td>
<td>White: 2 (6%)</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>72 (70%)</td>
<td>21 (68%)</td>
<td>21 (56%)</td>
<td>37 (100%)</td>
</tr>
<tr>
<td><strong>Profession</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full-time student: 84 (82%)</td>
<td>Full-time student: 25 (81%)</td>
<td>Full-time student: 30 (88%)</td>
<td>Full-time student: 29 (85%)</td>
<td></td>
</tr>
<tr>
<td>Student and other profession: 3 (3%)</td>
<td>Student and other profession: 2 (1%)</td>
<td>Other profession: 3 (1%)</td>
<td>Student and other profession: 1 (0%)</td>
<td></td>
</tr>
<tr>
<td>Other profession: 13 (13%)</td>
<td>Other profession: 4 (13%)</td>
<td>Not specified: 1 (0%)</td>
<td>Other profession: 6 (18%)</td>
<td></td>
</tr>
<tr>
<td>Not specified: 2 (2%)</td>
<td>Not specified: 1 (0%)</td>
<td>Not specified: 1 (0%)</td>
<td>Not specified: 1 (0%)</td>
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<tr>
<td>Table 2 Continued</td>
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<td></td>
</tr>
<tr>
<td><strong>Whole Group</strong></td>
<td><strong>Early Bilinguals (EB)</strong></td>
<td><strong>Late Bilinguals (LB)</strong></td>
<td><strong>Monolingual Controls (MC)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td>• High school diploma or equivalent: 2 (2%)</td>
<td>• High school diploma or equivalent: 1 (0%)</td>
<td>• High school diploma or equivalent: 1 (0%)</td>
<td>• Some college, no degree OR degree not yet completed: 28 (76%)</td>
</tr>
<tr>
<td></td>
<td>• Some college, no degree OR degree not yet completed: 73 (72%)</td>
<td>• Some college, no degree OR degree not yet completed: 19 (61%)</td>
<td>• Some college, no degree OR degree not yet completed: 26 (76%)</td>
<td>• Associate’s degree: 4 (1%)</td>
</tr>
<tr>
<td></td>
<td>• Associate’s degree: 12 (12%)</td>
<td>• Associate’s degree: 5 (16%)</td>
<td>• Associate’s degree: 3 (1%)</td>
<td>• Bachelor’s degree: 4 (1%)</td>
</tr>
<tr>
<td></td>
<td>• Bachelor’s degree: 8 (8%)</td>
<td>• Bachelor’s degree: 3 (1%)</td>
<td>• Bachelor’s degree: 1 (0%)</td>
<td>• Not specified: 1 (0%)</td>
</tr>
<tr>
<td></td>
<td>• Some graduate school, no degree OR degree not yet completed: 6 (6%)</td>
<td>• Some graduate school, no degree OR degree not yet completed: 3 (1%)</td>
<td>• Some graduate school, no degree OR degree not yet completed: 3 (1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Not specified: 1 (1%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of Languages Participant Has Experience With</strong></td>
<td>• 1: 10 (10%)</td>
<td>• 2: 14 (45%)</td>
<td>• 2: 32 (94%)</td>
<td>• 1: 10 (27%)</td>
</tr>
<tr>
<td></td>
<td>• 2: 70 (69%)</td>
<td>• 3: 12 (39%)</td>
<td>• 3: 1 (3%)</td>
<td>• 2: 24 (65%)</td>
</tr>
<tr>
<td></td>
<td>• 3: 16 (15%)</td>
<td>• 4: 2 (6%)</td>
<td>• 4: 1 (3%)</td>
<td>• 3: 3 (8%)</td>
</tr>
<tr>
<td></td>
<td>• 4: 3 (3%)</td>
<td>• 5: 2 (6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 5: 2 (2%)</td>
<td>• 6: 1 (3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 6: 1 (1%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of countries of residence (3 months +)</strong></td>
<td>• 1: 48 (47%)</td>
<td>• 1: 9 (29%)</td>
<td>• 1: 5 (15%)</td>
<td>• 1: 34 (92%)</td>
</tr>
<tr>
<td></td>
<td>• 2: 44 (43%)</td>
<td>• 2: 17 (55%)</td>
<td>• 2: 26 (76%)</td>
<td>• 2: 1 (3%)</td>
</tr>
<tr>
<td></td>
<td>• 3: 7 (7%)</td>
<td>• 3: 5 (16%)</td>
<td>• 3: 1 (3%)</td>
<td>• 3: 1 (3%)</td>
</tr>
<tr>
<td></td>
<td>• Not specified: 3 (3%)</td>
<td></td>
<td>• Not specified: 2 (6%)</td>
<td>• Not specified: 1 (3%)</td>
</tr>
</tbody>
</table>

*Note.* Percentages are rounded, so may not total 100%. Figures are rounded to the nearest whole number.

Other survey results are also rather homogeneous. As far as profession, 83 participants, or 81%, were full-time students. Of those, three also listed other professions: Intern, interpreter and researcher, and secretary. Just 14 participants (14%) did not identify as students, listing a variety of professions: Receptionist, salesperson (2), physical therapy aid, waitress, receptionist, translator, resident assistant, building supervisor, stay-at-home mom, teller, call center representative, data analyst, and intern. Profession was not specified for one participant. Education level also had little variation. The multiple-choice survey question permitted participants to indicate “no formal education” up through “postgraduate study” (all options are
listed with the entire survey in Appendix D). Seventy-three participants, or 72%, indicated “some college, no degree OR degree not yet completed.” Taken in sum, the survey results seem to indicate that the study’s typical participant was a White, full-time undergraduate.

Other variables, however, had more contrast. The survey also gathered information on the number of languages a participant had experience with, which showed some interesting results. 54% of the EB group had experience with three or more languages, versus 6% of the LB and 6% of the MC group, which is quite a large difference; number of languages is also discussed in the results section. Finally, country of residence (for three months or longer) also showed differences between groups. 71% of the EB participants had spent time in two or more countries, a number which was a similar 79% for the LB group, but just 6% for the MC group.

**Participant Compensation.** Participants had the option to choose one of three compensations for their involvement in the study. Individuals could choose to receive $30 cash, a small 3D printout of their brains based on their MRI scan, or “Sona credits”—a requirement for some BYU psychology classes that show the student was involved in the research process.

**Instruments**

**Survey.** As previously described, participants completed a detailed questionnaire about their language background, including what languages they had any experience with, from what age, how they learned the language, and how often they use the language, as well as information on what countries they have spent three or more months in and what languages they used while in the country. The survey also gathered information on demographics, requesting participants provide their age, gender, ethnicity, profession, and education level. The resulting data on age of Spanish acquisition was used to sort participants into research groups. The questions were also designed to quantify participant linguistic background more completely than previous studies on
the topic have done, though not every data point was used in the study’s analysis. In order to facilitate analysis, gender and ethnicity were coded as dichotomous variables. In the case of ethnicity, data were coded as White versus minority; those both White and Hispanic were included in the minority group. Levels of education and Spanish language use were translated to an ordinal scale. Three participants did not complete the survey. As previously mentioned, this survey is found in Appendix D, and its findings are summarized in Table 2.

**MRI Scanning.** All imaging was performed on a 3T Siemens TIM Trio MRI scanner (Erlangen, Germany) using a 32-channel head coil at the BYU MRI Research Facility. Each participant contributed a structural MRI scan and a resting-state functional MRI scan. Structural scans used a T1-weighted MP-RAGE sequence with the following parameters: TR=1900ms; TE=2.26ms; acquisition matrix: 215 × 256; field of view=218 × 250mm; slice thickness=1.0mm; voxel size=.977 × .977 × 1.0mm; flip angle=9°; and number of slices=176; GRAPPA factor=2. Resting state fMRI scans were performed using a T2*-weighted EPI sequence with the following parameters: TR=875ms; TE=43.6ms; slice thickness=1.8mm; acquisition matrix=100 × 100; flip angle=55°; number of slices=72; field of view=180 × 180mm; voxel size=1.8 × 1.8 × 1.8mm; multi-band factor=8; volumes per run=823 (total scan time=12min). EPI scans were oriented parallel to the long axis of the hippocampus.

All MRI scans were imported from DICOM to NIfTI file format using program *dcm2nii* (v. 1JUNE2015). As part of the file conversion process, structural scans were reoriented to the nearest orthogonal using rigid-body transformation and extraneous field of view was cropped. Structural scans were further processed using the Advanced Normalization Tools (ANTs) suite of programs (Avants et al., 2011), which was used to perform skull stripping, tissue segmentation, and cortical thickness calculation using program *antsCorticalThickness.sh*. Skull-
stripped structural scans were then rotated to the same orientation as the functional scans and then normalized to a lab specific template in MNI space using the ants.sh command. ANTs calculates a bidirectional warping from native subject space to template space.

Functional scans were first motion corrected by aligning all volumes to the middle volume using AFNI program 3dVolreg (v. AFNI_16.3.03) and then translated into MNI space using the warp vector fields calculated with ANTs. Scanner drift and residual head motion were then calculated using AFNI program 3dDeconvolve and were then used to identify effects of no interest in the fMRI signal using AFNI program 3dSynthesize. Effects of no interest were subtracted from the resting state data to produce a “cleaned” time course for all voxels.

A data-driven approach was used to define the Default Mode Network (DMN) in the sample. This allowed the examination of the functional connectivity between the regions of the DMN, specifically whether this measure was modulated by research group (that is, early bilingual, late bilingual, or monolingual) or by English or Spanish language proficiency. To identify the DMN, the bilateral retrosplenial cortex was first identified by segmenting the lab-specific template according to the Desikan-Killiany-Tourville protocol using the Joint Label Fusion toolkit and referencing the OASIS-TRT-20 dataset (Klein & Tourville, 2012; Tustison et al., 2014; Wang et al., 2013) via the ANTs command antsJointLabelFusion.sh. The seed region mask was used to extract a mean time course from each subject. Mean time courses were then used to calculate whole-brain correlations using AFNI program 3dTcorr1D. Pearson correlation r-values were Fisher z-transformed to ensure a normal distribution of scores for group-level analysis. The DMN was defined by identifying clusters with significant correlations with the retrosplenial seed region averaged across all subjects. To correct for multiple comparisons, all group-level analyses were thresholded using a voxel-wise p-value of $p<0.01$ and a spatial extent
threshold of \( k > 118 \) contiguous voxels for an overall p-value of \( p < 0.05 \) as determined by Monte Carlo simulations. Five significant clusters were identified: the medial prefrontal cortex, precuneus, retrosplenial cortex, and left and right angular gyri. The retrosplenial and precuneus clusters were immediately adjacent to one another, but since a strict threshold for identifying clusters was used (whereby voxels were required to touch on a face rather than just on an edge or a corner), they were separated out into two different clusters. Usable MRI scans were acquired for 90 of the study’s participants, with excess movement being the primary reason that some scans were excluded from analysis.

**Language Proficiency Assessment.** The study design called for all participants completed an English proficiency test, and any participant with experience with the Spanish language (from taking a semester in junior high to growing up with the language) to take a Spanish proficiency test. The tests were provided by Emmersion Learning, who administered the exams via an online platform, with participants completing them from a home computer.

Both proficiency tests used elicited imitation (EI), in which the test-taker hears an utterance in the target language and is prompted to repeat the utterance as accurately as possible. It is built on working (short term) memory research that shows that the storage capacity of unrelated items in the working memory is limited. If the participant is completely unfamiliar with the language of the utterance they hear, each syllable of the utterance will count towards that limited capacity, reducing their ability to accurately repeat the utterance to only a few syllables. However, a participant can increase what is stored in the working memory by “chunking” individual syllables together into larger units of meaning (Cowan et al., 1992; Cowan, 2001; Miller, 1956). Recent research in language processing has shown that as a learner becomes more proficient in a language, they increase their ability to piece together individual
syllables into larger “chunks” of meaning through their expanded knowledge of grammar and vocabulary (Baddeley, Gathercole, & Papagno, 1998; Ellis, 2001; Gathercole & Baddely, 1993; Speciale, Ellis, & Bywater, 2004). In this way, EI can reliably approximate a learner’s proficiency level by measuring the accuracy of the repetition of utterances of increasing length and complexity (Bley-Vroman & Chaudron, 1994; Burdis, 2014; Chaudron & Russell, 1990; Erlam, 2009; Vinther, 2002). The test is reconstructive in nature, in that the participant must process and reconstruct the prompt—not just rotely repeat it. The participant cannot accurately reconstruct and thus reproduce longer, more complex items if their interlanguage lacks the proper grammatical and lexical competence (Tomita, Susuki, & Jessop, 2009; Vinther, 2002).

This kind of assessment does not directly assess proficiency; instead, EI scores have been shown to correlate highly with other standard measures of oral proficiency across multiple languages, achieving correlations as high as 0.94 (Burdis, 2014; Cook, McGhee, & Lonsdale, 2011; Erlam, 2009; Graham, Lonsdale, Keddington, Johnson, & McGhee, 2008; Graham, McGhee, & Millard, 2010; Millard & Lonsdale, 2011). It is also efficient: In comparison, the OPI is a 20-30 minute conversation with a trained proctor, scored later by two other proctors, costing upwards of $140 per assessment, while an EI assessment requires 15 minutes or less, costs less than $20 per person, and is scored instantly (Burdis, 2014, p. 30; Vinther, 2002, p. 55). In sum, EI can be viewed as a proxy variable to assess proficiency, and can do so quite efficiently as well as accurately.

EI results for this study were delivered as a numeric score that was associated with an ACTFL proficiency level. In order to analyze these data, the associated proficiency level was assigned a number, with a score associated with the “Advanced High” to “Superior” level assigned a 10 to a score associated with no effective proficiency being assigned a 1. The
language tests yielded 78 scores for the English assessment and 68 Spanish scores. Scores were not submitted for every relevant participant largely due to technical issues that did not respond to troubleshooting.

Data Analysis

In order to analyze data, the AFNI suite of software programs (Cox, 1996) was used to pre-process and analyze fMRI data. Spatial normalization was carried out using ANTS, as previously described. Once functional connectivity scores were extracted, SPSS and Excel were used to examine correlations between connectivity scores and other data points using pair-wise correlations, or, in the case of group, repeated one-way ANOVA’s. If subjects were missing a data point for any given test, they were simply excluded from that particular analysis. All statistical analyses and their results are included in Appendix E.
Results

Demographics, Language Background, and MRI Results

The completed surveys offered insight into the participants’ background and language experience. Descriptive statistics for this information are found in Table 2. Data from the surveys were also analyzed for any relationship with MRI results or other variables. All data from statistical testing are included in Appendix E.

First, participants’ demographic information was examined. As with many of the other data collected for the study, participants’ age, gender, ethnicity, and education level were each tested for correlation with connectivity measurements from the five brain regions targeted in the study (namely the precuneus, left and right angular gyri, medial prefrontal cortex, and retrosplenial cortex) using a Pearson correlation. The p-value was calculated for each correlation and compared for significance with an alpha of 0.05. These results demonstrated there were no significant relationships between these variables and MRI results. ANOVA tests did, however, show that the research groups (EB, LB, and MC) differ significantly in some of these measures: The age of the EB (M=22.7, SD=2.991) and LB (M=22, SD=1.883) groups was significantly different from the MC (M=20.8, SD=2.213) group, with the former two older than the latter; a similar pattern was shown with ethnicity, where the MC (M=0, SD=0) group had significantly more White (versus minority) participants than the EB (M=0.936, SD=0.250) and LB (M=0.059, SD=0.239) groups (where White=0, minority=1).

The survey also yielded data on participants’ linguistic background. These data were used to examine the number of languages each participant had experience with, their estimation of their proficiency in each language, and their self-assessment of how often they used each. Some of these data are discussed later; other numbers from the survey were not analyzed for the
study—they were either found not relevant to answering the study’s research questions, or they generated data that were difficult to analyze effectively.

Taken from the information gathered on linguistic background, data on number of languages showed a significant inverse correlation with connectivity in three areas of the brain, namely the left angular gyrus \( r = -0.240, \text{df}=85, p=0.023 \), medial prefrontal cortex \( r = -0.216, \text{df}=89, p=0.041 \), and retrosplenial cortex \( r = -0.289, \text{df}=89, p=0.006 \). An ANOVA showed all three groups differ significantly in number of languages, with the EB group showing the highest mean at 2.8 (SD=1.036), followed by the LB group at 2.1 (SD=0.379) and finally the MC group at 1.8 (SD=0.570).

**Research Group and MRI Results**

Spanish AoA in this study refers to the age at which participants first had contact with the language. This in turn determined their research group, where the EB group consisted of individuals with an AoA of ten or younger, and the LB group with an AoA at 14 or later. The MC group was in turn to consist of monolingual individuals of English, though as mentioned previously, potential participants were not turned away if they had incidental experience with another language that they self-assessed to be at the “Novice” level of the ACTFL scale (27 of the 37 MC participants had this kind of language experience). Information on AoA was also collected for MC participants who reported any experience with the Spanish language, as were data on their Spanish proficiency and use of the language.

Examining these data, MRI results were first compared with research group. Figure 3 depicts the DMN regions and mean z-transformed correlation values (or connectivity scores) for the the three different research groups. A repeated-measures ANOVA revealed no main effect of group or cluster, but does show a significant cluster by group interaction \( F[8,356]=2.236, \text{df}=89, p=0.006 \).
Follow-up t-tests revealed that the interaction was driven by a significant difference between connectivity scores for the EB (M=0.252, SD=0.116) and LB (M=0.324, SD=0.108) groups in the medial prefrontal cortex (MPFC) (t= -2.454, p=0.017).

These results find a significant cluster by group interaction, driven by higher functional connectivity for the LB than EB group in the medial prefrontal cortex, though there were not significant interactions found when examining the other targeted areas of the DMN. Still, these statically significant findings likely indicate differences in attentional or memory processing in the LB group compared to the EB group. Similar to what was discussed in the review of literature, lower connectivity in the default mode network can be present in individuals with mild cognitive impairment as well as Alzheimer’s disease (Greicius et al., 2004; Koch et al., 2012). Interestingly, neither the LB nor EB differed significantly from the MC group’s medial prefrontal cortex connectivity.

**Participants Straddling Research Groups.** It was realized after data were collected that some EB participants did not strictly fit the criteria to be part of one research group only. The study’s design did not exclude EB participants who also had experience learning a language after age 10: All 31 participants of this group had experience learning a language before that age, and
17 also had experience learning a language after age 10 (including learning another language between ages 11-14).

In an effort to see if this fact had a significant impact on other analyses, two-tailed t-tests were performed comparing these subgroups’ MRI scores. Four individuals in the EB group did not have usable MRI results, so connectivity scores from the five DMN areas were compared for 12 participants who only had early language learning experience with 15 who had both early and later experience. This analysis showed there was not a significance difference between the subgroups for any of the five measured brain regions. This indicates the existence of these subgroups was likely not problematic to the study’s results.

**Language Proficiency and MRI Results**

Spanish proficiency was next examined in relation to functional connectivity within the DMN, specifically looking at all targeted DMN regions for correlations with Spanish EI scores. This analysis showed there was no significant correlation in any DMN region. Next, an exploratory whole-brain analysis was conducted to see if there were any regions outside of the five that were specifically examined for the study where functional connectivity with the DMN correlated with Spanish language proficiency. One small region in right dorsolateral prefrontal cortex (MNI coordinates X = 28, Y = 48, Z = 20) was revealed in this analysis (voxel-wise p<0.03, k>31 voxel cluster threshold, overall p<0.05); the area is shown in Figure 4. English EI scores were also measured for correlation with connectivity scores, but there were no significant relationships.
Some additional comparisons were made in effort to understand participants’ Spanish proficiency. An ANOVA showed the means of each group’s Spanish proficiency were all significantly different, with the mean for the MC group lowest at $M=5.188$ (SD=1.760), followed by the LB group at $M=8.192$ (SD=0.981), and the EB group at $M=8.926$ (SD=1.035) (where 1 represents no effective proficiency-Novice Low and 10 represents Advanced High-Superior—see Figure 2). Comparing participants’ self-assessment of how often they use Spanish with their Spanish proficiency yielded a significant positive correlation ($r=0.637$, $p=0.00001$), as did number of languages ($r=0.038$, $p=0.010$), age ($r=0.265$, $p=0.028$), ethnicity ($r=0.501$, $p=0.011E-05$) (where 1 was used for minority participants and 0 for White participants), and estimated proficiency ($r=0.746$, $p=0.00001$) when each compared with Spanish proficiency (see Appendix E). The same data on Spanish usage when directly compared with connectivity scores, however, did not show any significant correlation. Spanish proficiency is also, as previously mentioned, negatively correlated with AoA ($r=-0.426$, $p=0.0003$).

*Figure 4.* Region of right dorsolateral prefrontal cortex showing connectivity correlated with Spanish language proficiency
Limitations

Some elements of the study’s design, as well as some factors that came into play while collecting and analyzing data, were not ideal. First, not every data point was collected for every participant, as discussed in the relevant “Results” sections. In addition, some data were collected but was not easy to analyze, such as participants’ estimation of how much they have used any of their languages in their country or countries of residence.

Another limitation is the participant sample. The best group for studying the long-term effects of learning a language would ideally be the elderly. There were, however, concerns about finding a sufficient number of participants from this population, so the decision was made to study young people. The homogeneity of the study’s participants was also a limitation—it would have been ideal to study a group that was more reflective of the general population, particularly in ethnicity, education level, and profession. The study also did not have the capacity to measure languages other than English and Spanish, and was not able to only recruit participants with experience with one or both of these languages. Either limiting participants to these languages or measuring proficiency of every language would likely yield more exact results.
discussion

research group and mri results

Perhaps the most notable finding from the study is from the analysis on research group and DMN functional connectivity. Analysis showed that there were differences in functional connectivity within the DMN between the LB and EB groups, with the LB group having greater functional connectivity in the area of the medial prefrontal cortex when compared with the EB group. These are interesting findings, and show potential for using language learning as a way to help delay AD and dementia. It is notable that there are contrasting studies: Mechelli et al. (2004) and Luk, De Sa, and Bialystok (2011), and Atkinson (2016) all studied the cognition of and AoA of bilinguals, and all draw the conclusion that early or “lifelong” bilinguals demonstrate the cognitive advantage when compared with late bilinguals—Atkinson even states, “Delays in the development of dementia are unlikely to occur if participants become bilingual during adulthood...[and] it should not be recommended that individuals learn a second language as a method of preventing...dementia” (p. 48). At the same time, there are reasons that support this study’s results. The findings could be in part due to the idea of a cognitive reserve, and also could be related to changes in cognition that may be present when learning a language later versus earlier in life.

interpreting group results. When considering the findings, it is important to consider the concept of cognitive reserve. Researchers have found a number of activities help stave off AD and other dementia, specifically activities that challenge attention and memory, such as formal education, cognitively engaging jobs or hobbies, and activities such as music, video games, and, of course, languages (Anderson, 2015; Craik et al., 2010; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). Though scientists have observed that individuals who participate in
more of these types of activities during their lives tend to be less susceptible to symptoms of dementia, reasons for that effect are not entirely understood. It may be because the brains of these individuals use existing networks more effectively, or that they, with increased cognitive activity, recruit more networks that would not otherwise be active (Scarmeas & Stern, 2003; Stern, 2002). When individuals are learning a language later in life, they are likely engaging in activity that challenges their brain in a way that fosters cognitive reserve, an idea supported by these results.

These findings—showing more DMN connectivity in the LB group compared with the EB group—may then also demonstrate that individuals learning another language later in life may, in fact, be challenging their brains in a way that they would not have learning the same language as a child. As previously discussed, the concept of a “critical period” states that a child acquires a second language using the same process as acquiring their first. According to the theory, this period closes, however, as the individual ages, and subsequent languages are learned through cognitively explicit processes. It follows that this conscious learning of a language requires more cognitive effort than childhood acquisition. It also follows that this additional cognitive effort could lead the brain to develop physical differences associated with, for example, more connectivity in the DMN, considering the plastic nature of the brain. Such results have positive implications for those wishing to give a boost to their brains, but certainly do not discount the benefits of learning a language earlier in life. Languages in and of themselves allow individuals to learn about and connect with others as well as to open personal and professional doors, and it is valuable to learn one at any age.

Scientists have observed a natural process of pruning that takes place in the brain after childhood. There are, however, findings that connectivity can in fact increase in adulthood. One
study shows this while examining language learning specifically. Schlegel, Rudelson, and Tse (2012) conducted diffusion tensor imaging scans of 11 college students who took a nine-month intensive Chinese course as well as scans of 16 college students who did not. The researchers found the brains of the students in the language class showed evidence that white matter reorganized “progressively across multiple sites,” demonstrating cerebral plasticity in connection with second language learning after childhood (p. 1664). This study lends additional support to the idea that learning a language later in life is intellectually challenging enough to change the brain in ways learning a language earlier in life may not, as, at least according to the critical period hypothesis, languages are “acquired” during childhood and “learned” after puberty.

Another study corroborates these findings. Kaiser et al. (2015; see also Bloch et al., 2009), in a study referred to in Table 1, examine trilingual individuals who learned their L1 and L2 simultaneously (labeled simultaneous multilinguals, or SiM’s, n=22) versus successively (labeled SuM’s, n=22). This study is not a direct comparison to the current one, as there was an age difference between the groups, but all participants began acquiring their L1 and L2 before the age of nine. The researchers found significant differences between the groups, however, with the SiM group showing lower gray matter volume compared with the SuM group in the medial frontal gyrus, left and right inferior frontal gyri, right medial temporal gyrus, left inferior temporal gyrus, and right inferior posterior parietal gyrus. The authors of this study suggest the brains of the SiM group have learned to work more efficiently by learning two languages at once, stating, “Growing up in a multilingual environment in early childhood may change the individual’s cortical structure, enforcing it to generally build more efficient synaptic networks for language processing” (p. 4). This hypothesis supports the current study’s findings as well as
the idea that the LB participants’ brains have “worked harder” to learn a language, with physically observable results.

**The Monolingual Control Group.** Notably, however, while there was a significant difference in the medial prefrontal cortex connectivity of the EB and LB groups, neither group’s score was found to be statistically different from that of the MC group. The MC group did include individuals with some experience with more than one language in addition to those with experience with only one. This presents the possibility that these participants obscured the effect of a control group. In order to test this idea, two subgroups were formed, the first composed of true monolinguals (n=12) and the second of those with additional language learning experience (n=24). Connectivity scores from each of the five targeted brain areas were then compared between these subgroups with t-tests. These results, however, did not show a significant difference in the subgroups’ means for any connectivity area (see Appendix E)—which suggests the existence of the subgroups was not problematic to the study’s results. The role the MC group plays in the study’s results are not easy to understand, a fact that in turn underlines the need for further investigation in future research.

**Research Groups, AoA, and Other Data.** Some of the study’s other data points also help explain the study’s results. In addition to using the information to define research groups, Spanish language AoA was gathered as its own variable. These data included participants from all three research groups, as the MC group, as previously explained, included individuals with experience with more than one language if they self-assessed their resulting proficiency as at the “Novice” level. In total, 24 of the 37 MC participants had experience with Spanish.

Spanish AoA is not the same as research group, but analyses do show patterns that relate. First, an ANOVA showed AoA was significantly different for all three research groups, with the
age dramatically the lowest for the EB group (M=0.452, SD=1.767), followed by the MC group (M=13.826, SD=1.642), finally the LB group (M=16.265, SD=3.720). Correlations in turn showed those with a younger AoA were likely to have experience with more languages overall (r= -0.441, p=1.9E-05), use more Spanish (r= -0.420, p=5.4E-05), and be more proficient at Spanish (r= -0.426, p=-.003). As demonstrated, the EB group has the youngest average AoA in the study while the LB group has the oldest. These three factors are more characteristic of the participants with a younger AoA, many of whom are in the EB group.

In addition to its correlation with AoA, number of languages also, as stated in the results section, has a significant negative relationship with the measured connectivity of the left angular gyrus, medial prefrontal cortex, and retrosplenial cortex (see also Appendix E). AoA does not directly correlate with these connectivity scores. However, the negative correlation between AoA and number of languages means those with a younger AoA (and the EB group has a lower mean AoA) are more likely to have experience with more languages—and experience with more languages is in turn associated with lower connectivity scores. This echoes the finding that the EB group had lower medial prefrontal cortex connectivity compared with the LB group. Again, however, these items are not directly correlated.

**Participants Straddling Research Groups.** Mentioned in the results section, 48% of the EB group also had some kind of language learning experience after age 10. Kaiser et al. reported somewhat similar circumstances, that is, that all their participants (both SiM’s and SuM’s) began learning an additional third language at age nine or later. Kaiser et al. still found, however, significant differences between the research groups. They hypothesized: “Despite the fact of a late learned L3[,] the differences based on the age of L2 acquisition persist into adulthood and do not disappear” (p. 6). The conclusion that supports the present study: MRI
connectivity results were not found to be significantly different when comparing the two subgroups of the EB group. This result, as well as Kaiser et al.’s findings, seem to show that the effects of early language learning experiences still hold with additional language learning later in life. Still, it would likely be best to more carefully control these variables in future studies.

Implications for AD and Dementia. The study’s finding that LB’s show increased connectivity compared with EB’s has interesting implications for the treatment of AD. At present, there is little known about the treatment of the disorder, and even less known about curing it: The Alzheimer Association reports, “None of the [pharmacologic] treatments available today for Alzheimer’s disease slows or stops the malfunction and death of neurons…that cause[s]…symptoms and eventually make[s] the disease fatal” (2014, p. 14). Prevention (by its definition) of any pathology is notable, but becomes all the more important when it is one of our primary response to the disease. Indeed, the Alzheimer Association goes on to report that out of known, evaluated non-pharmacologic therapies for the disease, “only cognitive stimulation ha[s] findings that suggest a beneficial effect,” though they also note a dearth of research on the topic (p. 14). These results showing that becoming bilingual after puberty—once the hypothesized “critical period” for learning a language has closed—could influence the brain in ways that helps stave off AD are very important, then. These results could mean the cognitive benefits of bilingualism are not only available to individuals who happen to have been raised speaking more than one language, as studies previously cited in the “Review of Literature” section have found, but that they are available to those who learn a language later in life. This makes language learning for cognitive benefit a potential option for all, but also notably for individuals hoping to help prevent AD and dementia, such as individuals who have a close relative with the disease, genetic predisposition, other risk factors, or simply a concern for developing the disease—a
notable finding. Had the study found that the EB group demonstrated greater connectivity, it could have shown language learning was not an effective option for these individuals.

**Demographics, Language Background, and MRI Results**

It is interesting that age, gender, ethnicity, and education did not have any significant relationship with participants’ observed neural connectivity. These results could be seen as encouraging in terms of the effect of language and cognition not discriminating; they could also have to do with the study’s design.

**Language Cognition and Age.** The study participants’ ages did not have a significant relationship with the functional connectivity of the DMN. There are, of course, studies that show a connection between age and cognition, but either in old age or when looking at a larger span. As previously mentioned, the Alzheimer Association has found higher incidence of AD at older age for older adults (2014, p. 16). Plassman et al. (2007) show similar results: In a sample of 856 individuals 71 years or older, they found 13.9% had dementia, while 37.4% of those 90 or older did. Raz and Lindenberger (2011), however, when examining studies on this topic of age and cognition argue “individual differences among younger adults are not always useful for understanding the aging of brain and behavior” (p. 790). The sample of the present study, ages 18-30, then, may not be the best to measure the effect of age.

This idea has important implications, then, for the entire study and its conclusions about the connectivity scores in the DMN that were found—that is, that young, healthy adults may not show significant differences in cognition because of their stage in cognitive development. Looking at language and cognition specifically, some researchers have found the cognitive “bilingual advantage” is not always apparent in young, healthy adults, but is more visible in an older population and in children: One study had bilingual children, young adults, and older adults.
preform a Simon task. The researchers found a bilingual advantage in the reaction time of the children and older adults, but not the young adults (Bialystok, Martin, & Viswanathan, 2005). Another study looked at the Stroop effect in younger and older bilingual adults, and found a bilingual advantage in the older adults only (Costa & Santesteban, 2004). Bialystok, Poarch, Luo, and Craik (2014) had older and younger bilinguals and monolinguals perform executive function tasks. They found bilinguals tended to perform better, but there was a greater advantage for older adult bilinguals. Bialystok et al. (2012) suggested this pattern is “perhaps because the young adult group is at the developmentally peak age for cognitive control” (p. 6). Whatever the mechanism, it is possible that not all results were apparent in this study of young, healthy adults.

**Other Demographics.** The null results found when comparing gender and MRI results could perhaps be considered encouraging—cognition does not seem to discriminate against age. Still, it has been found that more women are affected by AD (Alzheimer’s Association, 2014; Gao, Hendrie, Hall, & Hui, 1998). It is possible that cognitive differences between genders may appear during aging, but not necessarily before. Whatever the reason for this trend as well as this study’s findings, we need to keep working to understand why there is a difference.

There was also no significant relationship found when examining participants’ ethnicity in relation to MRI findings. In other studies, there have been correlations found between the variables of ethnicity and cognition and/or dementia (Sink, Covinsky, Newcomer, & Yaffe, 2004; Zuckerman et al., 2008), but they have also been found to in turn have to do with factors such as immigration status, level of education, geography, diet, life expectancy, family history of the disease, and even rates of depression and physical activity (Flaskerud, 2009; Masel, Raji, & Peek, 2010; Momtaz, Hamid, Yusoff, & Ibrahim, 2013; Stouten, Veling, van der Helm, Laan, & van der Gaag, 2013). It of course does not follow that ethnicity alone would affect cognition, but
that it would matter because there are also trends in ethnicity and what is valued, how an individual is raised, economic status, and so on. This may be a reason for why ethnicity did not have a correlation with MRI results, as the participants shared many other variables, such as level of education which in turn may indicate, though it was not measured, similar socioeconomic status (as most are college students) and even religion (again, not quantified, but many participants were BYU students, where it has been reported 98.5% of students are Mormon (Schad, 2014)) (see Table 2). The ANOVA results previously mentioned are of note when considering ethnicity, however, namely that the EB group differed in its composition significantly when compared with the other two groups. Just viewing descriptive statistics on the groups’ ethnicity is demonstrative of this finding: 94% of the EB group was Hispanic or Hispanic and White, while 3% of the LB group and a dramatic 0% of the MC group were. The association between Hispanic individuals and a younger AoA is perhaps not surprising, as these individuals seem more likely to grow up around Spanish-speakers—though ethnicity on its own was not significantly correlated with any MRI results. This underlines the fact that ethnicity—and its relation to language and cognitive background—is not unidimensional, but instead one of many interrelated and factors that contribute to language and cognition.

When considering education, it is perhaps surprising that this variable did not factor into MRI results. As stated, a finding of the previously listed studies is that a higher level of education is associated with higher levels of cognition. The results could possibly have to do with how education was measured for this study. While possible responses here allowed participants to specify a level of education below a high school diploma or one of some nine levels of secondary education, other studies finding a positive correlation between education and cognition or dementia have seemed to classify education in fewer levels or in terms more
focused on levels of education below the college level: One defined education in terms of fewer or more than 11 years of schooling (Dufouil, Alpérovitch, & Tzourio, 2003); another as fewer or more than 12 years of school (generally the time required to finish high school) (Banks et al., 2014); another as formal education for five years or less, six to eight years, or nine or more years (Ngandu et al., 2007); and one as the categories “illiterate,” five different levels of primary or secondary education, or four levels of post-secondary education. Perhaps the level of education has a bigger impact when individuals are at an overall lower level of education (while 100% of this study’s participants had at least a high school education, see Table 2), perhaps the participants are too homogeneous to see a positive correlation (with 98% with some level of college education), perhaps this study used too many levels of distinction (ten) to measure education.

**Number of Languages.** As previously stated, the number of languages the study’s participants had experience was found to have an inverse relationship with the connectivity of the left angular gyrus, medial prefrontal cortex, and retrosplenial cortex, indicating those with more languages showed lower connectivity scores. The finding could indicate more languages means less of a chance to develop skills in any one of them to a point that makes a cognitive difference, as resources are spread between more languages rather than their use being focused on one. At the same time, however, there is also the reported positive correlation between number of languages and Spanish proficiency ($r=0.308$, $p=0.010$), indicating those who are better at Spanish are *more* likely—not less—to have experience with more languages. Another consideration may be that participants were asked to list every language they had any experience with, even if it was minimal. These were in turn included in the number of languages statistic, and could have possibly influenced these results. Finally, as mentioned, study results also
showed a negative correlation between number of languages and AoA ($r= -0.441$, $p=1.9\text{E}-05$), which may support the idea of a younger AoA (such as in the EB group) being associated with lower connectivity scores (as the MRI-number of languages results show). Whatever the reason for the association between number of languages and cognition, it seems to show the relationship between cognition and language background is not straightforward. As this study’s results seem to indicate, neural connectivity does not seem to be a matter of knowing more languages, speaking a language better, or having used it for a longer span of time.

**Language Proficiency and MRI Results**

There was no statistical significance found when examining participants’ English EI scores. This is perhaps not surprising, however, considering the little variation in the scores: All participants who took the exam scored between 8 (Advanced Low-Advanced Mid) and 10 (Advanced High-Superior), and an ANOVA showed no significant difference in scores between the three research groups ($F=0.596$, $p=0.554$).

Examining the Spanish language proficiency results, however, a small region in the right dorsolateral prefrontal cortex was found where functional connectivity with the DMN was negatively correlated with language proficiency. According to a neurosynth.org (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011) meta-analysis of fMRI papers reporting activations at this same coordinate, this region is associated with terms related to the cognitive control processes, such as "stop-signal" and "response inhibition," indicating that this region is part of the cognitive control network. DMN activity is often anti-correlated with activation in the cognitive control network, with activation of the DMN related to increased errors in ongoing behavioral performance (Weissman, Roberts, Visscher, & Woldorff, 2006), lower subsequent memory performance (Shrager, Kirwan, & Squire, 2008), and increased mind-wandering
behavior (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; M. F. Mason et al., 2007). Negative correlation between DMN functional connectivity to this region and language proficiency scores indicates that higher language proficiency may be related to greater suppression of the DMN by the cognitive control network in those with greater language proficiency skills, which may in turn support previously mentioned findings that bilingualism is associated with greater executive control, such as being able to suppress irrelevant information.

Another possible explanation is simply that lower proficiency is associated with greater mental effort—an idea that could likely be corroborated by any undergraduate in a 101 language class trying to string new words together to assemble a coherent sentence. As with other findings, this one also has contradictory evidence, some of which is found in the review of literature by Atkinson (2016) titled “Does bilingualism delay the development of dementia?” who writes, “taken together…studies suggest that bilingualism may only be protective if individuals are highly proficient in both languages,” though she goes on to note proficiency alone cannot account for all the variation found when examining language background and cognition and in the resulting studies (p. 47).

**Finding a Language Threshold**

One question these many analyses and findings raise is that of finding a threshold. Surely, the brain does not change after a new student’s first hour in Spanish class. There must be some kind of delineation where learning a language goes from no cognitive difference to a difference—or at least from undetectable cognitive changes to detectable ones. Is there a certain proficiency that has to be obtained in order to find cognitive benefit? Does the language have to be used a certain amount? Does a specific time have to pass? A threshold would be useful information for those wanting to learn another language to receive the cognitive benefits.
However this study’s data do not point to one: Proficiency was not correlated with the connectivity scores of any of the targeted DMN areas. Language use was not at all related. Once more, an older AoA is associated with the LB group (which showed comparatively higher connectivity in one DMN area), yet the older AoA was also found to correlate with lower proficiency, less Spanish use, and fewer languages over all, with the opposite correlations for a younger AoA (associated with the EB group and comparatively lower connectivity scores).

These results could certainly be interpreted to challenge how bilingualism has been defined in other research (see Table 1). Above, the review of literature reported on studies that defined bilingualism largely in terms of regular use of the languages (Bialystok et al., 2007; Chertkow et al., 2010; Craik et al., 2010; Gold et al., 2013; Luk, Bialystok, et al., 2011, 2011; Luk, De Sa, et al., 2011), though one simply sates bilinguals “had learned a second…language,” which could perhaps be interpreted as achieving a certain proficiency (Mechelli et al., 2004, p. 757). The present study’s results, however, seem to indicate these factors should not be used to define bilingualism, at least not if looking to do so in order to study its relation to cognition. Perhaps using language use or proficiency to define bilingualism reduces the chance of finding what factors are actually associated with its cognitive changes.

This study points to some factors that are not associated with cognitive changes, but it also does not offer an abundance of clues to what factors are—just LB (versus EB) group and number of languages had a definite correlation with DMN connectivity scores, though proficiency also correlated with activity in a small area of the brain outside of the DMN. These results do seem suggest that a language is more cognitively challenging with lower proficiency, less time since first coming in contact with it, and less time using it. Could it be that as a language becomes easier from use and practice the mind is in turn less challenged—to the point
it may even show physical changes? If nothing else, we likely should not automatically associate “native like” speech or “regular” use of two languages with higher cognitive benefits.

Implications for Teaching Foreign Languages

What do these results have to say for the learning and teaching of foreign languages? First and foremost, it is important to remember that, as previously stated, language learning has abundant benefits at any stage of life. The possibility that there could be cognitive advantages for those who learn a language later in life versus earlier does not erase how an additional language facilitates communication, fosters relationships, creates and strengthens communities, and opens the way to professional opportunities and international understanding. Language learning is always valuable.

The study’s results should not be seen as a reason to reduce language learning early in life, but instead as a reason to maintain, advocate for, and open opportunities to become bilingual as an adolescent and adult. It is important that language classes be made available in US secondary schools and universities; appropriate foreign language graduation and entry requirements also foster language learning. Universities can facilitate bilingualism by offering a range of languages and course options. Schools could consider creating beginning class options at a slower pace for fewer credit hours (in additional to more traditional classes) to make language learning more accessible to more students, as well as allowing and encouraging auditing language courses and even offering options tailored to advancing the language skills of heritage speakers. Universities can also play a role in making language learning more available to all adults with community education. Language clubs, foreign language housing programs, and study abroad—in secondary education, at universities, or with community rather than academic foundations—are also an important component of building bilingualism. Growing a
multilingual population in this way has the potential to make a significant impact on the advancement of AD and other dementias—as well as the potential to build a stronger society through better communication and understanding.
Conclusion

The study of what Dong and Li (2015) dub “the cognitive science of bilingualism” is complex and fascinating, involving a formidable cadre of variables and factors. In examining the said science, this study has found evidence to suggest exciting implications. Learning a language later in life—and then learning more of them—may have a cognitive impact that at best could play an important and significant role in the fight against an American onslaught of Alzheimer disease and dementia, but at least offers promising evidence that that the brain still experiences plasticity and can yield cognitive benefits even after the commencement of neural pruning at the close of childhood. These findings also leave us—as good research should—with more questions: Where else in the brain does language learning make its mark? How can we best utilize and then maximize this impact? What role do factors like age, education, and ethnicity play in a representative sample—or a population? Why have other studies found results contradictory to those found here? How could researchers perfectly quantify the linguistic experience? What would we find following mono- and multilinguals—and those who switch groups—throughout their early lives into old age? In examining this cognitive science of bilingualism, there are more questions than answers, the cycle of which may someday result in knowledge.
References


Research Participants Needed

If you speak English only, we’d like to know more about you. Study volunteers will complete a short language assessment, a memory test, and an MRI (brain scan), and in return will receive:

- $30
- A picture of your brain

Participation will take 1-2 hours.

Interested? Go to www.BrainAndLanguage.com to find out more.
Are you bilingual? ¿Eres bi-lingüe?

Participate in a study at the BYU MRI Research Facility.

If you speak English and Spanish, we’d like to know more about you. Study volunteers will complete a language assessment, memory test, and an MRI (brain scan), and in return will receive:

- $30
- A picture of your brain
- Your score on our language test
  (so you can find out just how good you are at Spanish and English)

Participation will take 1-2 hours.

Interested? Go to www.BrainAndLanguage.com to find out more.
Appendix B: Screening Questionnaire

Note: This electronic survey was designed to eliminate any potential participants who fell within the criteria for disqualification. Any answers that did not meet the study’s requirements were immediately shown the “thank you” message, the text of which is included directly below.

Thank you so much for your interest!

of the study’s results. Because your information doesn’t fall within these guidelines, we are sorry that we cannot ask you to participate.

We thank you again for your time and wish you the best.

Unfortunately, your information does not meet the requirements for participation in this study. These requirements are in place to ensure the safety of participants and to maximize the accuracy

1. How did you hear about this study?
2. When is your birthday?
3. Are you right- or left-handed?
   a. Right-handed
   b. Left-handed
   c. Ambidextrous
4. What is your native language/are your native languages? (The language or languages you have used to communicate with those around you from birth or a very young age)
   a. English
   b. Spanish
   c. English AND Spanish
   d. Another language or combination of languages
      i. Please list your native language(s)
5. What language(s) do you have a current working knowledge of?
   a. English
   b. Spanish
   c. English AND Spanish
   d. Another language or combination of languages
      i. Please list the languages you have a current working knowledge of
6. Have you ever had a traumatic brain injury (TBI)?
   a. Yes
   b. No
7. Have you ever been diagnosed with a mood or psychiatric disorder, such as attention deficit disorder (ADD/ADHD), anxiety, depression, autism spectrum disorder, alcohol or substance dependence, bipolar disorder, a personality disorder, etc.?
   a. Yes
   i. What neurological condition have you been diagnosed with?
   b. No

8. Have you ever been diagnosed with epilepsy, dementia, mild cognitive impairment, a brain tumor, stroke, multiple sclerosis (MS), Parkinson's disease, amyotrophic lateral sclerosis (ALS), or other neurological condition?
   a. Yes
   b. No

9. Are you color blind or color deficient?
   a. Yes
   b. No

10. Are you pregnant, unsure if you are pregnant, or hoping to become pregnant?
    a. Yes
    b. No

11. Have you ever had an MRI?
    a. Yes
    i. Did you have any complications with your previous MRI?
       1. Yes
       2. No
    b. No

12. Have you ever been injured by a metal object or foreign body, such as a bullet, a BB, shrapnel, etc.?
    a. Yes
    i. Is there any chance you could still have metal fragments in your body?
       1. Yes
       2. No
    b. No

13. Have you worked with metal as a welder, fabricator, etc.?
    a. Yes
    i. Were you ever injured with metal while working with the material?
       1. Yes
       2. No
    ii. Is there any chance you could still have metal fragments in your body?
        1. Yes
        2. No
    b. No

14. Do you have metal braces or permanent retainer that includes metal?
    a. Yes
    i. Please describe your metal dental devices:
    b. No

15. Do you have a tattoo or permanent makeup?
    a. Yes
    b. No
16. Do you have a pacemaker, replacement joint, implant, or other metal in your body that has not been addressed in previous questions? Note: If you are unsure, please select "yes."
    a. Yes
    i. Please describe the device(s):
    b. No

17. Do you weigh more than 300 pounds?
    a. Yes
    b. No

18. Do you find you become uncomfortable in tight spaces, or do you consider yourself claustrophobic?
    a. Yes
    b. No

19. Full name:
20. Phone number:
21. Email address:
22. It looks like you qualify to participate in our study!

If you are interested in doing so, we invite you to continue this survey. You will read about the study and its possible risks and benefits, give your consent to participate, and then indicate when you are available.

    a. Continue Survey
    b. I do not wish to participate
Appendix C: Consent to be a Research Subject

Introduction
My name is Carrie Gold, and I’m a master’s student at Brigham Young University. You may have heard speaking more than one language can influence an individual’s cognition and memory. I’d like to find out if that means learning another language as a kid or as an adult—or if it even matters.

You’ve completed a questionnaire and are qualified to participate. Now we’d like to tell you more about the study and about the risks and benefits of becoming a participant. This will help you decide whether or not you’d like to participate. It’s up to you whether you’d like to or not—doing so is totally voluntary. Take your time reading, and let us know if you have any questions.

If you do have questions about the study, you can contact Carrie Gold at 801-884-7454 or CarrieEGold@gmail.com. If you have questions about your rights as a research participant, contact an IRB administrator at 801-422-1461, irb@byu.edu, or at A-285A ASB, Brigham Young University, Provo, UT 84602.

Procedures
Participating in this study will take about two hours total, and will include the following:
1. You already completed a questionnaire about your background and experiences with different languages.
2. We’ll ask you to indicate when you’re available to come to the McDonald Building on the south side of the BYU campus. Someone will contact you to schedule a specific time. You’ll complete the rest of the research tasks during this appointment.
3. At your specified date and time, you’ll check in at 155 McDonald Building on the BYU campus
4. After you’re all checked in, you’ll complete the following: An English language assessment, a Spanish language assessment (if you speak Spanish), and a memory test.
5. Next, you’ll get ready for the MRI brain scan: You’ll be given one more screening form, you’ll remove anything metal (like spare change or hair clips) from your person, and you’ll secure your belongings in a locker. You may also be asked to change your clothes if you’re wearing things with metal on them.
6. Next, an MRI will be done of your head. MRI detects the magnetic properties of fluids and tissues and allows us to obtain high-resolution images of your brain. This will involve your lying quietly inside the center of a large doughnut-shaped magnetic machine for up to an hour. Your head will be positioned with cushions to keep it in the proper position. Towards the end of your scan, we will ask you some questions that you will answer while we continue the scan. This whole process will take about 60 minutes.
7. Finally, you’ll retrieve your belongings and change if necessary.
8. Before you leave, you’ll also receive your compensation money.

Possible Risks
We want to make sure you’re informed about any possible risks or discomforts of participating in this study.
We don’t anticipate any negative outcomes from completing the questionnaire or language assessment. As far as undergoing an MRI, there are no known negative effects from the scan process itself or being exposed to the machine’s magnetic field. However, because the scanner is very magnetic (and attracts other magnetic objects), it is important that we know about anything metal on or inside you, since there is a risk from being injured by something that is drawn to the machine’s magnet. Tell us if you have any metal clips or plates in your body; a pacemaker; metal fragments in eyes, skin, or body; a heart valve replacement; brain clips; venous umbrella; intracranial bypass; renal or aortic clips; prosthetic devices such as middle ear, eye, joint, or penile implants; joint replacements; hearing aid; neuro-stimulator; insulin pump; IUD; shunts/stents; metal mesh/coil implants; metal plates, pins, screws, or wires or any other metal implant; a tattoo; permanent makeup; if you have been a metal worker or welder; or if you have had an aneurysm surgery. In addition, we’re not sure if MRI’s are harmful to an unborn baby, so if you are pregnant or may be pregnant, we do not want you to participate.

Other than the scan itself, some people may find parts of the scanning process uncomfortable. The scanner makes a loud banging noise while operating. For this reason, you will be given earplugs to wear. In addition, receiving a scan involves lying inside the tube—or “donut hole”—of the machine. For this reason, some people get anxious or feel claustrophobic. If this happens to you, let us know, and we will stop the scan immediately. Finally, you may experience some muscular aches and fatigue from lying still on your back during the scan.

**Possible Benefits**
There aren’t really direct benefits to you from participating, but there are still some positive outcomes. Significantly, your participation will help contribute to new knowledge about multilingualism. In addition, we can share some results with you. We will give you the results to your language assessment, so you can know just how good you are at English and/or Spanish. We will also email you images from your brain scan.

**Incidental Findings**
We aren’t medical doctors. The MRI scans being performed are for research purposes only and are not of clinical quality. If we do observe any abnormalities on your scans, though, they will be forwarded to be read by a qualified medical professional, who will contact you with any possible concerns. From there, it will be your responsibility to arrange any clinical scans with your primary care physician.

**Confidentiality**
Research records will be kept completely confidential to the extent provided by law. Your identity will not be disclosed without your consent unless required by law. Your raw, de-identified MRI scans may be shared with other researchers for valid scientific purposes at a future time point. Your MRI scans may also be combined into larger databases for studies looking at brain/behavior measures in the larger population. If your MRI scans are shared in this manner, all identifying information will be removed so that you will not be identified from the data.
Compensation
You will be given $30 for your participation in this study which will be given to you after you've completed everything. If you do not complete all the research tasks, such as if you ask to be let out of the MRI scanner early or if the researcher needs to terminate the study for some reason, you will be given $10.

Participation
Participation in this research is voluntary. You have the right to withdraw at any time or refuse to participate entirely without concern of penalty or question or jeopardy to your class status, grade, or standing with the university.

Statement of Consent
By signing below, you signify you have read and that you understand the above consent, and that you desire of your own free will to participate in this study. You will receive a copy of the above consent via email.
Appendix D: Language Background Survey

1. What is your full name?

2. What is your phone number?

3. What is your email address?

4. What is your gender?
   a. Male
   b. Female
   c. Other:

5. How old are you?

6. What is your current occupation? (If you are a full-time student, please list "student")

7. Which of the following best describe you? Please check all that apply.
   a. Asian
   b. Black or African American
   c. Hispanic or Latino/a
   d. Native American, American Indian, or Alaskan Native
   e. Native Hawaiian or other Pacific Islander
   f. White
   g. Other
   h. I prefer not to answer

8. What is the highest level of education you have completed?
   a. No formal education
   b. Some schooling, no high school diploma or equivalent OR diploma not yet completed
   c. High school diploma or equivalent
   d. Some college, no degree OR degree not yet completed
   e. Associate’s degree
   f. Bachelor’s degree
   g. Some graduate school, no degree OR degree not yet completed
   h. Master’s degree
   i. Doctoral degree
   j. Postgraduate study

9. What languages do you have any experience with? This may be from speaking the language while growing up, taking a class, spending time in another country, and so on. The following questions ask you to tell about this language experience.

   Please think about one language at a time. Start with your native language.
10. Name of language #1

11. What is your proficiency in language #1?

Please use this information to estimate your language proficiency

NOVICE LOW
I can say a few words and some memorized phrases.

NOVICE MID
I know some words and phrases, but I probably wouldn't be able to hold a conversation with someone.

NOVICE HIGH
I can use short or incomplete sentences to have a brief, simple conversation about something familiar, but I don't understand everything and can't say a lot back.

INTERMEDIATE LOW
I can talk about familiar things, like family and hobbies, but not for very long. It's still hard to understand and answer questions, and people don't always understand me.

INTERMEDIATE MID
I can have conversations about familiar things, like myself, family, home, and daily activities without much trouble. More complex conversations, however, are still too hard.

INTERMEDIATE HIGH
I can handle uncomplicated tasks and basic social exchanges. I can speak using the past, present, and future tenses. I can talk for longer than a single sentence--up to paragraph-length, but not always. I still make a fair number of mistakes.

ADVANCED LOW
I can participate in informal and some formal conversations. I can use the past, present, and future, and people generally don't get confused when I speak. Grammar is still sometimes hard, and I still make mistakes. I can't always express myself.

ADVANCED MID
I can talk about almost anything I want to with clarity and accuracy, but abstract or complex topics are still sometimes too difficult for me to talk about for a long time. Overall, people understand me.

ADVANCED HIGH
I can talk about a wide range of topics, and I'm able to talk about abstract ideas, use specialty vocabulary, and hypothesize and support my opinions. I can't do this 100% of the time, though. I still make mistakes, and they tend to follow a pattern.
SUPERIOR
I can communicate with accuracy and fluency in all settings and on all topics, including abstract or complex ideas or topics with specialty vocabulary. I might make an occasional error, but my errors don't follow any particular pattern.

DISTINGUISHED
I am articulate in the language, and I can use it skillfully, accurately, and effectively. I can use persuasive and hypothetical language. My accent does not distract listeners. I use cultural references, such as idioms, from the language's culture(s). My errors are very occasional and isolated.

12. How did you learn OR are you learning this language?

Note: If this is your native language, please simply state so.

*Example answer: In college classes, practicing with roommates, and with a host family in Colombia*

13. At what age did you begin learning this language?

Note: If this is your native language and those around you used it since your birth, just state "since birth."

14. How often do you currently use this language?

*Example answer: A few times a week for a couple hours*

15. For what purposes do you currently use this language?

*Example answer: Tutoring others, listening to the radio, and reading things posted on Facebook*

16. Have you ever used or studied another language?

*Questions 10-16 were repeated for each subsequent language*

Where are you from? What other countries have you spent time in? The following questions ask about countries where you have lived.

17. What country were you born in?

What countries have you lived in for three months or longer? Please list the countries one at a time. Include the country you were born in.

18. Country of residence #1
Example answer: United States

19. Approximate length of residence in country #1

Example answer: 27 years

20. Languages spoken while in country #1

Example answer: English, Spanish, French

21. What percentage of time did you/do you use each language while in country #1?

Note: Percentages should add up to 100

Example answer: English 85%, Spanish 10%, French 5%

22. Have you spent three months or more in another country?

Questions 18-22 were repeated for each subsequent country of residence
## Appendix E: Statistical Results

**Pearson Correlations of DMN Region Connectivity Scores and Demographics/Language Background**

<table>
<thead>
<tr>
<th>DMN Region</th>
<th>Precuneus</th>
<th>Left Angular Gyrus</th>
<th>Medial Prefrontal Cortex</th>
<th>Right Angular Gyrus</th>
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*Correlation is significant at the 0.05 level*
Pearson Correlations of Demographics and Language Background

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*Correlation is significant at the 0.05 level

T-Test: MC Participants with One Language (n=10) vs. MC Participants with Multiple Languages (n=24)

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<th>Precuneus</th>
<th>Left Angular Gyrus</th>
<th>Medial Prefrontal Cortex</th>
<th>Right Angular Gyrus</th>
<th>Retrosplenial Cortex</th>
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*Significant at the 0.05 level

T-Test: EB Participants (n=12) vs. EB Participants with Later Language Experience (n=15)

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<th>Right Angular Gyrus</th>
<th>Retrosplenial Cortex</th>
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<tr>
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<td>p-value</td>
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<td>0.694</td>
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*Significant at the 0.05 level
## ANOVA and Post-Hoc T-Test for DMN Regions, Survey Data, and Proficiency

|                  | ANOVA |  |  | T-Test |  |  |
|------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                  | Group | F-value | p-value | EB vs. LB | t-value | p-value | EB vs. MC | t-value | LB vs. MC | t-value | p-value |
| Precuneus        | EB n=27 | M=0.252 | SD=0.116 | LB n=31 | M=0.324 | SD=0.080 | MC n=32 | M=0.293 | SD=0.077 | F=0.527 | p=0.592 |
| Left Angular Gyrus | EB n=27 | M=0.282 | SD=0.125 | LB n=31 | M=0.314 | SD=0.085 | MC n=32 | M=0.311 | SD=0.085 | F=0.892 | p=0.413 |
| Medial Prefrontal Cortex | EB n=27 | M=0.252 | SD=0.116 | LB n=31 | M=0.324 | SD=0.108 | MC n=32 | M=0.293 | SD=0.077 | F=3.704 | p=0.029* |
| Right Angular Gyrus | EB n=27 | M=0.308 | SD=0.126 | LB n=31 | M=0.286 | SD=0.101 | MC n=32 | M=0.290 | SD=0.101 | F=0.259 | p=0.773 |
| Retro-splenial Cortex | EB n=27 | M=0.280 | SD=0.074 | LB n=31 | M=0.297 | SD=0.068 | MC n=32 | M=0.308 | SD=0.076 | F=1.124 | p=0.330 |
| Age              | EB n=27 | M=22.70 | SD=2.991 | LB n=31 | M=22.00 | SD=1.883 | MC n=32 | M=20.80 | SD=2.213 | F=5.705 | t=1.203 | p=0.233 |
| Gender           | EB n=31 | M=0.323 | SD=0.475 | LB n=34 | M=0.559 | SD=0.504 | MC n=37 | M=0.432 | SD=0.502 | F=1.857 | p=0.161 |
| Ethnicity        | EB n=31 | M=0.936 | SD=0.250 | LB n=34 | M=0.059 | SD=0.239 | MC n=37 | M=0.0 | SD=0.502 | F=235.083 | t=14.463 | p<.00001* |
| Level of Education | EB n=31 | M=3.613 | SD=1.054 | LB n=34 | M=3.382 | SD=0.954 | MC n=36 | M=3.333 | SD=0.676 | F=0.893 | p=0.413 |
| Number of Languages | EB n=31 | M=2.839 | SD=1.036 | LB n=34 | M=2.088 | SD=0.379 | MC n=37 | M=1.811 | SD=0.570 | F=18.994 | t=3.947 | p<.00001* |

*Significant at the 0.05 level
<table>
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*Significant at the 0.05 level