A Bilingual Advantage? The Functional Organization of Linguistic Competition and Attentional Networks in the Bilingual Developing Brain

by

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To my parents, whose love encouraged my curiosity.

Para mis padres, cuyo amor estimuló mi curiosidad.

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ABSTRACT

Early life experiences are thought to alter children's cognition and brain development, yet the precise nature of these changes remains largely unknown. Research has shown that bilinguals' languages are simultaneously active, and their parallel activation imposes an increased demand for attentional mechanisms even when the intention is to use one of their languages (cf. Kroll & Bialystok, 2013). Theoretical frameworks (Adaptive Control hypothesis; Green & Abutalebi, 2013) propose that daily demands of dual-language experiences impact the organization of neural networks. To test this hypothesis, this dissertation used functional Near-Infrared Spectroscopy (fNIRS) to image brain regions in young monolingual and bilingual children (53 English monolinguals, 40 Spanish-English bilinguals; ages 7-9) while they performed a verbal attention task assessing phonological interference and a non-verbal attention task assessing attentional networks. The results did not reveal differences in behavioral performance between bilinguals and monolinguals, however, the neuroimaging findings revealed three critical differences between the groups: (i) bilingual children engaged less brain activity in left frontal regions, than monolinguals, when managing linguistic competitors in one language thus suggesting efficient processing; (ii) bilinguals showed overall greater brain activity, than monolinguals, in left fronto-parietal regions for attentional networks (i.e., alerting, orienting, and executive); and (iii) bilinguals' brain activity in left fronto-parietal regions during the Executive attentional network was associated with better language abilities. Taken together, these findings suggest that attentional mechanisms and language processes both interact in bilinguals' left fronto-parietal regions to impact the dynamics of brain plasticity during child development. This

work informs neuro-cognitive theories on how early life experiences such as bilingualism impact brain development and plasticity.

CHAPTER I

Introduction

Bilingualism brings a variety of linguistic, cultural and social experiences to children: they must be able to flexibly alternate between two languages, identities, and literacies. Theoretical perspectives suggest that attentional control mechanisms are integral for children's language acquisition, such as supporting the adjudication of competing linguistic input when distinguishing the meanings of similar sounding words (e.g., "I" versus "eye") in sentence structures (Mazuka, Jincho & Oishi, 2009). Bilingualism creates a doubled demand for language processing by activating features from both languages, which in turn may impose an increased demand for attentional mechanisms even when the intention is to use one language (Dong & Li, 2015; Hernandez, Li, & MacWhinney, 2005; Kroll & Bialystok, 2013). Attentional control is the ability to focus selectively, cast out unnecessary information, and shift focus accordingly (Posner, 2012). Numerous studies have documented 'advanced' attentional control performance by bilinguals relative to monolinguals (Bialystok, 1999; Bialystok, Craik, & Freedman, 2007; Bialystok & Martin, 2004; Craik, Bialystok, & Freedman, 2010; Kovács & Mehler, 2009; Singh et al., 2015; Yang, Yang, & Lust, 2011; Yoshida, Tran, Benitez, & Kuwabara, 2011). Yet, the notion and nature of a "bilingual cognitive advantage" continues to be the subject of great scientific debate, with inconclusive evidence in support of advantage, delay, or no impact of bilingualism on cognitive function (Antón et al., 2014; Hilchey & Klein, 2011; Paap &

Greenberg, 2013; Paap, Johnson, & Sawi, 2015). While some researchers concur that bilingual experiences may extend to alter domain-general mechanisms, others consider the impact of such experiences to be restricted within linguistic processes (Casaponsa, Carreiras, & Duñabeitia, 2015; Lallier, Acha, & Carreiras, 2016). Neuroimaging offers a potential solution for uncovering bilingual differences on cognitive processes that may (or may not) manifest as behavioral differences in task performance (Vaughn, Greene, Ramos Nuñez, & Hernandez, 2015). Thus, this dissertation aims to be the first to investigate whether bilingualism impacts attentional control mechanisms that support the adjudication of competing linguistic input, in performance and in the developing brain.

To shed light on the mechanisms by which bilingual experiences might influence children's cognitive development, I will investigate whether bilingualism yields early-emerging changes on the functional organization of attentional control mechanisms during childhood—a period of rapid brain development. This inquiry will be accomplished via a targeted investigation to answer three research questions: does bilingualism have an impact on the brain's functional organization of children's attentional networks? Is there a cortical overlap in the brain between the processes of attentional control and the adjudication of competing linguistic input? And, does cortical activity, within an overlapping brain region for language processing and attentional control, explain advantageous performance in bilingual children? Thus, this dissertation has three research aims: (1) to uncover children's brain activity when processing linguistic competitors, (2) to uncover the neurodevelopmental organization for attentional networks in children, including whether the regions engaging attentional networks are the same regions that differ in functionality between bilinguals and monolinguals during language processing, and (3) to investigate whether any differences are due to language abilities or attentional control performance,.

To answer the experimental questions posed by this dissertation, I tested early-exposed Spanish-English bilinguals and English monolinguals (ages 7-9) during a developmental period in which these abilities are malleable and especially employed in educational settings. I used functional near-infrared spectroscopy (fNIRS) to image the frontal, temporal, and parietal cortices while children completed a linguistic competition task (e.g., selecting a picture when simultaneously shown another picture with a similar initial sound, such as *candy – candle* vs. *candy – pencil*). Children also completed the Attentional Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002), which is a nonverbal visuospatial attention task that builds upon a cue alerting and orienting scheme (Posner, 1980) along with a flanker paradigm (Eriksen & Eriksen, 1974). I hypothesize that bilingual and monolingual children will differ in their responses (performance and/or brain activity) in tasks demanding attentional control for processing linguistic and non-linguistic competitors. If found, I expect my results to reveal that the neural resources within left frontal regions, that are necessary for language selection, are altered for nonverbal attentional mechanisms as a result of bilingualism. The findings will highlight the impact of early language experiences on brain plasticity and the functional reorganization of mechanisms via daily experiences during brain development. These results will inform theories of child brain and cognitive development, and will have practical implications for parents and educators of young bilingual children.

Theories on Bilingual Language Selection and Cognitive Advantages

From word recognition to discourse, even when the intention is to use just one of their languages, bilinguals' languages compete for selection (Dong & Li, 2015; Hernandez et al., 2005; Kroll & Bialystok, 2013; Kroll, Bobb, & Hoshino, 2014; Kroll, Dussias, Bice, & Perrotti, 2015). For example, when an individual must select an image for the word "*candy,*" as they hear the phonemes "*c-a-…*" other words whose names begin with similar phonemes may come to mind and compete for selection, such as "*cart,*" "*can*" or "*candle*" –these are known as within-language competitors. Bilinguals also experience between-language competition since words in their other language are also activated, so that Spanish-English bilinguals also activate words like "*casa [house],*" "*cama [bed]*" or "*carta [letter]*". Previous work shows that when a word is presented along with images of between-language competitors, bilinguals tend to look at them prior to selecting the target image (Bartolotti & Marian, 2012; Blumenfeld & Marian, 2011, 2013; Marian & Spivey, 2003). Bilinguals also tend to respond faster to cognates whose written form and meaning is similar across languages (e.g. *piano* for English and Spanish) and slower to interlingual homographs whose written form is similar across languages but have different meanings (e.g. *pie* in Spanish is "foot") (Dijkstra, Grainger, & van Heuven, 1999).

In the context of bilinguals' joint-language activation, two models have been proposed to explain how increased demand on linguistic selection uses attentional control mechanisms. One is the Bilingual Interactive Activation Model (BIA+; Dijkstra & Van Heuven, 2002), which takes a domain-specific bottom-up approach. The BIA+ has employed computational models using phonologic and semantic lexical representations to simulate how languages become active and compete for selection in the context of both within- and between-language competitors (e.g., De Groot & Christoffels, 2006). The model simulates the representations of words in hierarchical nodes and how adjacent representations are inhibited in both languages during word selection. Second, the Inhibitory Control model (IC; Green, 1998) is based on the Supervisory Attentional System (Norman & Shallice, 1986; Shallice & Burgess, 1996). This model takes a top-down approach and suggests bilinguals recruit domain-general Executive Function (i.e., attentional and inhibitory control) mechanisms to manage language competition. These models are not mutually exclusive; they simply differ with regard to how bilinguals' joint-language activation influences (and is influenced by) attentional control. That is, linguistic properties determine the role of Executive Function mechanisms for the BIA+ model, while those mechanisms are a central part of the IC model. Importantly, both models indicate the need for a more complete description of how attention is managed during language processing in bilinguals and of the outcome of such management, especially within the brain. The notion behind the 'bilingual cognitive advantage' hypothesis was based on the IC model, in which it was first suggested that alternating between languages could improve attentional control mechanisms, and behavioral performance when tested individually (Bialystok, 1999).

Contradictory evidence has emerged on whether bilinguals show advanced attentional control performance across diverse bilingual populations who vary in the degree of language similarity and cultural backgrounds (Tran, Arredondo, & Yoshida, 2015; Yang et al., 2011), age of second language acquisition (simultaneous vs. sequential bilinguals; Kapa & Colombo, 2013), and age (infants vs. school age vs. adults; Antón et al., 2014; Hilchey & Klein, 2011; Paap & Sawi, 2014). For instance, a study by Kapa and Colombo (2013) demonstrated that after controlling for age and vocabulary knowledge, children (ages 6-14) with early bilingual exposure (before age 3) had faster reaction times than monolingual peers and bilinguals with later second language exposure (after age 3) (see also Tran et al., 2015). Using the same task, Antón et al. (2014) failed to find any evidence of better attentional control in bilinguals (ages 7-11) who were living in a region where two languages are often used simultaneously. Examples like these two studies have fueled a debate on the reliability of bilingual benefits for attentional control

(Duñabeitia & Carreiras, 2015). A review by Hilchey and Klein (2011) revealed two important issues in this literature: first, any advanced performance for bilinguals in attentional control appears random and, therefore, is possibly due to other variables impacting performance, such as those aforementioned, IQ, or socioeconomic status (see also Morton & Harper, 2007, 2009). Second, there is a developmental variation for studies that find bilingual differences, as those assessing young children (before age 5) or elderly tend to often show a bilingual advantage in comparison to those assessing older children and young adults (Antón et al., 2014; Bialystok, 1999; Carlson & Meltzoff, 2008; Costa, Hernández, & Sebastián-Gallés, 2008; Duñabeitia et al., 2014; Kovács & Mehler, 2009; Singh et al., 2015). After age 5, any differences between bilinguals and monolinguals are likely not observed due to peak performance for a variety of standard experimental measures (Antón et al., 2014; Duñabeitia et al., 2014). The precise impact of bilingualism might still be in place for attentional control, but easier to detect in very young or very old populations who tend to show more variance in their performance (see also Bialystok, Craik, & Luk, 2012). Thus, this dissertation includes a sample of an age range (7-to-9 year olds) in which previous research does not support the 'bilingual cognitive advantage' (Antón et al., 2014), in order to investigate whether bilingual influences in attentional control performance are observed in the brain.

Bilingual Language Control in the Brain: The Adaptive Control Hypothesis

One of the fundamental questions in brain development is how different cortical regions develop their functional specificity for higher cognitive functions and are related to human behavior. The neural 'Interactive Specialization' hypothesis suggests that multiple neurons are simultaneously active early in development, and consequently neural networks are poorly organized (Johnson, 2001, 2011). Throughout development, as networks compete for allocation over various cognitive functions, neurons begin to specialize within particular brain regions (Johnson, 2001, 2011). The outcome of such competition is the establishment of neural networks that are most efficient (or specialized) for specific cognitive abilities (Johnson, 2001, 2011). For instance, neonates (0-3 days old) show bilateral brain activation in temporal regions when they begin to hear speech (May, Byers-Heinlein, Gervain, & Werker, 2011). Shortly thereafter, 5-day-old neonates' brain activity is confined to left temporal regions (Imada et al., 2006). As infants gain greater experience with their linguistic environment, brain activity to speech processing includes left frontal and temporal regions (Dehaene-Lambertz et al., 2006). Bilingualism is one of these common early-life experiences thought to influence an individual's mind and brain, yet little is known on how bilingual experiences can alter the brain's specialization for language and cognitive functions.

The Adaptive Control hypothesis provides a framework on the neural and cognitive control processes that adapt to daily demands of language control for bilinguals (Abutalebi & Green, 2016; Green, 2011; Green & Abutalebi, 2013). It is important to note that this framework does not propose that the same mechanisms at play for joint-language selection will have an *advantageous* transfer effect on domain-general cognitive mechanisms, as suggested by the research showing bilinguals perform better than monolinguals. However, the framework alludes to the likelihood that these mechanisms may alter brain networks, and acknowledges the lack of evidence supporting a 'bilingual cognitive advantage' in domain-general Executive Function mechanisms.

The Adaptive Control hypothesis (Green & Abutalebi, 2013) proposes three interactional bilingual contexts (single-language, dual-language and dense-code switching contexts), how each differs and how they impact the adaptation of eight cognitive control processes. Of interest to this dissertation, is the single-language context in which each language is used in different environments; for instance, bilingual children who took part in this dissertation project spoke English in the school environment, whereas Spanish was used at home with family members. The single-language context demands for bilinguals to suppress the language that is not in use for an extended period of time, in which case the Adaptive Control hypothesis suggests that this context impacts two of the eight cognitive control processes; they are, 'goal maintenance' (i.e., sustained attention) and 'interference control,' the latter includes conflict monitoring (i.e., selective attention) and interference suppression (i.e., inhibitory control). The framework, supported by previous research, suggests a neural network that includes frontal and parietal regions supports both of these cognitive control processes (Abutalebi & Green, 2016; Green & Abutalebi, 2013). Frontal regions are thought to be involved in resolving conflict, holding and storing relevant information in mind, while parietal regions are thought to be involved in monitoring conflicting and non-conflicting information (Corbetta & Shulman, 2002). Altogether, the network includes the dorsal anterior cingulate cortex/pre-supplementary motor area, left prefrontal cortex, left caudate, and bilateral inferior parietal lobes (e.g., Abutalebi & Green, 2016; Kerns et al., 2004; Luk, Anderson, Craik, Grady, & Bialystok, 2010). Given that fNIRS can only measure cortical regions (not sub-cortical), the frontal and parietal regions are of interest to the present project.

Little is still known about the emergence of cognitive processes in the brain, and whether bilingual environments could impact their specialization and functional organization. Both goal maintenance and interference control processes can be assessed via inhibitory and attentional control experimental paradigms. Luk et al. (2010) used a combination of a flanker (attention) and Go/No-Go (inhibition) tasks to assess both of these mechanisms simultaneously, and found bilinguals recruit an extensive bilateral network while monolinguals recruit left temporal and parietal regions. However, Luk et al. (2010)'s paradigm makes it difficult to dissociate between inhibitory and attentional control mechanisms. Garbin et al. (2010) used the Go/No-Go and showed that bilingual adults activate left inferior frontal regions, while monolingual adults activated right inferior frontal regions (see also Bialystok et al., 2005). Yet, none of these studies have investigated the development of the fronto-parietal network and its direct link to attentional control and language processes. Two exceptions are a recent study by Barac et al. (2016) in which they use electrophysiological event-related potentials (EEG/ERPs) while 5-year-old children completed a Go/No-Go task, and found bilinguals show larger prefrontal cortex amplitude and latencies (P3) than monolinguals (Barac, Moreno, & Bialystok, 2016). Another exception is my recent work (Arredondo, Hu, Satterfield, & Kovelman, 2015), in which I used fNIRS while children (7-13 years old) completed a flanker (attentional control) task and, similar to Garbin et al. (2010)'s results, found monolinguals activate right frontal regions, whereas bilinguals exhibited left frontal activation. Given these results, left frontal regions may be one possible set of loci that begins to alter early in development as a function of dual-language experiences (Green & Abutalebi, 2013).

Specific Aims and Hypotheses

This dissertation was designed to investigate whether daily demands of dual-language experiences impact the adjudication of competing linguistic input and the functional organization of attentional networks in a child's developing brain, along with their behavioral performance. I hypothesize that bilingual and monolingual children will differ in their responses (performance and brain activity) for processes of language competition and attentional control. If my hypothesis is supported, I expect the results will reveal that the neural resources within left frontal brain regions, that are necessary for language processing, functionally re-organize nonverbal attentional control processes as a result of bilingualism. Hence, bilingual children's brain activity for verbal and nonverbal attention processes may overlap within left frontal regions. In contrast, I expect monolingual children's results to show activation in left frontal regions for linguistic competition and right frontal regions for nonverbal attentional control processes. Furthermore, if bilinguals perform better in the attentional control task (higher accuracy, faster response time) than monolinguals, then differences in bilinguals' brain activity should be related to 'advanced' performance.

I devised a project consisting of two experimental paradigms that demanded attentional processes, a linguistic competition task and a nonverbal attentional task. Participants completed both tasks within one neuroimaging testing session. Chapter 2 examines bilingual and monolingual children's brain activity during the linguistic competition task assessing within-language competitors in English. Chapter 3 examines bilingual and monolingual children's brain activity during the Attentional Network Test, as well as whether brain activity is related to task performance, language abilities or age of second language exposure. Chapter 4 discusses whether both tasks reveal responses that overlap in brain regions and their theoretical implications, limitations of the project, and future directions.

Aim #1 (Chapter 2): To image the functional organization of children's processing of linguistic competitors. The Adaptive Control hypothesis (Green & Abutalebi, 2013) suggests a left frontal and bilateral parietal network for managing dual-language competition. Given that I am examining bilingual and monolingual children's brain activity during a linguistic competition task assessing within-language competitors in English, I expect both groups will activate similar brain regions within the left frontal and bilateral parietal regions. Any differences in the intensity of brain responses may stem in left frontal regions, especially for bilingual children, whom experiences involve an increased daily amount of adjudicating language competition in two languages.

Aim #2 (Chapter 3): To image children's functional organization for attentional networks, including whether the regions engaging attention during language processing (Chapter 2) are the same regions that differ in functionality between bilinguals and monolinguals during nonverbal attention. The Adaptive Control hypothesis (Green & Abutalebi, 2013) has proposed that daily demands of bilingual experiences will alter the neural networks and cognitive processes involved in managing two languages. Consistent with this view, bilinguals' daily demands for language selection should incur a set of changes in the attentional processes that will differ from monolingual children within the brain's left frontal cortex.

Aim #3 (Chapters 3 and 4): To investigate whether any differences in children's neurodevelopmental trajectory for attentional networks is due to language abilities or attentional control performance. An important analytical component of Aim #3 is the investigation of attentional regions that will be identified in Aims #1 and #2. The overarching hypothesis of this dissertation is that bilingualism might influence the neuro-cognitive organization for dual-language functions. To test this hypothesis, Chapter 2 will identify brain regions engaged in linguistic competition that demand attentional mechanisms, which I predict will be within left dorsolateral prefrontal regions. In Chapter 3, I will investigate whether the functionality of regions identified in Chapter 2 are also altered for bilingual and monolingual children during a nonverbal attention task. Should the data confirm my hypothesis, I will then investigate whether brain functionality in common regions are due to performance, age of bilingual exposure, amount of daily dual-language exposure, or dual-language abilities. This last portion is exploratory, however, I expect that any relationships to brain activity might be due to greater dual-language abilities. These brain-behavior associations would suggest that language-driven conflict resolution influences the development of attentional networks in bilingual children.

CHAPTER II

Study 1: Are Two Better Than One? Language Competition in the Developing Brain

When listening to speech, multiple lexical items may become active (Marslen-Wilson, 1987); for instance, when we hear the word "*candy,*" other words whose names begin with similar phonological onsets may also come to mind, such as "*cart,*" "*can*" or "*candle.*" Importantly, bilinguals experience doubled competition, so that Spanish-English bilinguals also activate words like "*casa [house],*" "*cama [bed]*" or "*carta [letter]*" (Marian & Spivey, 2003). Managing this type of inter-language competition is likely supported by attentional control mechanisms, and possibly the source of a 'bilingual cognitive advantage' on attentional control performance (Blumenfeld & Marian, 2013; Kroll et al., 2015). Overall, this dissertation aims to provide a direct link between processing linguistic competitors and its impact on the early-emerging changes in attentional control mechanisms. The goal of this dissertation's first study is to establish children's brain regions that support linguistic competition.

An individual's mental lexicon is essential for spoken word comprehension (Jackendoff, 2002); it contains information on a word's meaning, phonological information on its sounds, statistical likelihood on its proximity to other words, grammatical information on how to use it in a sentence, and its relation to thematic and taxonomic categories (MacDonald, 1997; Markman & Hutchinson, 1984; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). The mental lexicon also implicates which words are selected or become active, stored, processed, and retrieved by the speaker (Swinney, 1979). Some research suggests that bilinguals hold mental lexicons for each language separately (Gerard & Scarborough, 1989; MacNamara & Kushnir, 1971), while recent research suggests an interaction between both of their languages is more likely (e.g., Dijkstra & Van Heuven, 2002; Kroll & Stewart, 1994; Linck, Hoshino, & Kroll, 2008; van Heuven, Dijkstra, & Grainger, 1998).

Cross-linguistic interference is a common experience for bilinguals, so that words that begin with similar phonological onsets in both languages become active and compete for selection (see example above; Bartolotti & Marian, 2012; Marian & Spivey, 2003). Both within- and between-language distractors impact bilinguals' performance, so when a word is presented along with images of between-language competitors but not within-language competitors, bilinguals tend to look at them prior to selecting the target image (Bartolotti & Marian, 2012; Blumenfeld & Marian, 2011, 2013; Marian & Spivey, 2003). For instance, an eye-tracking study revealed that Spanish-English bilinguals tended to alternate their eye-gaze when they heard a word and were presented with images in which another item's direct translation matched the phonological onset of the target, such as the target *'pool'* and '*thumb [Spanish translation: pulgar]'* as the competitor (Blumenfeld & Maria, 2013; Marian & Spivey, 2003). Such findings exemplify not only the cognitive demands in bilinguals' language processing, but also the general notion that both of their languages are relatively co-active (Hernandez et al., 2005; Kroll, 2015; Van Hell & Dijkstra, 2002).

Research on bilinguals' parallel language activation suggests that Executive Function mechanisms may support the resolution of inter-language conflict, and the effects of such regulation likely extends beyond linguistic processing (cf. Kroll et al., 2015). Evidence suggests that bilinguals' increased experience with attentional control mechanisms in the language domain may advance its performance in nonverbal domain-general mechanisms (Bialystok, 2015); however, inconclusive evidence and confounding variables often challenge these results (Hilchey & Klein, 2011; Morton & Harper, 2007, 2009; Paap & Sawi, 2014). Nevertheless, monolinguals and bilinguals differ in their behavior and neural resources for managing competing linguistic input in one language. For instance, bilinguals who performed better in an Executive Function task (Stroop task), also experienced less linguistic competition, but this correlation was not significant for monolinguals (Blumenfeld & Marian, 2011, 2013). Using functional magnetic resonance imaging (fMRI), Marian et al. (2014) showed that while bilingual and monolingual adults perform similarly in the adjudication of linguistic competitors in one language, monolinguals showed greater brain activity than bilinguals in anterior cingulate and superior frontal gyrus, which are regions associated to Executive Function (Marian, Chabal, Bartolotti, Bradley, & Hernandez, 2014). Instead, bilinguals showed less brain activity in these regions, and their brain activity correlated with better Executive Function (Simon task) performance (Marian et al., 2014). These findings suggest that group differences are likely a result from greater efficiency in managing linguistic competition: Bilinguals' daily experience managing linguistic competitors is manifested in less brain activity along with improved Executive Function. Instead, monolinguals experience greater conflict managing linguistic competitors in their only language, as revealed by their increased brain activity in regions associated with allocating Executive Function mechanisms. Of importance is to note that this work is correlational, yet suggestive of a relationship between the amount of experiences in managing linguistic competition and altered domain-general mechanisms.

Theoretical perspectives suggest that cognitive processes and neural networks adapt to bilinguals' linguistic demands, and such changes may start emerging early in development

(Green & Abutalebi, 2013; Kroll & Bialystok, 2013; Kroll et al., 2015). One way of investigating differences in linguistic interference is by controlling dual-language demands and examining how only one language interferes (Blumenfeld & Marian, 2011; Marian et al., 2014). To the best of my knowledge, no experimental research has yet provided a direct link between managing linguistic competitors and attentional control mechanisms. The present study will establish the developmental link in children's brain regions supporting the adjudication of competing linguistic input during a within-language paradigm, and whether monolinguals and bilinguals exhibit differences in brain activity. Prior work with English-speaking adults shows activity in left inferior and superior frontal regions, as well as left posterior regions including superior temporal and supramarginal gyrus, in response to a within-language competition task (Marian et al., 2014; Righi, Blumstein, Mertus, & Worden, 2010). Given bilinguals' increased experience managing dual-language competition on a daily basis, I hypothesize bilingual and monolingual children will differ in their brain activity when processing linguistic competitors in one language. As shown by Marian et al. (2014), I expect monolinguals will show greater brain activity in left frontal regions, which are associated with Executive Function processing. However, the present work is studying a younger developmental age than previous research (Marian et al., 2014), alternatively bilingual and monolingual children might not reveal differences on cortical activity yet, and instead present similar responses.

Following the present study (Chapter 2), this dissertation will investigate the functional organization of attentional control mechanisms (Chapter 3) and provide a direct link between the brain regions supporting linguistic competition, including whether dual-language abilities impact attentional control mechanisms (Chapters 3 and 4).

Method

Participants

Ninety-two children took part in the study: 52 English monolinguals (31 females, 21 males; age range = 7.1 – 9.7 years, mean age [M_{age}] = 8.36, standard deviation [SD] = 0.74) and 40 Spanish-English speaking bilinguals (22 females, 18 males; age range = 7.1 – 9.9 years, M_{age} = 8.15, SD = 0.75). Selection criteria for bilingual participants were as follows: early and systematic exposure to Spanish from birth and to English by the age of 5, with a minimum of 3 years of English exposure prior to testing, daily exposure to both languages (Spanish in the home and English outside the home) at the time of testing, and adequate dual language competence that included standard scores that were within 2-standard deviations from the mean (>70, standard score M = 100) in English and Spanish receptive vocabulary abilities.

From this sample, 19 monolinguals and 14 bilinguals were excluded from neuroimaging analyses for the following: 3 bilinguals were excluded due to low Spanish scores, 2 monolinguals and 3 bilinguals were left-handed, 1 monolingual and 2 bilinguals reported language or attention impairments, 2 monolinguals and 5 bilinguals had noisy neuroimaging data likely due to dark hair obstructing light signal, 2 monolinguals and 1 bilingual experienced technical issues that yielded incomplete data, and 12 monolinguals reported substantial exposure to a second language (Hebrew, Spanish) at some point in their lives for about 5-hours a week and included production of simple three-word sentences in another language. After the aforementioned exclusion of children, the final samples included 26 Spanish-English bilinguals and 33 English monolinguals. From the 33 monolinguals, 26 were selected to match the bilingual sample in gender and age. In addition, from these children, 5 bilinguals and 4 monolinguals yielded noisy neuroimaging data in the present study (likely due to motion artifacts, see below for details), thus details on the final samples follow.

The present study includes data from 21 Spanish-English bilinguals (9 females, 12 males; age range = 7.1 – 9.9 years) and 22 English monolinguals (11 females, 11 males; age range = 7.1 – 9.7 years). All children were right-handed, neurotypical, raised and educated in a Midwestern town in the United States. The study was reviewed and approved by institutional review boards; parents and children completed respective informed consent and assent forms. As a thank you for their participation, children received a Frisbee and 5 trinkets as thank you gifts. Families also received monetary compensation, and their child's standardized vocabulary and reading scores.

All families were recruited from the same neighborhoods and were of similar socio-economic status; see Table 1. Children did not differ in English language proficiency and cognitive abilities ($p > .05$), except for nonverbal intelligence in which monolinguals performed better than bilinguals, although individual and group average standard scores were within typical ranges (85 to 115). For monolingual children, English was the only language spoken at home. For all children, English was the language of school instruction, but were also receiving a 30-to-60 minute per week foreign language class (Spanish or Chinese) at their school. At the time of testing, 11 bilingual children were attending a Spanish-heritage language learning Saturday school for 2-to-3 hours, which included daily Spanish literacy homework. Most bilingual children were born in the United States, except 3 children who were born in a Spanish-speaking country. Most bilingual children's parents, except 1 mother and 3 fathers, were native Spanish speakers and all families reported consistent use of Spanish at home with their child(ren) by at least one parent.

Behavioral Measures

Parent questionnaires. Parents were asked to complete questionnaires on their family's demographics, their child's first and second language acquisition, delays and learning impairments, as well as their views on their child's bilingual, bicultural abilities and academic potential. The following questionnaires were included: Language Background and Use questionnaire (LBU; Kovelman, Baker, & Petitto, 2008a), which provided information on the child's cognitive, language and motor development, plus any family history of learning impairments; questions from the John D. and Catherine T. MacArthur Foundation Research Network on Socioeconomic Status and Health questionnaire (retrieved from: www.macses.ucsf.edu), which provided information on the family's educational level and household income; a modified version of the Educational Socialization Scale (Bempechat, Graham, & Jimenez, 1999; renamed to 'Parental Academic Socialization scale'), it was adapted to ask parents how they motivate their children to do well in school; a modified version of the Parents' Racial Socialization Scale (Hughes & Johnson, 2001; renamed 'Parental Ethnic Socialization'), it was adapted to ask parents on the importance of their child's competency in their languages (English and Spanish) and cultures (Latino and American). The questionnaire packet was available to parents in English and Spanish; see Appendix A for the English version given to parents of bilingual children.

Child assessments. ***English phonology*** was assessed using the Elision subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). During testing, the experimenter asked the child to say a word, and then to repeat it without saying a portion of it. For example, "*Say winter, now say winter without saying /t/,*" the correct response is "*winner*." Participants earned 1 point for correct items; the task included 6 practice items and 20 testing items. Testing began on the first item and stopped when the ceiling item was reached (or 3 consecutive errors). Standard scores are based on a mean of 10 (SD = 3).

English vocabulary was assessed using the Verbal Knowledge subtest from the Kaufman Brief Intelligence Test (KBIT-2; Kaufman & Kaufman, 2004). During testing, the experimenter presented the child with a matrix of 6 images along with a question or a word, and the participant pointed to the best representing picture. Basal and ceiling levels were established; standard scores are based on a mean of 100 (SD = 15).

Spanish vocabulary was assessed using the Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition (ROWPVT-4; Brownell, 2000), which is a standardized assessment normed with Spanish-English bilinguals from the United States. Similar to the English assessment, the experimenter presented the child with 4 images and a word, and participants pointed to the best representing picture. Basal and ceiling levels were established; standard scores are based on a mean of 100 (SD = 15).

English and Spanish syntax was assessed using the Word Structure subtest from the Clinical Evaluation of Language Fundamentals (CELF-4; Semel, Wiig, & Secord, 2003, 2006). The assessments measure participants' ability to apply morphology and syntactic rules. Participants earn 1 point for correct items; 32 testing items were presented for English, and 29 items for Spanish; percentages are reported.

English reading was assessed using the Word Identification subtest from the Woodcock Reading Mastery Tests (Revised 2nd edition; Woodcock, 1998). During testing, the experimenter presented the child with a word to read aloud. Basal and ceiling levels were established; standard scores are based on a mean of 100 (SD = 15).

Nonverbal intelligence was assessed using the Matrices subtest from KBIT-2 (Kaufman & Kaufman, 2004), which measures the ability to find spatial and abstract relationships among a set of pictures and patterns. During testing, children selected the missing piece in a 'puzzle' (out of 4 options). Basal and ceiling levels were established; standard scores are based on a mean of 100 (SD = 15).

Naming speed was assessed using the Numbers subtest from the Rapid Automatized Naming (RAN; Wolf & Denckla, 2005). During testing, children were asked to name 50 numbers on a card as fast as possible; the numbers included: 2, 6, 9, 4, and 7. Standard scores are based on a mean of 100 (SD = 15).

Attentional control was assessed using the Pair Cancellation subtest from the Woodcock-Johnson III Tests of Cognitive Abilities (Woodcock, McGrew, & Mather, 2001). During testing, children were presented with randomly sequenced images of dogs, balls, and cups on a piece of paper. Children were instructed to circle as many ball-dog pairs in 3-minutes. Participants earned 1 point for correct circled object-pairs; raw scores are reported, the maximum score for this task is 69.

Linguistic Competition Neuroimaging Measure

Children completed a modified child-friendly version of a phonological language-priming task that is based on prior work by Marian and colleagues (Marian & Spivey, 2003; Marian et al., 2014). The task mimics the type of conflicting linguistic competition that bilinguals experience on a daily basis across both languages; however the task assesses it in a within-language (i.e., English) paradigm. The task included a Phonologically Related (experimental) condition, a Phonologically Unrelated (control) condition, a Baseline simple word-to-picture matching (control) condition, and rest jittered periods. Each condition consisted of a target word and a competitor. In the Phonologically Related condition, the target's name (e.g., *candy*) overlapped with the phonological onset of a competing image (e.g., *candle*). In the Phonologically Unrelated condition, the target and competitor's name do not overlap on their phonological onset (e.g., *candy* and *apple*). In the Baseline control condition, the target image is displayed alongside a scrambled indecipherable image. See Figure 1.

Each trial began with a display of the stimuli pictures, one image appeared on the center-left side of the screen and another one on the center-right. Following 500-ms, participants heard the Target word and had 2500-ms to respond; thus, each trial was 3000-ms in length. The task was set-up as an event-related design with a total of 63 trials, 21 trials per condition. The task was randomized using OptSeq2 (Dale 1999) and comprised of 25% phonologically related trials, 25% phonologically unrelated trials, 25% baseline trials, and 25% jittered rest periods (63 seconds randomized across the task). The task lasted about 4-½ minutes and was presented using E-Prime 2 (Psychology Software Tools, Inc.) on a 30-inch HP Z30i LED monitor connected to a Dell Optiplex 780 desktop computer; sound played via two Creative Inspire T12 2.0 multimedia speakers. A two-button box (Current Designs, Inc.) was connected to the desktop computer to record participants' responses. Trials were deemed incorrect if the participant pressed the incorrect button, or did not respond. Performance was assessed by accuracy and response time.

Stimuli. All stimuli were controlled to ensure that there was no phonological onset overlap in their Spanish translation that would compete against English Target words. Target (phonemes: M = 3.30, SD = 0.80; syllables: M = 1.11, SD = 0.32) and competitor words (phonemes: M = 2.98, SD = 0.82; syllables: M = 1.10, SD = 0.81) were in average length 3 phonemes (M = 3.19, SD = 0.79) and monosyllabic (M= 1.10, SD = 0.29), all of which were non-significant across conditions *ps* > .05. Stimuli across conditions do not differ on word frequency (SUBTLEXUS; Brysbaert & New, 2009), phonological neighborhood size (CLEARPOND; Marian, Bartolotti, Chabal, & Shook, 2012), concreteness and imageability (MRC Psycholinguistic Database; Coltheart, 1981); all *ps* > .05. For each trial, stimuli words with a lower frequency were chosen as the target word. A female speaker, native of the region and same locale as participants, recorded all words. Stimuli sound files do not differ in sound length (*ps* > .05), in average all words played in under one second: Phonologically Related words in average took 820ms (SD = 137), Phonologically Unrelated in average took 805ms (SD = 119), and Baseline words in average took 747ms (SD = 152). See Appendix B for target and competitor words for all conditions.

Black and white line drawings were obtained for each item from Microsoft Office Clip Art or Google Images. Pilot testing with 6-to-9 year old children revealed images had high naming consistency; see Appendix B.

Procedure

During the visit, parents and children were first explained how the session would be carried out, then families were given time to review consent and assent forms in their language of choice (English or Spanish). Once these initial forms were signed, parents were asked to complete questionnaires while their child took part in the testing session. Children completed the imaging portion and behavioral assessments in separate testing rooms. Behavioral tasks assessing English abilities were completed with a native English-speaking experimenter, while those assessing Spanish abilities were completed with a native Spanish-speaking experimenter. Given that the testing session took at least 2-hours to complete (2 ½ hours for bilinguals), children were allowed to take 5-minute breaks any time during the session, and were provided with snacks and juice.

During the fNIRS brain-imaging portion of the study, children watched cartoons while experimenters set the cap and optodes in place, and pictures of the probe placement were taken. Prior to completing the Linguistic Competition imaging task, children were instructed to press buttons from a two-button control box as quickly as possible (left or right); button presses varied on the location an image matched the Target word. Prior to testing, children completed a practice session with 9 trials (3 baseline, 3 phonologically unrelated, 3 phonologically related) that were not part of the testing session.

After fNIRS data acquisition, most children took part in a digitization of the probeset (except 2 monolinguals and 3 bilinguals due to fatigue or technical failure). While children wore the cap, the left portion of the probeset and reference points (Inion, Nasion, Cz, pre-auricular left and right) were digitized using a Polhemus Patriot 6DOF.

Neuroimaging Data Acquisition

The study used a TechEN-CW6 fNIRS system with 690 and 830 nm wavelengths. The set-up included 14 emitters of near-infrared light (sources) and 24 detectors, yielding 44 data channels sampled at 50-Hz spaced about 2.7 cm apart (22 channels per hemisphere; see Figure 2). Optodes were mounted onto a custom-built head cap constructed from a lycra ‘Speedo’ swimming cap, with attached soft silicone TechEN grommets that held the optodes in place during data collection. The cap was applied consistently for each participant using the international 10-10 transcranial system positioning (Jurcak, Tsuzuki, & Dan, 2007) for the following points: Inion, nasion, auricular left and right, Fz, FpZ, Cz, T7/8 and F7/8.

Estimation of brain regions. In order to estimate the brain regions maximally covered by the channels, the probeset and reference points (Inion, Nasion, Cz, pre-auricular left and right) were digitized on a mannequin head using a Polhemus Patriot 6DOF Digitizer. The coordinates provided by the digitizer were then applied on AtlasViewer GUI (Aasted et al., 2015), a MATLAB-based software, to estimate the brain coordinates in Montreal Neurological Institute (MNI) stereotactic space. The MNI brain coordinates of the geometric structure and measurement setting for the optodes (emitters and detectors) were then partitioned into 1000 voxel points that were then applied to the mid-point of each data channel (between each source and detector pair) on a 3D image brain template (provided by https://irc.cchmc.org/software/pedbrain.php). The corresponding brain regions and Brodmann areas (BA) were estimated using the xjView Database in MATLAB (http://www.alivelearn.net/xjview). The brain areas covered by the 1000 points distributed along each channel are recognized as the brain areas covered by that channel. If a channel covered more than one area, the area indices were arranged in sequence according to the proportion of the 1000 points falling within the given regions (see Figure 2c).

Neuroimaging Data Analyses

Data visualization was done using Homer2, a MATLAB-based software retrieved from the NITRC database (Huppert, Diamond, Franceschini, & Boas, 2009). First, the 690 and 830nm wavelengths timeseries data were examined to exclude participants whose signal quality was below 3 molar units and did not reveal cardiac signal, likely due to a large amount of motion artifacts and/or hair obstruction, for over 50% of 690 data channels (4 monolinguals, 5 bilinguals).

The remaining data (22 monolinguals, 21 bilinguals) were then preprocessed using NIRS Toolbox (Barker, Aarabi, & Huppert, 2013), and several customized MATLAB scripts that included Homer2's motion detection (hmrMotionArtifactByChannel) and Spline (hmrMotionCorrectSpline) functions (Huppert et al., 2002). The following preprocessing steps were completed in the following order: optical density change data conversion, motion artifact detection, motion artifact correction via spline interpolation, and concentration change data conversion. First, the raw time course data was converted into units of optical density change. Next, the optical density change data went through a quality control step for integrity and presence of signal and motion artifacts, on a channel-by-channel basis (Scholkmann, Spichtig, Muehlemann, & Wolf, 2010). Signal changes with amplitude greater than one threshold of a standard deviation of 50 within half a second were identified as an artifact, and masked for an additional 1-second. After artifacts were identified, a spline interpolation motion correction with a parameter set to 0.99 was applied. Spline interpolation replaces the motion segments by reconstructing the motion and replacing it with a combination of the mean value of the identified segment and the mean value of the previous segment to ensure a continuous signal (Brigadoi et al., 2014; Cooper et al., 2012; Scholkmann et al., 2010). The optical density change data was then converted into hemoglobin concentration change data using the modified Beer-Lambert law, yielding oxygenated (HbO) and deoxygenated hemoglobin (HbR) values.

Hemoglobin data can be contaminated by physiological noise, especially when sampled at a temporal resolution greater than 10-Hz, leading to serially correlated error terms (Barker et al., 2013). Thus, a multiple regression General Linear Model (GLM) approach falls within statistical parametric mapping assumptions (Friston, Ashburner, Kiebel, Nichols, & Penny, 2006), and is one way of correcting for autocorrelations (Barker et al., 2013; Poline & Brett, 2012). Thus, each participant's hemoglobin concentration data was analyzed using a GLM via an ordinary least squares (OLS) fit, assuming the dual-gamma canonical hemodynamic response function peaking 8-seconds after trial onset (Friston, et al., 2006; Hu, Hong, Ge, & Jeong, 2010). The first-level GLM analysis estimated beta values, which are indices of percent signal change, for each condition (Phonologically Related, Phonologically Unrelated, and Baseline). Second-level group analyses were conducted using a multivariate linear mixed-effects model for each data channel. The group-level linear mixed-effects model included conditions (Phonologically Related, Phonologically Unrelated, and Baseline) and groups (monolingual, bilingual) as fixed effects, participants were treated as a random effect variable, and hemoglobin beta values (HbO and HbR) as the predicting dependent variables. HbR analyses are reported in Appendix C. All within- and between-group statistical analyses were also evaluated at a False Discovery Rate (FDR) threshold correction of $p < .05$ (see Benjamini & Hochberg, 1995).

Results

Behavioral Performance

Bilingual language and cognitive competence tasks. *T*-tests comparisons between bilingual and monolingual children's performance on English language measures and cognitive tasks did not reveal any significant differences among the groups ($p > .05$), except in the nonverbal intelligence task in which monolinguals performed better than bilinguals (see Table 1). Since the groups were significantly different in nonverbal intelligence performance, analyses that controlled for any effects from this variable were additionally carried out. However, these analyses did not reveal that significant effects in the Linguistic Competition task performance (accuracy and response time) and brain activity were different from when the variable was not included as a covariate. Given that individual and group average standard scores were within typical ranges (85 to 115) for bilingual participants, the following analyses are presented without controlling for nonverbal intelligence effects.

In addition, comparisons between bilingual children's English and Spanish language measures revealed that bilinguals were significantly more proficient in English than Spanish, as would be expected of bilinguals with English-dominant schooling and neighborhood environments that are typical of southeast Michigan; see Table 1.

Linguistic competition task. Accuracy performance on the linguistic competition task was high for all participants (see Table 1), indicating that children were successful in completing the task. *T*-tests revealed that monolinguals were overall more accurate than bilinguals, and this difference stemmed from significant differences in accuracy performance during the Phonologically Unrelated condition; see Table 1. A mixed 2 (between-group variable: monolingual, bilingual) x 3 (within-group variable; condition: Phonologically Related, Phonologically Unrelated, and Baseline) ANOVA revealed a main effect of group ($F(1, 123) = 6.29$, $p = .013$, $\eta p^2 = .049$), in which monolinguals (M = 97.4%, SD = 5.03) performed better than bilinguals (M = 94.7%, SD = 8.87). The ANOVA also revealed a main effect of condition ($F(2, 123) = 24.11$, $p < .001$, $\eta p^2 = .28$), indicating that children were less accurate in the Phonologically Related condition (M = 90.86%, SD = 10.00, $p < .001$) in comparison to the Phonologically Unrelated (M = 98.40%, SD = 3.19, $p < .001$) and Baseline (M = 98.98%, SD = 2.94, $p < .001$) conditions. The ANOVA did not reveal a significant interaction between the groups and conditions ($p > 0.05$), suggesting that the language groups did not reveal differences in their performance by condition.

A similar mixed 2 x 3 ANOVA for response time revealed a significant main effect of condition ($F(1, 123) = 40.61$, $p < .001$, $\eta p^2 = .40$), indicating that children were slowest in the Phonologically Related condition (M = 1730.98 ms, SD = 135.66, $p < .001$) followed by the Phonologically Unrelated (M = 1552.54 ms, SD = 131.16, $p < .001$) and Baseline (M = 1469.58 ms, SD = 143.84, $p < .001$) conditions. The ANOVA did not reveal a main effect of group, or an interaction between the groups and conditions ($p > 0.05$), suggesting that the language groups did not differ in their response time performance by condition.

Functional Neuroimaging

The group-level linear mixed-effects model that included groups (monolingual, bilingual) and conditions (Phonologically Related, Phonologically Unrelated, and Baseline) as fixed effects, and treated participants as a random effect, revealed significant main effects of group, condition, and interactions between the factors; see Table 2 and Figures 3 and 4. Since the language groups were significantly different in nonverbal intelligence performance, the variable was also included as a covariate in the regression. However, the analyses revealed that it did not significantly predict brain activity, thus it was removed and not included in the subsequent brain imaging analyses.

The main effect of condition revealed that children showed significant activation across the conditions in one left frontal channel (Ch 6), two channels overlaying the same parietal regions in both hemispheres (Ch 20), and two additional left parietal channels (Ch 18 and 21). As can be seen in Figure 3, participants had the strongest levels of activation in these channels during the Phonologically Related (the most challenging condition), followed by the Phonologically Unrelated and Baseline conditions.

The main effect of group revealed that monolingual children showed greater activation in the left frontal channel (Ch 6) than bilinguals. The results did not reveal significant suprathreshold activity for bilinguals as compared to monolinguals.

Group by condition interactions manifested in bilateral (right: Ch 20, left: Ch 17 and 21) parietal regions that stemmed from differences in brain activity among bilinguals and monolinguals across the control conditions (Baseline and Phonologically Unrelated); see Figures

3 and 4. Specifically, right parietal (Ch 20) showed similar activity for both control conditions in monolinguals, while bilinguals showed greater activity in Baseline than in the Phonologically Unrelated condition. One left parietal (ch 17) channel showed similar activity for both control conditions in bilinguals, while monolinguals showed negative activity in Baseline and increased positive activity in the Phonologically Unrelated condition. The remaining left parietal channel (Ch 21) showed similar activity for both control conditions in monolinguals, while bilinguals showed increasing activity from Baseline to the Phonologically Unrelated condition.

To explore a-priori questions about the relationship between children's ability to complete the linguistic competition task and their brain function, we conducted ad-hoc correlational analyses on the channels showing significant brain activity. Correlational analyses included each participant's betas for each condition and their corresponding performance (accuracy and response time) in each condition. Correlational analyses were first carried out including both groups' brain activity betas and performance for each condition, and then separately for each group. Overall, correlational analyses for each group revealed similar results in comparison to when both groups were included together, thus only these latter ones are reported. Correlational analyses between accuracy and brain activity did not reveal significant relationships. However, correlational analyses between response time and brain activity revealed significant positive relationships on the left frontal channel (Ch 6, $r(129) = .24$, $p = .007$) and two parietal channels (Ch 17, $r(129) = .25$, $p = .005$; Ch 20, $r(129) = .19$, $p = .036$). These positive correlations suggest that when response times were faster, left frontal and parietal regions showed less brain activity, similarly when response times were longer, these regions showed greater activity.

Discussion

When listening to speech, words compete for selection (Marian & Spivey, 2003). Bilinguals experience doubled competition, which is thought to possibly alter the neuro-cognitive mechanisms (i.e., domain-general attention) supporting word selection (Bartolotti & Marian, 2011; Blumenfeld & Marian, 2013; Poarch & van Hell, 2012). The first goal of this dissertation was to examine monolingual and bilingual children's brain activity when processing linguistic competitors in one language (e.g. *car, cat* vs. *car, pen*), and whether the language groups exhibited differences. In the present study, bilingual and monolingual children (ages 7-9) completed an English linguistic competition task while undergoing fNIRS neuroimaging. Given previous work suggesting bilinguals' increased experience with managing linguistic competitors in both languages and more efficient Executive Function performance (Blumenfeld & Marian, 2013; Kroll et al., 2015), I hypothesized that bilingual and monolingual children would differ in brain activity patterns when processing linguistic competitors. Specifically, I expected monolingual children would show greater brain activity than bilinguals in areas associated with executive processing supporting linguistic competition, specifically left frontal regions (as shown by Marian et al., 2014). The results revealed both monolingual and bilingual children showed task-related activation in left frontal and bilateral parietal regions. While performing the task, monolingual children also showed greater brain activity than bilinguals in a left frontal region, which is an area associated with Executive Function. Bilinguals' decreased brain activity in the task is consistent with my hypothesis and may be related to children's early and continuous dual-language experiences with managing linguistic competitors.

Children's brain activity was especially pronounced in the left hemisphere, thus the results are consistent with research suggesting a left fronto-parietal network supporting linguistic processes (Friederici, 2012; Friederici & Gierhan, 2013; Gabrieli, 2009). In the present study, children activated channels overlaying left inferior and middle frontal gyri, inferior and superior parietal regions, as well as one channel overlaying right inferior parietal lobe. Previous research suggests that these regions in a fronto-parietal network are active for phonological, lexico-semantic, and syntactic processes, which are overall necessary for the extraction of the mental lexicon (Friederici, 2012; Friederici & Gierhan, 2013). While in relation to Executive Function, particularly attention processes, these regions are thought to be involved in the monitoring, planning and execution of attention (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002b; Corbetta & Shulman, 2002). Thus, the present developmental results suggest that children activate a left fronto-parietal network similar to that of adults', and possibly due to these regions' involvement for supporting the adjudication of linguistic competitors (Marian et al., 2014; Righi et al., 2010).

Theoretical perspectives suggests that within this network may underlie the neural resources supporting language processing and Executive Function mechanisms altered by bilingual experiences (Abutalebi & Green, 2016; Kroll et al., 2015; Kroll & Bialystok, 2013; Marian et al., 2014; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008). Previous work often reveals that bilinguals activate left fronto-parietal regions to a greater extent than monolinguals in language processing tasks (Jasinska & Petitto, 2013; Kovelman et al., 2008a, 2008b), however the present results do not support these previous findings (see also Marian et al., 2014). These disparities might be due to multiple differences between the studies. For instance, the tasks that find bilinguals show greater brain activity than monolinguals typically assess morpho-syntactic features of language, while the present study assessed phonological processes. Another possibility may be that these children are early-exposed to both languages and highly proficient in English, which is their second language, while previous studies include adults and later-exposed participants who vary in their language proficiency. Thus, it may be plausible that if bilinguals in the present study were compared to Spanish monolinguals in a linguistic competition task assessing Spanish phonological processes, the results might reveal that bilinguals show greater brain activity than monolinguals for these regions.

Analyses on behavioral performance revealed minimal group differences in task accuracy suggesting monolingual participants were more accurate than bilinguals, however these differences stemmed from the Phonological Unrelated condition (see Table 1), thus undermining the likelihood that task accuracy may have significantly affected group differences in brain activity. Overall, children were less accurate and took longer to respond during the Phonologically Related, followed by the Phonologically Unrelated and then Baseline conditions. Regardless of bilingualism, correlational analyses revealed children displayed greater brain activity in left frontal and parietal channels during longer response times, which other neuroimaging studies on language processes have also noted as a trend of similar effects (cf. Taylor, Rastle, & Davis, 2014). Such results suggest that since the Phonological Related condition took the longest for all children to respond, this condition may be driving the brain activity results.

A limitation of the present study is that the statistical analyses lack contrasts between the conditions and include all condition (Baseline, Unrelated, Related) as part of the task effects results. Thus, these analyses do not address whether greater brain activity effects were specifically driven by the Phonological Related condition, including whether such group differences stem from bilinguals' greater experience managing linguistic competitors in both of their languages. Nevertheless, bilinguals' daily experiences in managing inter-language competitors may provide them with additional practice for allocating resources when processing language competitors in one language. The present results are consistent with previous neuroimaging work in adults showing that monolinguals activate greater left frontal regions for linguistic competitors (Marian et al., 2014), thus the present results extend these findings with children suggesting that such effects may be lifelong. Monolingual children's greater activation in left frontal regions is possibly due to their increasing need to allocate Executive Function neural resources triggered within left frontal regions that might be necessary when processing the task's linguistic competitors, as seen in Figure 3. While bilingual children's brain activity is possibly a result from more efficient allocation of neural resources that may result from their increased experiences managing linguistic competitors in their lifetime. A direct link between linguistic and domain-general attentional control processes in the brain will continue to be investigated in the coming chapters of this dissertation.

Conclusion

Theories of bilingual development suggest that dual-language experiences during early cognitive and brain development may impact the functional representations of cognitive systems (Abutalebi & Green, 2016; Green & Abutalebi, 2013). The present study provides developmental evidence suggesting that monolingual and bilingual children recruit the same regions as adult research during a task assessing within-language competitors (Marian et al., 2014). In addition, the results suggest that monolingual children recruit left frontal regions to a greater extent than bilinguals, and these differences may be due to bilinguals' parallel activation of their languages that might impose cognitive demands impacting their efficiency in allocating resources when one of their language competes in the bilingual brain (Kroll, Bobb, & Wodniecka, 2006; Marian & Spivey, 2003; Thierry & Wu, 2007). Importantly, the present study suggests that left dorsolateral frontal region may support linguistic processes that are possibly engaged in bilinguals' dual-language capabilities. It is plausible that these capabilities may be associated to bilinguals' advantageous performance in domain-general Executive Function mechanisms (Blumenfeld & Marian, 2011, 2013; Kroll & Bialystok, 2013; Kroll et al., 2015). In the coming chapters, I investigate whether the functional organization of attentional control mechanisms underlie the same regions as linguistic competition, and their relation to dual-language abilities.

CHAPTER III

Study 2: The Functional Organization of Attentional Networks in the Bilingual Brain

Evidence suggests that Executive Function mechanisms, including attentional control, are integral to bilinguals' language selection processes (Blumenfeld & Marian, 2011, 2013; Marian et al., 2014). In turn, such continuous experiences in language selection are thought to create an increasing demand for Executive Function mechanisms, which may consequently advance bilinguals' performance (Bialystok et al., 2012; Dong & Li, 2015). Theoretical perspectives have suggested that cognitive systems adapt dynamically to individuals' experiences and consequently incur a set of changes in the responsiveness of their functional representations in the brain (Baum & Titone, 2014; Green & Abutalebi, 2013; Johnson, 2011). Hence, changes in Executive Function behavior are possibly reciprocal to neural changes and are likely observable in bilingual individuals. The present study investigates the nature of neuro-cognitive plasticity for Executive Function in bilinguals, and its impact in behavioral performance in relation to children's functional brain organization of attentional control.

A number of studies document bilinguals' better performance than monolinguals on attentional control tasks prior to age 5 (Bialystok, 1999; Kovács & Mehler, 2009; Singh et al., 2015; Yang et al., 2011), yet inconsistent results on those age 5 and older have fueled a debate on the reliability of such bilingual advantage findings (Antón et al., 2014; Bialystok, Craik, Klein, & Viswanathan, 2004; Craik et al., 2010; de Bruin, Treccani, & Della Sala, 2015; Duñabeitia &

Carreiras, 2015; Paap et al., 2015). The Attentional Network Task (ANT; Fan et al., 2002) is a common measure for studying bilinguals' attentional control because it is devoid of language and thought to tap into key components of attention by using nonverbal stimuli (e.g., Costa et al., 2008; Kapa & Colombo, 2013; Tran et al., 2015; Yang et al., 2011). The ANT is a visuospatial attention task, that builds upon a cue scheme along with a flanker paradigm to measure three attentional networks: (i) Alerting, which is the ability to maintain a mental state of sensitivity to the task at hand and to incoming information; (ii) Orienting, which is the ability to disengage, shift, and re-engage one's attention; and (iii) Executive, which is the ability to monitor and resolve conflict (Fan et al., 2002; Posner, 2012). Bilinguals experience within- and cross-linguistic competition that is likely managed by the Executive attentional network (Bialystok, 2015; Blumenfeld & Marian, 2013; Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010; Kroll et al., 2015). Thus, advantageous performance in the ANT Executive network would support the notion that bilingualism positively impacts attentional control performance (Costa et al., 2008; Kapa & Colombo, 2013; Tran et al., 2015; Yang et al., 2011); however, confounding variables often challenge these results (Hilchey & Klein, 2011; Morton & Harper, 2007, 2009; Paap & Sawi, 2014).

Everyday experiences may indeed alter performance in a variety of cognitive tasks, but another way of assessing changes is by investigating how brain processes (structural and functional) adapt to these demands (Vaughn et al., 2015). Indeed, the Adaptive Control hypothesis (Green & Abutalebi, 2013) is one perspective proposing that bilinguals' linguistic demands impact the organization of neural networks involved in language selection (see also Abutalebi & Green, 2016). The hypothesis suggests that Executive Function mechanisms support the maintenance and representation of bilinguals' target (in use) language in mind, and ensure efficient suppression of the non-target language. Thus, early exposure to two languages may change the brain in three ways: (i) structurally (i.e., grey matter), (ii) functionally (i.e., tuning neuronal populations or responsiveness), and (iii) in connectivity (i.e., white matter). An increasing amount of work is finding how the brain’s left hemisphere changes as a result of early exposure to two languages. For instance, research has shown that early bilingual exposure and greater dual-language proficiency increases grey matter volume in the left hemisphere relative to those later-exposed (before age 5 vs. at 10-15 years; Mechelli et al., 2004; Olulade et al., 2016). Moreover, bilinguals activate left frontal lobe to a greater extent than monolinguals during various language tasks, even for those scarcely exposed and highly proficient bilinguals (Guo, Liu, Misra, & Kroll, 2011; Jasinska & Petitto, 2013; Kovelman et al., 2008a, 2008b). These changes to the anatomy and function of the left hemisphere are often attributed to bilinguals’ necessity for incorporating two vocabularies (Mechelli, et al., 2004), complex morpho-syntactic structures (Jasinska & Petitto, 2013; Jasinska, Berens, Kovelman, & Petitto, 2016), as well as the complex demands of dual language switching (Abutalebi & Green, 2008; Hernandez, 2009).

During language switching tasks and when managing cross-linguistic competition, bilinguals recruit brain regions typically associated with Executive Function, including the anterior cingulate cortex (ACC), left fronto-parietal and caudate regions (Abutalebi & Green, 2007, 2008, 2016; Luk, Green, Abutalebi, & Grady, 2012; van Heuven et al., 2008). Another plausible idea is that dual-language experiences may extend to non-linguistic Executive Function mechanisms and reorganize the functionality of brain regions supporting these processes (Green & Abutalebi, 2013; Kroll, 2015). Indeed, during a non-linguistic Executive Function (Go-NoGo) task, bilingual adults engaged left frontal regions, while monolingual adults engaged right frontal regions (Garbin et al., 2010). Furthermore, a recent study (Coderre, Smith, van Heuven, &

Horwitz, 2016) revealed that bilingual adults show overlapping brain activity for language processing and non-linguistic Executive Function within left frontal regions, however this was not the case for monolinguals. Thus, linguistic experiences may alter children's development of cognitive mechanisms that better support language selection, and brain activity in left frontal regions might be one possible set of loci altered by bilingual experiences (Abutalebi & Green, 2016; Coderre et al., 2016; Green, 2011).

Yet few have inquired into the childhood plasticity of Executive Function processes (Arredondo et al., 2015; Barac et al., 2016), this is likely coupled with the increasing inconclusive research on whether bilinguals indeed show advantageous performance in these mechanisms. My research suggests that monolingual and bilingual children (7-13 years old) vary in brain activity using a flanker paradigm similar to that of the ANT Executive network (Arredondo et al., 2015). This study revealed that both bilinguals and monolinguals activated bilateral frontal regions for attentional control. However, when the groups were contrasted against each other, monolinguals showed greater brain activity in right frontal regions, whereas bilinguals showed greater brain activity in left frontal regions. Given that left frontal regions are involved in language processing (see Chapter 2) and that activity in this region may be altered by dual-language demands (Abutalebi & Green, 2016; Coderre et al., 2016), these results suggested attentional processes may indeed show different patterns for monolingual and bilingual speakers. Nevertheless, the first-time findings were obtained for only a small sample size, wide age range, and brain activity measurements that were restricted to the frontal lobe. Given these limitations, the present chapter aims to expand on previous results by investigating whether bilingualism impacts the brain's functional organization of attentional networks (i.e., Alerting, Orienting, and

Executive) across frontal, temporal and parietal lobes, and whether developmental differences, especially in the Executive network, are due to dual-language experiences.

Present Study

Theoretical perspectives suggest that bilingualism could alter brain networks and behavioral performance in domain-general mechanisms supporting linguistic processes (Bialystok et al., 2012; Bialystok, 2015; Green & Abutalebi, 2013). Consistent with the Adaptive Control hypothesis, I hypothesize that bilingual and monolingual children will differ in their neurodevelopmental organization for attentional networks, of marked interest is the Executive attentional network. The present chapter has two aims: (i) to investigate whether monolingual and bilingual children exhibit differences on their functional brain organization for attentional control, and whether it is related to advantageous performance by bilinguals, as well as (ii) whether any differences are due to dual-language abilities. The present work will be the first to provide both behavioral and neuroimaging evidence for establishing a developmental link between the brain regions involved in nonverbal attention and linguistic control processes in the brain.

Method

Participants

See Chapter 2 for details on the full sample and selection criteria. The present study includes data from 26 Spanish-English bilinguals (12 females, 14 males; age range = 7.1 – 9.9 years) and 26 gender- and age-matched English monolinguals (12 females, 14 males; age range = 7.1 – 9.7 years). Similar to Chapter 2, all children were right-handed, neurotypical, raised and educated in a Midwestern town in the United States. All families were recruited from the same neighborhoods and were of similar socio-economic status; see Table 3. At the time of testing, half (13) of the bilingual sample attended a Spanish-heritage language learning school during the weekend for 2-to-3 hours/week, which also included daily Spanish literacy homework. Most bilingual children were born in the United States, with the exception of 5 children who were born in a Spanish-speaking country and immigrated to the United States in the first 5 years of their life. Most bilingual children's parents, except 1 mother and 5 fathers, were native Spanish speakers and reported consistent use of Spanish at home with their child(ren) by at least one parent.

Measures

Parent questionnaires and child assessment were identical to those described in Chapter 2. The ANT was completed in the same session for all participants following the Linguistic Competition task (Chapter 2).

Attentional Network Task (ANT; Fan et al., 2002). Children completed a modified child-friendly version of the original ANT developed by Fan and colleagues (Fan et al., 2002; Rueda et al., 2004). The ANT requires participants to monitor their attention and solve trials with conflicting and non-conflicting information (Posner, 2012). The task uses a combination of warning cues along with a flanker paradigm to affect reaction times and assess three attentional networks: Alerting, Orienting, and Executive attention. (Posner, 1980; Eriksen & Eriksen, 1974).

The task requires that participants selectively attend to the directionality (left or right) of a Target, while ignoring the directionality of surrounding flankers (Fan et al., 2002). In the present study, the Target was the central stimulus in a horizontal row of five goldfish, presented above or below the fixation point, over a blue background. Warning cues are integrated into the paradigm to assess the Alerting and Orienting networks. Three types of warning cues were presented throughout the task: Central cue, which provided information that a trial was forthcoming but not where the target would appear; Spatial cues (top or bottom), which provided information that a trial was forthcoming and also where the target will appear; No cue, which did not provide any information that a trial was forthcoming. Following cue display, either a Congruent (control condition) or an Incongruent (experimental condition) trial was presented; see Figure 5. During Congruent trials, the Target faced the same direction as flanker fish (→→→→→ or ←←←←←). During Incongruent trials, participants resolve visuospatial conflicting information as the Target faces the opposite direction from flanker fish (→→←→→ or ←←→←←).

The following subtractions are then used to assess the three attentional networks: (i) Alerting is assessed by subtracting performance in all No cue trials from Center cue trials, (ii) Orienting of attention is assessed by subtracting performance in all Center cue trials from Spatial cue trials, and (iii) Executive attention is assessed by subtracting performance in Congruent trials (across all cue types) from Incongruent trials. See Figure 5.

All stimuli were displayed on a computer screen. A fixation point (+) was presented in the center of the screen throughout the task. Each trial consisted of a cueing event (an asterisk) presented for 150-ms, followed by a 400-ms interval, and then by the presentation of a target and flankers for 1700-ms; see Figure 5. The task was set-up as an event-related design and randomized using OptSeq2 (Dale, 1999). Each participant completed 5 runs, which allowed children to take a short break to rest, and to increase the number of trials given the sample size. Each run was comprised of 48 randomized trials, including 24 Congruent and 24 Incongruent trials. For half of the trials, the row of fish appeared above the fixation point, and for the remaining trials they appeared below the fixation point. For each run, the trials included 16 of each cue type (16 Center cues, 16 Spatial cues [8 top cues and 8 bottom cues], and 16 No cues).

Across all 5 runs, the entire task was comprised of 240 trials (120 Congruent and 120 Incongruent trials) of which 80 were Spatial cues, 80 were Center cues, and 80 were No cues.

Sixty-seconds of jittered Rest periods were randomly distributed across each run. If the participant did not respond during the Target display, the trial was deemed incorrect. Each run lasted about 2 minutes and the entire task lasted about 10 minutes. The task was presented using E-Prime 2 (Psychology Software Tools, Inc.) on a 30-inch HP Z30i LED monitor connected to a Dell Optiplex 780 desktop computer. A two-button control box (Current Designs, Inc.) was connected to the desktop computer to record participants' responses. Trials were deemed incorrect if the participant pressed the incorrect button, or did not respond. Performance was assessed by accuracy and response time.

Procedure

The procedure was identical to that described in Chapter 2. Prior to completing the ANT, children were instructed to help "Goldie, the goldfish" and his friends find a hidden treasure chest using a map. Children were told that Goldie (Target central fish in a row of fish) is in charge of guiding his friends to the treasure chest, but Goldie's friends get confused sometimes and go the wrong way; hence, the child's job was to press buttons to indicate to Goldie's friends where Goldie was going (left or right). Prior to arriving to the treasure chest, children visited four spots in the ocean (Starfish coast, Beluga Bay, Turtle Island, Pelican Harbor). Once arriving to each spot, children took a short 1-2 minute break and earned prizes (e.g. stickers, trinkets).

Children were instructed to press buttons on a two-button control box as quickly as possible (left or right); button presses varied on the location of Goldie (Target fish) during Congruent and Incongruent trials. Children were then instructed to maintain their fixation to the screen. Prior to testing, children completed a practice session with an experimenter, in which they received feedback for correct and incorrect responses; children did not receive feedback during testing. During the practice session, children completed 24 trials including 12 Congruent and 12 Incongruent, of which 8 were No cues, 8 were Center cues, and 8 were Spatial cues. Children had to show clear understanding of the instructions to complete the neuroimaging session. Children were supervised throughout testing and were encouraged by the experimenter in between runs.

Neuroimaging Data Acquisition

The ANT was completed in the same session for all participants following the Linguistic Competition task, thus data acquisition was identical to that described in Chapter 2.

Neuroimaging Data Analyses

A total of 255 ANT file runs were analyzed: 128 monolingual runs and 127 bilingual runs. Data visualization was done using Homer2, a MATLAB-based software retrieved from the NITRC database (Huppert et al., 2009). First, the 690 and 830nm wavelengths timeseries data were visually examined to exclude participants whose hemoglobin signal quality was below 3 molar units and did not reveal cardiac signal, likely due to a large amount of motion artifacts and hair obstruction, for over 50% of 690 data channels. From this procedure, 3 ANT runs from one bilingual participant and 2 ANT runs from one monolingual participant were excluded.

The remaining data were then preprocessed using NIRS Toolbox (Barker et al., 2013), and several customized MATLAB scripts via the same procedure as those described in Chapter 2. Thus, the following preprocessing steps were completed: optical density change data conversion, motion artifact detection, motion artifact correction via spline interpolation, and concentration change data conversion.

Each participant's hemoglobin concentration data went thru two first-level General Linear Models (GLM) analyses via an ordinary least squares (OLS) fit: one GLM estimated beta values for the Cuing conditions (No cues, Central cues, and Spatial cues) assuming the dual-gamma canonical hemodynamic response function peaking 4-seconds after trial onset, and the second GLM estimated beta values for Congruence conditions (Congruent and Incongruent) assuming the dual-gamma canonical hemodynamic response function peaking 8-seconds after trial onset (Friston, et al., 2006; Hu et al., 2010). Next, two second-level group analyses were conducted using a multivariate linear mixed-effects model for each data channel. One group-level GLM included Cuing conditions and groups (monolingual, bilingual) as fixed effects, participants as the random effect variable, and hemoglobin beta values (HbO and HbR) as the predicting dependent variables. The second group-level GLM included Congruence conditions and groups (monolingual, bilingual) as fixed effects, participants as the random effect variable, and hemoglobin beta values (HbO and HbR) as the predicting dependent variables. HbR analyses are reported in Appendix D and E. All within- and between-group statistical analyses were also evaluated at a False Discovery Rate (FDR) threshold correction of $p < .05$ (see Benjamini & Hochberg, 1995).

To investigate a-priori questions on brain activity in left frontal regions as it relates to bilingual children's language abilities and attentional control performance, variables were regressed out from bilinguals' Executive attentional network analyses on regions in which there was greater bilingual brain activity for both the ANT and Linguistic Competition tasks. The following variables were used as regressors: ANT performance (accuracy and response time), Spanish and English vocabulary and morpho-syntax measures (scores in each task, as well as a summation score from each measure in both languages), and age of second language exposure.

Results

Behavioral Performance

Bilingual language and cognitive competence tasks. *T*-tests comparisons between bilingual and monolingual children's performance on English language measures and cognitive tasks did not reveal any significant differences among the groups ($p > .05$, see Table 3). Comparisons between bilingual children's English and Spanish language measures revealed bilinguals were significantly more proficient in English than Spanish, as would be expected of bilinguals with English-dominant schooling and neighborhood environments that are typical of southeast Michigan; see Table 3.

Children did not differ in English language proficiency and cognitive abilities ($p > .05$), except for nonverbal intelligence in which monolinguals performed better than bilinguals, also seen in Chapter 2 (Study 1). Since the groups were significantly different in nonverbal intelligence performance, analyses that controlled for any effects from this variable were additionally carried out. However, the nonverbal intelligence variable was not a significant predictor of ANT performance (accuracy and response time) and brain activity, and the analyses did not reveal that significant effects were different from when the variable was not included as a covariate. Previous research has shown that standardized testing, including intelligence, may not be valid across non-Western cultures, and differences in performance between majority and minority groups may be due to socio-cultural factors and/or stereotype threat (Nguyen & Ryan, 2008; Valencia & Suzuki, 2000; Wicherts & Dolan, 2010). Given that individual and group average standard scores were within typical ranges (85 to 115) for bilingual participants, the following analyses are presented without controlling for nonverbal intelligence effects. Notably, groups did not differ in the remaining tasks, thus any differences between the groups are not likely due to intelligence performance.

ANT cuing conditions. Accuracy performance was high for all participants (above 90%; see Table 4), indicating that children were successful in completing the task. The following subtractions assess two attentional networks using the cuing conditions: (i) Alerting is assessed by subtracting performance between No cue trials and Center cue trials, and (ii) Orienting of attention is assessed by subtracting performance between Center cue trials and Spatial cue trials. Independent-sample *t*-tests did not reveal group differences in accuracy or response time performance for the Alerting and Orienting attentional networks; see Table 4.

In addition, analyses of variance (ANOVA) were carried out: A mixed 2 (between-group variable: monolingual, bilingual) x 3 (within-group variable; Cue conditions: No cue, Center cue, Spatial cue) ANOVA for accuracy on Cue conditions did not reveal significant main effects of group or condition, or a group by condition interaction, suggesting that all children were similarly accurate across conditions. A similar 2 x 3 ANOVA for response time performance revealed a main effect of Cue condition ($F(2, 150) = 7.10$, $p = .001$, $\eta p^2 = .086$), indicating that children took significantly longer to respond to the No Cue condition (M = 880.98 ms, SD = 84.34) in comparison to Center cue trials (M = 863.38 ms, SD = 89.42, $p = .009$) and Spatial cue trials (M = 817.21 ms, SD = 93.55, $p < .001$). This ANOVA did not reveal a significant main effect of group, or a group by condition interaction, suggesting that the language groups did not differ in their performance by condition.

ANT congruence conditions. The Executive attentional network is assessed by subtracting performance between Congruent and Incongruent trials across all cue types. An independent-samples *t*-test did not reveal group differences in accuracy or response time performance for the Executive attentional network; see Table 4.

A mixed 2 (between-group variable: monolingual, bilingual) x 2 (within-group variable; Congruency condition: congruent, incongruent) ANOVA for accuracy revealed a significant main effect of Congruency condition ($F(1, 100) = 17.28$, $p < .001$, $\eta p^2 = .15$), indicating that children were significantly more accurate for the Congruent (M = 98.76%, SD = 1.22) than Incongruent (M = 97.11%, SD = 2.57) trials. The ANOVA did not reveal a significant main effect of group, or a group by condition interaction, suggesting that the language groups did not reveal differences in their performance by condition.

A similar 2 x 3 ANOVA for response time performance also revealed a main effect of Congruency condition ($F(1, 100) = 19.11$, $p < .001$, $\eta p^2 = .16$), indicating that children took significantly longer to respond to Incongruent (M = 892.30.98 ms, SD = 89.48) than Congruent trials (M = 816.74 ms, SD = 86.95). This ANOVA also did not reveal a significant main effect of group, or a group by condition interaction, suggesting that the language groups did not differ in their performance by condition.

Functional Neuroimaging

ANT cuing conditions: Alerting and Orienting attentional networks. Similar to task performance analyses, the following subtractions are used to assess brain activity for the attentional networks using the cuing conditions: (i) Alerting is assessed by subtracting brain activity in No cue trials from Center cue trials (Center cues > No Cues), (ii) Orienting of attention is assessed by subtracting brain activity in Center cued trials from Spatial cue trials (Spatial cues > Center cues). First, one-sample *t*-tests were carried out using the Alerting (Center cues > No Cues) and Orienting (Spatial cues > Center cues) network contrasts for each group.

However, the results did not reveal any significant activity for the Orienting network, for either language group. On the other hand, the results for the Alerting network revealed widespread brain activity across hemispheres and lobes. Thus, to best summarize the results, mixed-effect ANOVAs were carried out which include all the cuing conditions in one analysis. The ANOVAs consider Cuing conditions and group effects, and results are similar to those obtained by the initial one-sample *t*-tests.

A linear mixed-effects model that included groups (monolingual, bilingual) and Cuing conditions (No cues, Center cues, Spatial cues) as fixed effects, treating participants as a random effect, revealed significant main effects of group, condition, and interactions between the factors; see Table 5 and Figure 6.

The main effect of Cuing condition revealed that children showed significant activation in the following channels: two in right frontal (Ch 7 and 8), four in left frontal (Ch 6, 7, 9 and 10), one in right temporal (Ch 14), one in right parietal (Ch 18), and four in left parietal regions (Ch 15, 16, 18 and 20). Overall, participants consistently showed the greatest brain activity when the Center cue was presented, often followed by Spatial cues, and the least amount of activity for No Cues; see Figures 6 and 7.

The main effect of group revealed that the greatest brain activity for monolingual children was shown for the channel overlaying right temporal (Ch 14) regions, as compared to bilinguals; while bilinguals did not show activity in this channel. The main effect of group also revealed that the greatest brain activity for bilingual children, in comparison to monolinguals, included the following channels: two in right frontal (Ch 7 and 8), one in left frontal channel (Ch 10), and one in left parietal channel (Ch 16). See Figures 6 and 7.

Group by condition interactions manifested in right frontal (Ch 7 and 8) and parietal (Ch 18) regions, as well as left parietal (Ch 16), and stemmed from differences in brain activity among bilinguals and monolinguals between the No Cue and Spatial cues; see Figures 6 and 7. Specifically, the interactions in right frontal channels stemmed from bilinguals' greater activity in the No Cue trials than Spatial cues, while monolinguals showed similar activity for both No Cues and Spatial cues. The interaction in right parietal (Ch 18) stemmed from bilinguals' deactivation in No Cues and Spatial cues, while monolinguals showed similar increasing activity in both of those conditions, and both groups showed significantly positive activity when Center cues were presented. Finally, the interaction in left parietal (Ch 16) stemmed from both groups showing deactivation in No Cues, followed by monolinguals' deactivation for Spatial cues while bilinguals showed increasing activity, and both groups showed significant activity for Center cues. Overall, these interactions suggest the groups vary in patterns across Cue conditions, but especially sensitive to differences are the No Cue and Spatial Cue trial types.

ANT Congruence conditions: Executive attentional network. Similar to task performance analyses, the Executive attentional network is assessed by subtracting brain activity in Congruent from Incongruent trials (Incongruent > Congruent). One-sample *t*-tests were carried out for each group's Executive attentional network contrast. However, the results did not reveal any significant activity for monolingual children, thus mixed-effect ANOVAs were carried out to best summarize the results. The results for bilinguals' one sample *t*-test are presented in Figure 10b.

A linear mixed-effects model that included groups (monolingual, bilingual) and Congruency conditions (Congruent, Incongruent) as fixed effects, treating participants as a random effect, revealed significant main effects of group, condition, and interactions between the factors; see Table 6 and Figure 8.

The main effect of Congruence condition revealed that children showed significant activation in left frontal (Ch 8 and 11) and parietal (Ch 18 and 21) regions; see Figures 8 and 9. The main effect of group revealed that bilingual children also showed greater activation in left frontal (Ch 7, 9, 10 and 11) and parietal (Ch 19, 20 and 22) regions, as compared to monolinguals. Monolingual children did not show significantly greater activation in any channel in comparison to bilingual children.

Group by condition interactions manifested in bilateral frontal channels (right: Ch 9 and 10; left: Ch 6, 7 and 9), as well as one right parietal channel (Ch 20); see Figures 8 and 9. In the next sentences, the term ‘ratio’ is used to describe when brain activity between bilinguals and monolinguals differed during the Incongruent and Congruent conditions and consequently this difference was larger in one group than in another. Most interactions stemmed from differences in the ratio of increasing brain activity from Congruent to Incongruent conditions among bilinguals and monolinguals. The interaction for one left frontal (Ch 6) channel showed smaller ratio differences between the conditions for monolinguals, than bilinguals. In contrast, the interaction for the adjacent left frontal channel (Ch 7) stemmed from a smaller ratio difference between conditions for bilingual children whom showed similar brain activity for both conditions, while monolinguals showed a greater increasing ratio of brain activity for Congruent to Incongruent trials. The interaction for another left frontal (Ch 9) channel revealed that monolinguals had similarly low brain activity for both conditions (greater for Congruent than Incongruent), and bilinguals had increasing brain activity from Congruent to Incongruent trials. In the right hemisphere, the interaction for one right frontal channel (Ch 9) stemmed from monolinguals' greater activity in both conditions, while bilinguals showed similarly low brain activity for Congruent to Incongruent trials. Interestingly the interaction for the adjacent right frontal channel (Ch 10) stemmed from monolinguals showing low brain activity for both conditions, while bilinguals showed a greater increasing ratio of brain activity for Congruent to Incongruent trials. Finally, the interaction for right parietal (Ch 20) stemmed from greater brain activity for Congruent trials in bilinguals than monolinguals, and deactivation for bilinguals in the Incongruent trials while monolinguals showed low activity.

Brain Activity and Regressor Variables in the Executive Attentional Network

This dissertation's third research goal is to investigate whether brain activity within overlapping regions in which linguistic competitors are processed along with attentional control mechanisms, explains advantageous Executive Function performance in bilingual children, or whether differences in brain activity are due to language abilities. The present study did not reveal advantageous performance by bilingual children, nevertheless separate analyses for the ANT Executive Network were carried out controlling for the following variables: accuracy, response time, and family's income. These analyses were focused on regions of interests, specifically on the channels that showed brain activity for main effects of condition and group including, left frontal (Ch 7-11) and left parietal (Ch 18-22) channels. Separate group-level linear mixed-effects models for each covariate were carried out, they included both groups (monolingual, bilingual) and Congruency conditions (Congruent, Incongruent) as fixed effects, and treated participants as a random effect. Performance (accuracy and response time) or family's income were not significant predictors of brain activity. Thus, these results suggest that the initial findings are representative of brain activity for the task and performance does not predict differences in brain activity between the groups in this study, yet monolingual and bilinguals show different patterns of brain activity for the task.

Chapter 2 revealed that bilingualism likely impact linguistic competition processes in children's left frontal regions. Similarly in the present study, bilingual children showed greater activity in a left fronto-parietal network when processing executive attentional control mechanisms, than monolingual children. Indeed, one sample *t*-tests on contrasts assessing linguistic competition (Chapter 2: Related > Unrelated conditions) and attentional control (Executive attentional network: Incongruent > Conguent) processes revealed that bilingual children's brain activity overlaps in regions underlying left middle frontal gyrus (Ch 6) and left parietal regions (Ch 17 and 20); see Figure 10. To investigate a-priori questions on bilinguals' greater brain activity for the ANT Executive Network as it relates to their dual-language abilities, separate group-level linear mixed-effects models were carried out controlling for the following variables: Spanish and English vocabulary and morpho-syntax measures (scores in each task, as well as a summation score from each measure in both languages), and age of second language exposure. These analyses were focused on regions of interests that showed significant brain activity for main effects of condition and group (left frontal: Ch 6-11; left parietal: Ch 17-22). Separate linear mixed-effects models for each covariate included Congruency conditions (Congruent, Incongruent) as fixed effects, and treated bilingual participants as a random effect.

The linear mixed-effects models revealed that Spanish and English vocabulary and morpho-syntax measures were significant predictors of bilingual children's brain activity in left fronto-parietal regions, while age of second language exposure was not a significant predictor of bilinguals' brain activity; see Table 7. The analyses revealed that English morpho-syntax were significant predictors of left frontal channel Ch 6 and Ch 8, as well as parietal Ch 22. English vocabulary was also a significant predictor of left frontal Ch 6 and Ch 8. Spanish morpho-syntax and vocabulary, as well as English vocabulary, were all significant predictors of left frontal Ch 9 and Ch 10. Spanish morpho-syntax was also predictive of brain activity in left frontal Ch 11, as well as parietal Ch 18, 20 and 22. For all regressions, most channels revealed significant activity for Incongruent trials as compared to Congruent trials (see Table 7); one exception was Ch 11 which did not show significant activity for either condition, although betas were higher for Incongruent than Congruent trials.

Discussion

Bilingualism is a typical linguistic experience, yet relatively little is known about its impact on children's cognitive and brain development. The goal of the present chapter was to examine the consequences of bilingualism on the functional organization of children's attentional networks. In the present study, bilingual and monolingual children (ages 7-9) completed the Attentional Network Task (ANT) while undergoing fNIRS neuroimaging. Consistent with the Adaptive Control hypothesis, I hypothesized that the increased demand for attentional control mechanisms will impact bilingual children's brain responsiveness in attentional networks, specifically the Executive network. The results did not reveal differences between bilingual and monolingual children's behavior performance in the ANT, however two key findings on the dynamic impact of bilingualism in children's brain networks emerged from the present study: first, bilingual children showed greater brain activity, than monolingual children, in left fronto-parietal regions across attentional networks (Alerting, Orienting, and Executive). Second, bilinguals' brain activity for the Executive attentional network was related to their English and Spanish language abilities (vocabulary and morpho-syntax). These results suggest that bilingualism may influence the developmental nature of the brain’s functional specialization for attentional control, and possibly Executive Function.

Alerting and Orienting Attentional Networks

Attentional processes are present in early infancy (Ross-Sheehy, Schneegans, & Spencer, 2015) and play a key role in cognitive, emotional and social development (Grossmann & Johnson, 2010). The Alerting network is associated with maintaining a focused state, while the Orienting network is associated with the ability to shift that focus (Fan et al., 2002; Posner, 2012). The ANT uses warning cues as stimuli to distinguish the processes of these two attentional systems. Neuroimaging research with monolingual adults reveals that both the Alerting and Orienting networks engage a bilateral fronto-parietal network, however right frontal and left parietal activity is the most representative across the literature since any differences are often due to task design (Corbetta et al., 2000; Corbetta & Shulman, 2002; Fan et al., 2005; Konrad et al., 2005; Nee, Wager, & Jonides, 2007; Petersen & Posner, 2012).

When presented with warning cues, both monolingual and bilingual children in the present study activated a similar fronto-parietal network as adults (Konrad et al., 2005). Activity in frontal regions is related to the Alerting network, since these regions are thought to be involved in storing relevant information in mind, which coincides with processing cues as it alerts participants of an upcoming trial (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Fan et al., 2005; MacDonald, Cohen, Stenger, & Carter, 2000). Activity in parietal regions is related to the Orienting network, since these regions are thought to be involved in processing visuospatial information, which coincides with processing cues as they orient participants where the Target will appear (Corbetta & Shulman, 2002). One caveat of the present study may be that all three cues were included in the same analyses, since the Orienting contrasts (Spatial > Center) did not reveal significant activity. Yet, by including all three cues into one analyses, the study gained statistical power and a thorough view into how the three cues compare in brain activity across the paradigm. These analyses revealed that Center cues, which are associated with the Alerting network, involved greater brain activity in fronto-parietal regions for children. While brain activity for Spatial cues often showed similar activity as when No Cues were presented, these results suggest that both bilinguals and monolinguals may still be developing brain activity for the Orienting attentional network. However, children responded faster to Spatial cues, followed by Center and No Cues, which is in accordance to typical behavioral performance (Mezzacappa, 2004; Rueda et al., 2004; Tran et al., 2015), since Spatial cues assist participants in locating the Target more so than Center and No cues. Little is known about the development of attentional networks in childhood, yet Konrad et al. (2005) showed that children ages 8-12 did not show similar brain activity in comparison to adults, and suggested that any developmental differences might be due to their top-down neural modulation (i.e. Norepinephrine and Acetylcholine) stemming from subcortical regions to the fronto-parietal network (Corbetta et al., 2000; Marrocco & Davidson, 1998; Thiel, Zilles, & Fink, 2005; Witte & Marrocco, 1997). Thus, the results suggest that behavioral performance might not fully correspond to the functional brain organization for the Alerting and Orienting attentional network, as also shown in Konrad et al. (2005), and is possibly due to neural processes that are not yet established for children in this developmental period. Nevertheless, these activation patterns should be taken with caution given the small sample size.

Few studies have investigated children's brain activity for attentional networks, thus the present study provides new insight into how language experiences may impact their developmental trajectories (e.g., Abundis-Gutiérrez, Checa, Castellanos, & Rueda, 2014; Bunge et al., 2002a; Konrad et al., 2005; Posner, Rothbart, Sheese, & Voelker, 2014). The main effects of group revealed monolingual children activated a channel overlaying a right temporal region, as compared to bilinguals. Activity in this region is consistent with previous developmental work suggesting that children activate this region to a greater extent than adults for the Alerting and Orienting networks, and this area along with parietal regions support children's shifting of attention (Abundis-Gutierrez et al., 2014; Corbetta & Shulman, 2002; Konrad et al., 2005). On the other hand, bilingual children activated bilateral frontal regions and a left temporo-parietal channel, to a greater extent than monolinguals; see Table 5 and Figure 6. Previous neuroimaging work with adults, but not children, show that activity in frontal and parietal regions is consistent with mature Alerting and Orienting attentional networks (Abundis-Gutierrez et al., 2014; Konrad et al., 2005). Thus, greater frontal activity in bilingual children may suggest a more 'mature' functional organization that may also be driving the main effects of condition results. However, the alternative is in line with the Adaptive Control hypothesis, suggesting that bilingualism alters the functional organization for attentional networks (see Arredondo et al., 2015).

Given that the analyses do not provide the Alerting and Orienting contrasts between the conditions, the present study is limited in providing specific indices of brain regions in attention, which in turn do not distinguish whether bilingualism impacts brain activity or accelerates the maturation of attention development. This is of importance since research shows that bilingualism increases grey matter volume, thus children by this age may already show changes in neuronal populations (Mechelli et al., 2004; Olulade et al., 2015). Yet given the lack of group differences in task accuracy and response times for these networks (see Table 4), these findings suggest that bilingual and monolingual children simply show different patterns. Future research is needed to address in better detail whether these differences are due to neuronal differences that emerge early in development from bilingual contexts that then exhibit group differences in brain activity for the Alerting and Orienting attentional network.

Finally, the results revealed interactions among the groups and conditions in right frontal and left parietal regions, which previous neuroimaging work suggests are the most sensitive brain regions to changes in stimuli and task differences for attentional processes (Nee et al., 2007; Wager, Jonides, & Reading, 2004). Overall, the results in the present study are consistent with work indicating that a fronto-parietal network is still developing for bilingual and monolingual children in order to better support the Alerting and Orienting attentional systems.

Executive Attentional Network

The Executive attentional network is associated with the ability to resolve conflict (Fan et al., 2002; Posner, 2012). Previous research has shown that adults activate bilateral dorsolateral prefrontal regions, with robust responses in right inferior frontal gyrus, while children often show greater left middle frontal gyrus activity (Abundis-Gutiérrez et al., 2014; Bunge et al., 2002a; Konrad et al., 2005; Posner et al., 2014). The present study revealed that children engage left fronto-parietal regions for the Executive attentional network; as shown in Figure 9, this activity was greater for Incongruent trials, which require participants to resolve visuospatial conflicting information, than Congruent (control) trials. As shown in previous research, children appear to have a left lateralized or a more bilateral brain response than adults (Bunge et al., 2002a; Durston et al., 2002; Moriguchi & Hiraki, 2013; Moriguchi, Sakata, Ishibashi, & Ishikawa, 2015). These hemispheric differences are typical of early development across a variety of Executive Function tasks, suggesting children's left hemisphere is more efficient at extracting, re-evaluating rules and flexibly applying them (Bunge & Zelazo, 2006; Moriguchi & Hiraki, 2013; Moriguchi et al., 2015; Zelazo, Carlson, & Kesek, 2008).

Specifically, monolingual children engaged similar brain responses for both conditions in a left frontal (Ch 11) and a left parietal (Ch 18) channel, and showed a reverse pattern (Congruent > Incongruent) in a left parietal channel (Ch 21). Children may still be learning to differentiate between instances that require conflict resolution, thus may often tend to have a more similar response for both Incongruent and Congruent conditions, or even a reverse pattern of greater activation to Congruent than Incongruent conditions (Arredondo et al., 2015; Konrad et al., 2005). Both language groups showed greater activity in Congruent trials in a channel overlaying a right parietal region, which is likely engaged for visuospatial non-conflictual events. Overall, these results show similar developmental patterns as previous work using monolingual children of a similar age range (Arredondo et al., 2015; Konrad et al., 2005). Finally, one of the channels in right frontal (Ch 9) showed a trend of greater activity across both conditions for monolingual children than for bilinguals, which also supports previous results with slightly older monolingual children showing greater activity in right-than-left frontal regions (Arredondo et al., 2015). It is plausible that monolinguals' brain activity in the present study is suggestive of typical brain activity that is in the process of still developing neural specificity for attentional control. Thus, children in this age range may not yet have mature, adult-like specialization for the Executive attentional network in right frontal regions, since the Incongruent condition seems to be beginning to engage those regions supporting improved visuospatial strategies.

In contrast, bilingual children revealed differences in brain activity between Incongruent and Congruent conditions, that were largely evident in the resulting interactions in left frontal regions (Ch 6, 7, 9). Bilinguals also showed overall greater activity in left frontal regions than monolinguals. While research with monolingual adults show greater right frontal activity during nonverbal visuospatial attention tasks (Bunge et al., 2002b; Fan et al., 2005; Konrad et al., 2005;

Nee et al., 2007; Wager et al., 2005), studies with bilingual adults show robust activity in left inferior frontal regions that suggest hemispheric changes are likely to dual-language demands (Garbin et al., 2010; Coderre et al., 2016). Furthermore, these results extend on my previous findings with children (ages 7-13) showing that bilingual children in a smaller age range (7-9 years) have already specialized their left frontal activity for attentional control, while monolingual children are still specializing their right frontal activity. Thus, the results are consistent with the Adaptive Control hypothesis, suggesting that bilingualism may alter and potentially accelerate the developmental course of functional specialization for attentional control, specifically within the Executive attentional network, in the left hemisphere.

Dual-Language Abilities Impact the Executive Attentional Network

The second goal of the present chapter was to investigate whether any differences, especially in bilinguals' brain activity, were due to task performance, language abilities or age of second language acquisition. Of especial interest is the Executive attentional network, due to prior evidence suggesting bilinguals' advanced performance in Executive Function mechanisms. The present study did not reveal that group differences in brain activity were predicted by performance (accuracy and response time) or family's income. However and most importantly, English and Spanish vocabulary and morpho-syntactic language abilities were predictors of bilinguals' brain activity in left frontal and parietal regions. Furthermore, the betas in the predictor variables were negative for English measures and positive for Spanish measures suggesting that English abilities decreased brain activity, while Spanish increased it within left fronto-parietal regions. Bilinguals in the present study are growing up in a context in which English is the majority language, and were more proficient in English than in Spanish, which is their heritage minority language. Thus, to be bilingual in the United States is rather more effortful for these children since they are at risk of losing their heritage language, and becoming 'monolingual-like'. Given this, the results suggest that bilinguals' language abilities may impact brain activity in left fronto-parietal regions. Previous work has suggested that children's left hemisphere is more efficient at extracting, re-evaluating rules and flexibly applying them (Bunge & Zelazo, 2006; Moriguchi & Hiraki, 2013; Moriguchi et al., 2015; Zelazo et al., 2008), thus these results may suggest that bilinguals' increasing abilities in extracting the linguistic rules in both languages supports the specialization of this region for those similar capacities.

Conclusion

Theories of bilingual development suggest that dual-language experiences during early cognitive and brain development may impact the functional representations of attentional systems (Abutalebi & Green, 2016; Green & Abutalebi, 2013). Overall, the results suggest that both bilingual and monolingual children may still be developing their attentional networks and most activity stems from a left fronto-parietal network. While children recruit similar regions across the networks, the groups reveal differences in which bilingual children recruit brain regions in left frontal to a greater extent than monolinguals. Given that the present study did not find differences in task performance among the groups, these differences suggest that demands in dual-language processing may alter the brain functional organization of attentional mechanisms and these differences may not necessarily correspond to behavior task performance. In the final chapter, I discuss the theoretical implications for an altered functional organization of attentional control which also underlie the same left fronto-parietal regions as in linguistic competition (Chapter 2), and their relation to dual-language abilities and experiences. The General Discussion also considers limitations and future research directions for developing new research questions on academic achievement.

CHAPTER IV

General Discussion

Over the course of language acquisition, children encounter a variety of linguistic contexts that require conflict resolution and may demand attentional control mechanisms (e.g., adjudicating the meanings of similar sounding words such as *'I'* and *'eye'*; Mazuka et al., 2009). This dissertation investigated the theoretical account that the doubling of linguistic contexts, as is typical in bilingual language acquisition, may influence attentional control abilities and the emerging functional organization of attentional networks in the developing brain (Bialystok et al., 2012; Dong & Li, 2015; Green & Abutalebi, 2013; Kroll et al., 2015). The results of this dissertation did not reveal differences in behavioral performance between bilinguals and monolinguals in tasks demanding attentional control for processing linguistic and non-linguistic competitors. The neuroimaging findings, however, revealed three critical differences between the groups: (i) bilingual children engage less brain activity in left frontal regions, than monolinguals, during a task assessing linguistic competitors in one language, thus possibly suggesting efficient processing by bilinguals; (ii) bilinguals show overall greater brain activity, than monolinguals, in left fronto-parietal regions during a task assessing attentional networks (i.e., alerting, orienting, and executive); and (iii) bilinguals' brain activity in left fronto-parietal regions during the task conditions assessing Executive attentional network is associated with better language abilities. Taken together, these findings may suggest that attentional control and language processes both interact in bilinguals' left fronto-parietal regions and may impact the dynamics of brain plasticity during child development.

Research Questions and Theoretical Implications

The Adaptive Control hypothesis (Abutalebi & Green, 2016; Green & Abutalebi, 2013; Green, 2011) suggests that bilingualism creates recurrent linguistic demands, which in turn influence neural networks and their associated cognitive mechanisms, to better support linguistic experiences. This perspective provides a framework on how domain-general Executive Function mechanisms and associated brain regions are involved in bilinguals' language selection. Processes of language selection and Executive Function engage mostly distinct brain regions that better support each of their domains, but also both engage left prefrontal cortex and basal ganglia. Thus, this dissertation addressed the hypothesis that bilingualism might influence the development of attentional networks within the left frontal regions.

Does bilingualism have an impact on the brain's functional organization of children's attentional networks? The results reveal that bilingual children engage left fronto-parietal regions, to a greater extent than monolinguals, during a nonverbal task assessing attentional networks. Prior work suggests monolinguals engage right frontal regions for Executive Functions, in contrast bilingual children and adults engage left frontal regions (Arredondo et al., 2016; Barac et al., 2016; Garbin et al., 2010; Coderre et al., 2016). The results of this dissertation support the notion that cognitive systems may adapt to early bilingual experiences and that this set of changes may already be present by age 7. These results reveal that the functional representations of attentional processes may be especially malleable early in development, and these changes might be continuously reinforced throughout a person's lifetime (Baum & Titone, 2014; Green & Abutalebi, 2013; Johnson, 2011).

Is there a cortical overlap between processes of attentional control and the adjudication of competing linguistic input? The results reveal that children engage overlapping left fronto-parietal regions during tasks assessing verbal and nonverbal attentional processes. Chapter 2 reveals that, similar to adults, children engage a left fronto-parietal network during a task that required children to process competing linguistic input (see Marian et al., 2014). Chapter 3 provides evidence that bilingualism may alter the attentional networks by engaging left fronto-parietal regions to a greater extent than monolinguals. In turn, brain activity in these regions is associated with bilinguals' better language abilities. These results support the Adaptive Control hypothesis (Green & Abutalebi, 2013) and suggest that attentional control mechanisms may be altered as a result of bilinguals' language abilities.

Within the frontal lobe, the neural basis for selective attention and working memory mechanisms includes both inferior and middle frontal regions (Awh & Jonides, 2001; de Fockert, Rees, Frith, & Lavie, 2001; Gazzaley & Nobre, 2011). Both of these frontal regions are connected via white matter tracts (Catani, Jones, & ffytche, 2004), and are involved in solving conflict, including holding and storing relevant information in mind (Botvinick et al., 2001; Fan et al., 2005; MacDonald et al., 2000). Multiple studies now show that bilinguals activate left inferior and middle frontal regions for a variety of Executive Function tasks across the lifespan (e.g., Arredondo et al., 2015; Coderre et al., 2016; Garbin et al., 2010). A recent study, however, found that bilingual adults show overlapping left inferior frontal gyrus activity for an attentional control task and a dual-language semantic categorization task (Coderre et al., 2016). Thus, one possibility is that the left middle frontal gyrus is more sensitive in supporting Executive Function mechanisms early in childhood, and left inferior frontal gyrus is engaged later in development.

The development of attentional mechanisms also suggests a left-to-right switch, in which the left hemisphere's efficiency at extracting and re-evaluating rules is especially pertinent early in development, and right hemisphere is engaged with greater maturity. Research with monolinguals suggests that left frontal regions are associated with the capacity to flexibly manage and select rules, while right frontal regions are associated with monitoring aspects of attentional control (cf. Vallesi, 2012). However, these capabilities are currently debated in the research community, since brain hemispheres interact to optimize human behavior (Vallesi, 2012). Several meta-analyses of attentional control studies with monolingual adults find predominantly brain activity in right inferior frontal cortex during nonverbal attention paradigms (Nee et al., 2007; Wager et al., 2005). In contrast, greater activity in left homologous regions is found during verbal attention paradigms (Nee et al., 2007; Wager et al., 2005). This suggests that laterality differences in the adult brain vary by the visuospatial or verbal nature of stimuli (Nelson et al., 2009), and by difficulty levels in which left frontal regions support better performance (Swick, Ashley, & Turken, 2008). For instance, Swick et al. (2008) showed that adults with left inferior frontal gyrus damage had higher error rates during a nonverbal attention paradigm, especially during difficult conditions. These results suggest that left inferior frontal gyrus is still critical and relevant for attention, even in adulthood once these networks have reached 'maturity'.

For early-exposed bilinguals, however, their developmental trajectory on attentional mechanisms seems left lateralized (Arredondo et al., 2015; Coderre et al., 2016; Garbin et al., 2010). Multiple studies now show, including the present study, that bilingualism may optimize the left hemisphere: structurally (Mechelli et al., 2004; Olulade et al., 2015), functionally (Guo et al., 2011; Jasinska & Petitto, 2013; Kovelman et al., 2008a, 2008b), and its connectivity (Li, et al., 2015; Luk et al., 2011). Differences in left frontal activity for bilinguals are possibly due to language abilities and fluency (Costa & Sebastián-Gallés, 2014). Indeed, the present study revealed that English vocabulary and morpho-syntactic measures were significant predictors of decreasing activity in these brain regions, while Spanish vocabulary and morpho-syntactic measures were significant predictors of increasing brain activity in left fronto-parietal.

Languages bring their own set of rules and structures, in which children explore how words are related to one another, in order to make predictions and master language acquisition (Pinker, 1994). It is plausible that bilinguals' doubled management of their languages' rules and structures may be one factor altering left fronto-parietal regions. Indeed, research suggests that language acquisition (Byers-Heinlein & Werker, 2013), language comprehension (Fedorenko, 2014) and syntactic structures (Kapa & Colombo, 2014; Novick, Trueswell, & Thompson-Schill, 2005, 2010) recruit frontal regions associated to Executive Function mechanisms. Findings from training studies reveal that attentional control mechanisms may be malleable and show increasing brain activity following continuous practice (Jaeggi, Buschkuehl, Jonides, & Shah, 2011), yet we also know that these effects quickly disappear when the training activities are discontinued (Jaeggi, Buschkuehl, Jonides, & Shah, 2012). Consistent with this view, Valian (2014) suggests that bilingualism could serve as an everyday training regimen for Executive Function mechanisms. Since bilingualism provides individuals with daily increasing knowledge for both languages, such activities may continue to strengthen neural connections throughout development (Hebbian idea; Hebb, 1949), which may explain why bilinguals show greater brain activity in left fronto-parietal regions across the lifespan.

Does cortical activity, within an overlapping brain region for language processing and attentional control, explain advantageous performance in bilingual children? The results reveal both bilingual and monolingual groups performed similarly in the linguistic competition task and ANT. In addition, this dissertation's regression analyses controlling for task performance do not predict differences in brain activity between the groups. Thus, the neuroimaging results suggest that bilingualism may alter brain activity, and that these changes may not necessarily be associated to performance.

Conflicting evidence on bilinguals' advantageous performance has especially emerged using the ANT with 7-9 year olds (Antón et al., 2014; Kapa & Colombo, 2013). Interestingly, Barac et al. (2016) showed better performance by 5-year-old bilingual children was related to differences in electrical activity (as measured by electroencephalography [EEG]) amplitudes and latencies (P3 and N2), in comparison to monolingual peers. The present results do not provide a direct link between behavioral and cortical brain activity measures that identify a 'bilingual advantage,' or how it might differ if better performance was related to brain activity. The present study, however, suggests that bilinguals may use different circuitries than monolinguals, and may even develop a 'mature' network earlier than monolingual children since bilingual 7-9 year-olds already show a left-lateralized network alike bilingual adults. However, the participants in our previous study (Arredondo et al., 2015) showed a trend for better attentional control accuracy performance and greater left frontal activity, including left inferior frontal gyrus, than in the present study; thus, one area for future research is to explore whether better performance by bilinguals is related to greater activity in left inferior frontal gyrus.

Alternative Perspective

The present work shows children activate overlapping brain regions in left fronto-parietal during tasks assessing verbal and nonverbal attentional processes, and brain activity in these regions was associated with bilinguals' better language abilities. While these results prescribe to the theoretical perspective by the Adaptive Control account (Green & Abutalebi, 2013) suggesting that attentional control mechanisms may be altered as a result of bilinguals' language abilities. An alternative position to these results is that differences in brain activity in the left hemisphere are possibly due to bilinguals' experiencing some level of difficulty when they manage their languages. Previous work has suggested that children's left-brain activity during Executive Function tasks is indicative of an immature brain cognitive network, since adults show activity in right-brain regions (Bunge et al., 2002b, Konrad et al., 2005). Thus, bilinguals' greater brain activity in the left hemisphere for a nonverbal attentional control task might by indicative of experiencing some difficulty with their languages. While all children were highly accurate and successful in completing the task, nevertheless it is plausible that bilingual children grapple with two languages in their lifetime. Future research should investigate bilinguals who are successful in language-switching versus those who struggle, how attentional networks differ between high versus low ANT performers, and how attentional networks emerge in children's lifetime when first exposed to a second language.

Limitations

This dissertation's statistical analyses limit the implications of the results. First, the linear mixed effect models analyze differences in overall activity (averaged across conditions) between bilinguals and monolinguals, it does not index differences that are recruited more strongly when a specific cognitive mechanisms is performed. Thus, contrasts between experimental and control conditions should be carried out for the present research's claims on the specific processes underlying the management of linguistic competition (Study 1; Phonologically Related>Unrelated) and attentional networks (Study 2; Center>No Cue, Spatial>Center; Incongruent>Congruent). Second, additional between-study analyses should be carried out (e.g., Group [Bilingual, Monolingual] x Task [ANT, Language] interaction) and would be useful to understand the hemispheric asymmetries reported in Studies 1 and 2, as well as to provide further evidence that the groups show differences in the functional overlapping regions between verbal and nonverbal attentional processes. Finally, regressions during brain activity in the Executive attentional network were not conducted for the monolingual group since group effects revealed bilinguals showed greater activity than monolinguals. Thus, additional regressions including language ability as a covariate would provide further evidence that monolinguals' brain activity may also interact with attentional mechanisms.

The present research has additional limitations worth noting in its methodology. First, the linguistic competition task (Chapter 2) did not test bilinguals' typical dual-language processing, specifically between-language competitors. It is plausible that the nature of the task structure and processes under investigation would be different if tested under different conditions. Second, while fNIRS is motion tolerant and child-friendly, its methodology is limited in spatial resolution (~3 cm), and consistency when applying the head probeset may vary from participant to participant due to head size and variability across individuals' brain structures. One alternative for future research is to combine fNIRS and fMRI measurements to cross-validate results. Third, the age range in the present study has shown inconclusive behavioral evidence on whether bilinguals show advantageous performance than monolinguals, especially in the ANT. Generally, children in this age range perform well at a variety of experimental measures, thus they may not necessarily show any differences on group performance. This lack of variability in performance questions whether the present study would have shown associations between brain measurements and performance if a more sensitive task would have been employed, or by including a younger sample whose performance was more variable. Finally, all neuroimaging studies to date showing

Executive Function differences in brain activity for bilinguals are Spanish speakers. It would be of interest to show that these differences are also present for individuals who speak other languages and are members of other ethnicities and cultures, thus these findings should be generalized with caution.

Future Directions

Attentional mechanisms guide overall human learning, and the regulation of socio-cognitive development and behavior (cf. Posner, 2012). We know from training studies that Executive Function mechanisms, including attention, are malleable skills that can be altered to improve academic achievement (Jaeggi et al., 2011). Research shows that children’s Executive Function performance predicts their outcomes on physical health, school readiness and academic achievement, more so than IQ (Blair & Razza, 2007; Eigsti et al., 2006; Moffit et al., 2011). Relatedly, attentional mechanisms are a strong predictor of children’s reading abilities (Lan, Legare, Cameron Ponitz, Li, & Morrison, 2010), and interventions have led to improvements in performance (Diamond, Barnett, Thomas, & Munro, 2007). Could bilingualism serve as an everyday training experience for Executive Function mechanisms, in order to improve children’s academic achievement, especially in low socio-economic status (SES) communities?

Noble et al. (2005; 2012) has shown that SES can impact language and Executive Function performance, as well as respective brain activity (Nobel, Houston, Kan, & Sowell, 2012; Noble, Norman, & Farah, 2005). Specifically, they find that low SES children perform worse in phonological awareness tasks and show less brain activity than middle SES peers. Low SES families are exposed to multiple stressors, including financial stress, low-levels of nutrients in food intake, and hardship conditions in their neighborhoods and communities. Consequently, these stressors affect the child’s language abilities, cognitive development and academic achievement (Bradley & Corwyn, 2002; McLoyd, 1998; Sirin, 2005). However, low SES bilingual children have been shown to outperform low and middle SES monolingual peers on a variety of cognitive tasks assessing Executive Function and language learning (Hackman & Farah, 2009; Mezzacappa, 2004), suggesting that bilingual effects on attention may surpass negative effects of SES (Carlson & Meltzoff, 2008; Engel de Abreu et al., 2012). Although a low SES social context may negatively impact a child, future research should investigate whether a bilingual environment could further support brain regions associated with attentional skills and language acquisition, which in turn could positively impact children's academic achievement and cognitive development.

Conclusion

In the contexts of increased global migration and growth of multilingual communities, research-based models of child development that include bilingualism in context are vital for addressing the needs of language acquisition and cognitive development. The evidence suggests that bilingualism may alter functions of the mind and brain. This dissertation provided an investigation on the impact of bilingualism in children's networks, and evidence that left fronto-parietal regions may be susceptible to linguistic experiences that attune their responsiveness. Still, more research is necessary to address these mechanisms at play. Nevertheless, the present results provide new insight and carry implications for understanding experience-dependent brain plasticity in order to better inform models of neuro-cognitive development.

Table 1

Study 1: Participants' average scores (standard deviation) in language and cognitive tasks.

Measures	**Monolinguals (n = 22)**	**Bilinguals (n = 21)**	***T*-values**
Age	8.12 (0.80)	8.09 (0.77)	0.12
IQ [a]	118.68 (9.21)	108.95 (13.45)	2.78**
Demographics			
Income [b]	8.14 (1.77)	6.32 (2.43)	2.74**
Mother's education [c]	6.91 (1.31)	5.76 (2.49)	1.91
Father's education [c]	6.55 (1.77)	5.29 (2.87)	1.74
English Behavioral Measures			
Phonological Awareness [d]	10.86 (2.55)	11.29 (3.08)	0.49
Vocabulary [a]	114.36 (10.90)	110.95 (10.68)	1.04
Morpho-syntax (%)	92.53 (6.33)	89.06 (10.10)	1.36
Reading [a]	119.45 (9.47)	115.52 (10.03)	1.32
Spanish Behavioral Measures			
Vocabulary [a]	--	92.14 (10.03)	7.46***
Morpho-syntax (%)	--	66.88 (24.04)	4.15**
Cognitive Tasks			
Naming Speed – Numbers [a]	105.14 (11.34)	108.81 (15.75)	0.88
Pair Cancellation Score	45.41 (7.68)	47.33 (10.38)	0.69
Grammaticality Judgment Task			
Accuracy (%)			
Overall	97.40 (5.03)	94.70 (8.87)	2.25*
Baseline	98.92 (2.52)	99.05 (3.40)	0.14
Phonologically Unrelated	99.57 (1.40)	97.18 (4.02)	2.62*
Phonologically Related	93.70 (6.96)	87.88 (11.88)	1.97
Reaction Time (ms)			
Overall	1555.48 (148.93)	1584.63 (118.37)	0.71
Baseline	1452.30 (171.14)	1487.68 (109.66)	0.80
Phonologically Unrelated	1528. 72 (148.85)	1577.49 (148.85)	1.23
Phonologically Related	1719.08 (128.30)	1743.44 (145.06)	0.58

Notes. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$
[a] Scores are standardized at a mean of 100 (typical average scores range between 85 and 115).
[b] Options for demographic responses on yearly household income were the following: (1) less than $5,000; (2) $5,000 - $11,999; (3) $12,000 - $15,999; (4) $16,000 - $24,999; (5) $25,000 - $34,999; (6) $35,000 - $49,999; (7) 50,000 - $74,999; (8) $75,000 - $99,999; (9) $100,000 and greater. Three families (2 bilingual, 1 monolingual) voluntarily skipped this question.
[c] Options for responses on education were the following: (1) primary school, (2) some secondary school, (3) High school diploma or equivalent (GED), (4) some college, (5) Associate's degree, (6) Bachelor's degree, (7) Master's degree, (8) Doctorate degree [Ph.D], (9) Professional degree [MD, DD, DDS, etc].
[d] Scores are standardized at a mean of 10 (SD = 3).

Table 2

Brain activity, neuroimaging effects for the linguistic task competition in monolinguals and bilinguals.

Channel	Cortical Region	F-value	*p*-value
Main effect of condition			
20	Right inferior parietal lobe	10.05	< .001*
6	Left middle/inferior frontal gyri	6.07	.003
18	Left supramarginal gyrus/inferior parietal lobe	4.56	.012
20	Left inferior parietal lobe	7.00	.001*
21	Left inferior/superior parietal lobe	11.87	< .001*
Main effect of group			
Monolingual > Bilingual			
6	Left middle/inferior frontal gyri	6.82	.010
Bilingual > Monolingual			
No suprathreshold activation			
Interaction of group and condition			
20	Right inferior parietal lobe	6.11	.003
17	Left inferior parietal lobe	3.36	.038
21	Left inferior/superior parietal lobe	7.63	< .001*

Notes. * Indicates the threshold passed the false discovery rate (FDR) multiple comparisons correction.

Table 3

Study 2: Participants' average scores (standard deviation) in language and cognitive tasks.

Measures	**Monolinguals (n = 26)**	**Bilinguals (n = 26)**	***T*-values**
Age	8.08 (0.75)	8.04 (0.75)	0.22
IQ [a]	116.19 (13.98)	108.62 (12.27)	2.08*
Demographics			
Income [b]	8.24 (1.64)	6.54 (2.36)	2.94**
Mother's education [c]	6.96 (1.28)	5.81 (2.55)	2.06*
Father's education [c]	6.65 (1.70)	5.35 (2.81)	2.03*
English Behavioral Measures			
Phonological Awareness [d]	10.65 (2.56)	11.00 (3.09)	0.44
Vocabulary [a]	115.23 (11.05)	110.00 (11.75)	1.65
Morpho-syntax (%)	93.00 (5.89)	88.69 (9.40)	1.79
Reading [a]	119.81 (8.94)	115.69 (10.72)	1.50
Spanish Behavioral Measures			
Vocabulary [a]	--	93.23 (9.98)	6.46***
Morpho-syntax (%)	--	68.63 (22.74)	4.39***
Cognitive Tasks			
Naming Speed – Numbers [a]	105.31 (10.72)	107.35 (15.31)	0.56
Pair Cancellation Score	44.81 (8.84)	44.15 (11.53)	0.23

Notes. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

[a] Scores are standardized at a mean of 100 (typical average scores range between 85 and 115).

[b] Options for demographic responses on yearly household income were the following: (1) less than $5,000; (2) $5,000 - $11,999; (3) $12,000 - $15,999; (4) $16,000 - $24,999; (5) $25,000 - $34,999; (6) $35,000 - $49,999; (7) 50,000 - $74,999; (8) $75,000 - $99,999; (9) $100,000 and greater. Three families (2 bilingual, 1 monolingual) voluntarily skipped this question.

[c] Options for responses on education were the following: (1) primary school, (2) some secondary school, (3) High school diploma or equivalent (GED), (4) some college, (5) Associate's degree, (6) Bachelor's degree, (7) Master's degree, (8) Doctorate degree [Ph.D], (9) Professional degree [MD, DD, DDS, etc].

[d] Scores are standardized at a mean of 10 (SD = 3).

Table 4

Participants' average performance in the attentional network task (ANT).

Measures	**Monolinguals (n = 26)**	**Bilinguals (n = 26)**	***T*-values**
Networks			
Accuracy (%)			
Alerting Network	-0.12 (2.32)	-0.38 (2.52)	0.39
Orienting Network	0.42 (2.32)	0.36 (2.36)	0.09
Executive Network	-1.51 (2.00)	-1.80 (2.51)	0.46
Reaction Time (ms)			
Alerting Network	-14.31 (27.45)	-20.90 (35.67)	0.75
Orienting Network	-55.18 (34.87)	-37.15 (37.57)	1.79
Executive Network	77.84 (38.05)	73.28 (39.52)	0.42
Cuing Conditions			
Accuracy (%)			
No cues	98.08 (2.16)	97.91 (2.44)	0.27
Center cues	97.96 (2.24)	97.53 (2.38)	0.68
Spatial cues	98.38 (1.85)	97.88 (1.69)	1.01
Reaction Time (ms)			
No cues	869.70 (80.53)	892.27 (88.10)	0.96
Center cues	855.40 (84.03)	871.36 (95.49)	0.64
Spatial cues	800.22 (95.70)	834.21 (89.97)	1.32
Congruency Conditions			
Accuracy (%)			
Congruent trials	98.82 (1.21)	98.70 (1.25)	0.36
Incongruent trials	97.32 (2.50)	96.90 (2.68)	0.57
Reaction Time (ms)			
Congruent trials	802.75 (85.06)	830.73 (88.21)	1.16
Incongruent trials	880.60 (86.05)	904.01 (92.97)	0.94

Table 5

Brain activity, neuroimaging effects for the ANT alerting and orienting networks.

Channel	Cortical Region	F-value	*p*-value *
Main effect of condition			
7	Right middle, superior frontal gyri	8.10	< .001
8	Right middle, superior frontal gyri	5.71	.003
14	Right superior, middle temporal gyri	5.31	.005
6	Left middle frontal gyrus	5.96	.003
7	Left middle frontal gyrus	10.05	< .001
9	Left middle, superior frontal gyri	3.89	.02
10	Left middle, inferior frontal gyri	5.32	.005
15	Left temporo-parietal junction	15.73	< .001
16	Left inferior parietal, fusiform gyrus	6.76	.001
18	Left supramarginal gyrus, inferior parietal lobe	10.84	< .001
20	Left inferior, superior parietal lobe	4.78	.009
Main effect of group			
Monolingual > Bilingual			
14	Right superior, middle temporal gyri	6.55	.010
Bilingual > Monolingual			
7	Right middle frontal gyrus	5.54	.019
8	Right middle, superior frontal gyri	9.58	.002
10	Left middle, inferior frontal gyri	6.39	.012
16	Left inferior parietal, fusiform gyrus	9.72	.002
Interaction of group and condition			
7	Right middle frontal gyrus	7.45	< .001
8	Right middle, superior frontal gyri	6.14	.002
18	Right supramarginal gyrus, inferior parietal lobe	4.29	.014
16	Left inferior parietal, fusiform gyrus	8.47	< .001

Notes. * All thresholds passed the false discovery rate (FDR) correction for multiple comparisons at $p < 0.05$.

Table 6

Brain activity, neuroimaging effects for the ANT executive network.

Channel	Cortical Region	F-value	*p*-value
Main effect of condition			
8	Left middle, superior frontal gyri	4.56	.033
11	Left middle, superior frontal gyri; precentral	11.83	< .001*
18	Left inferior parietal, supramarginal gyrus	5.85	.016*
21	Left superior parietal lobe	5.94	.015*
Main effect of group			
Monolingual > Bilingual			
No suprathreshold activation			
Bilingual > Monolingual			
7	Left middle frontal gyrus	11.87	< .001*
9	Left middle, superior frontal gyri	8.14	.005*
10	Left middle, inferior frontal gyri	5.72	.017
11	Left middle, superior frontal gyri; precentral	4.14	.042
19	Left superior parietal lobe	6.16	.013
20	Left inferior, superior parietal lobe	11.45	< .001*
22	Left superior parietal lobe, occipital	5.55	.019
Interaction of group and condition			
6	Left middle frontal gyrus	29.94	< .001*
7	Left middle frontal gyrus	18.61	< .001*
9	Left middle, superior frontal gyri	6.72	.010*
9	Right middle, superior frontal gyri	5.73	.017
10	Right middle, inferior frontal gyri	5.45	.019
20	Right inferior, superior parietal lobe	5.57	.019

Notes. * Indicates the threshold passed the false discovery rate (FDR) correction for multiple comparisons at $p < 0.05$.

Table 7

Effects of language abilities in left fronto-parietal for the Executive attentional network in bilinguals.

Channel	**Predictor**	**Unstandardized Beta**	***t***	**Incongruent**		**Congruent**	
				Unstandardized Beta	***t***	**Unstandardized Beta**	***t***
Ch 6	English Morpho-syntax	-260.46	-3.04**	25.55	2.95**	9.61	1.10
Ch 8	English Vocabulary	-193.33	-2.34*	24.81	2.86**	8.88	2.33*
	English Morpho-syntax	-193.76	-2.28*	30.11	3.13**	10.58	1.09
	Spanish Vocabulary	429.11	1.69^	32.16	3.32***	12.66	1.29
Ch 9	English Vocabulary	-265.53	-2.92**	43.98	4.35***	30.40	2.97**
	Spanish Vocabulary	665.97	2.61**	44.78	4.37***	31.20	3.01**
	Spanish Morpho-syntax	90.94	2.26*	43.66	4.27***	30.08	2.91**
Ch 10	English Vocabulary	-284.49	-3.22**	31.35	3.06**	24.56	2.37*
	Spanish Vocabulary	549.65	2.14*	30.50	2.94**	23.71	2.26*
	Spanish Morpho-syntax	102.12	2.56*	30.68	2.96**	23.90	2.28*
Ch 11	Spanish Morpho-syntax	109.36	2.58**	12.96	1.26	-1.65	-0.16
Ch 18	Spanish Morpho-syntax	132.91	2.91**	36.63	3.40***	11.21	1.03
Ch 20	Spanish Morpho-syntax	179.37	2.51**	41.34	2.46*	15.66	0.92
Ch 22	English Morpho-syntax	-340.67	2.12*	42.75	2.80**	29.90	1.94*
	Spanish Morpho-syntax	136.72	2.14*	50.14	3.23***	37.40	2.39*

Notes. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$
[a] Covariate scores used in this analyses were a summation of English and Spanish morpho-syntax measures.

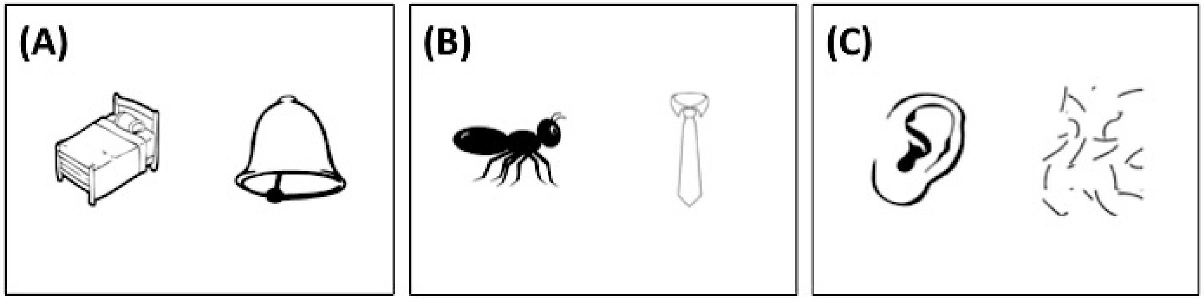
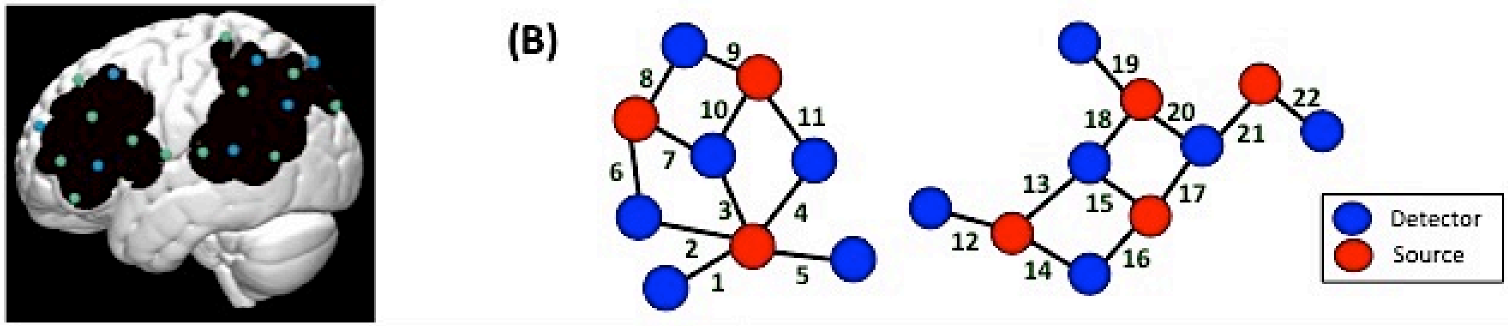


Figure 1. Example trials for the English Linguistic Competition task. During the trial, participant heard a target word and was presented with two images, a target image and a competitor. (A) Phonologically Related experimental condition, “bed” and “bell”. (B) Phonologically Unrelated control condition, “ant” and “tie”. (C) Baseline control condition, “ear” along with a scrambled indecipherable image.

(A) (B)



(C)

Channel	Region	BA	Channel	Region	BA
1	Anterior Temporal/Inferior Frontal (IFG)	38, 47	12	Superior/Middle Temporal	22, 41, 42
2	IFG	47, 45	13	Temporo-Parietal Junction (TPJ)	
3	IFG	45	14	Superior/Middle Temporal	
4	IFG	44	15	TPJ	
5	IFG/Temporal	44, 21	16	Inferior Parietal Lobe, Fusiform Gyrus	
6	Middle Frontal Gyrus (MFG)	46	17	Inferior Parietal Lobe (IPL)	39, 40
7	Middle Frontal Gyrus (MFG)	46	18	Supramarginal Gyrus, IPL	40
8	MFG/Superior Frontal Gyrus (SFG)	46, 10	19	Superior Parietal Lobe (SPL)	40
9	MFG/SFG	46, 9, 10	20	IPL/SPL	39, 40
10	MFG/IFG	45, 46	21	SPL	
11	Precentral Gyrus		22	SPL, Occipital Lobe	7, 19

Figure 2. Functional NIRS probe configuration (left hemisphere shown). **(A)** Dots correspond to optode placements at a distance of ~2.7 cm, over an average brain template (blue circles = sources/emitters of light; green circles = detectors. **(B)** Probe-set and channel configuration for left hemispheres, numbers denote connections (channels) between sources and detectors. **(C)** Brain regions covered by the fNIRS measurement as maximally overlaid by the probe arrangement in the order of greatest probability for each channel (BA = Brodmann Area).

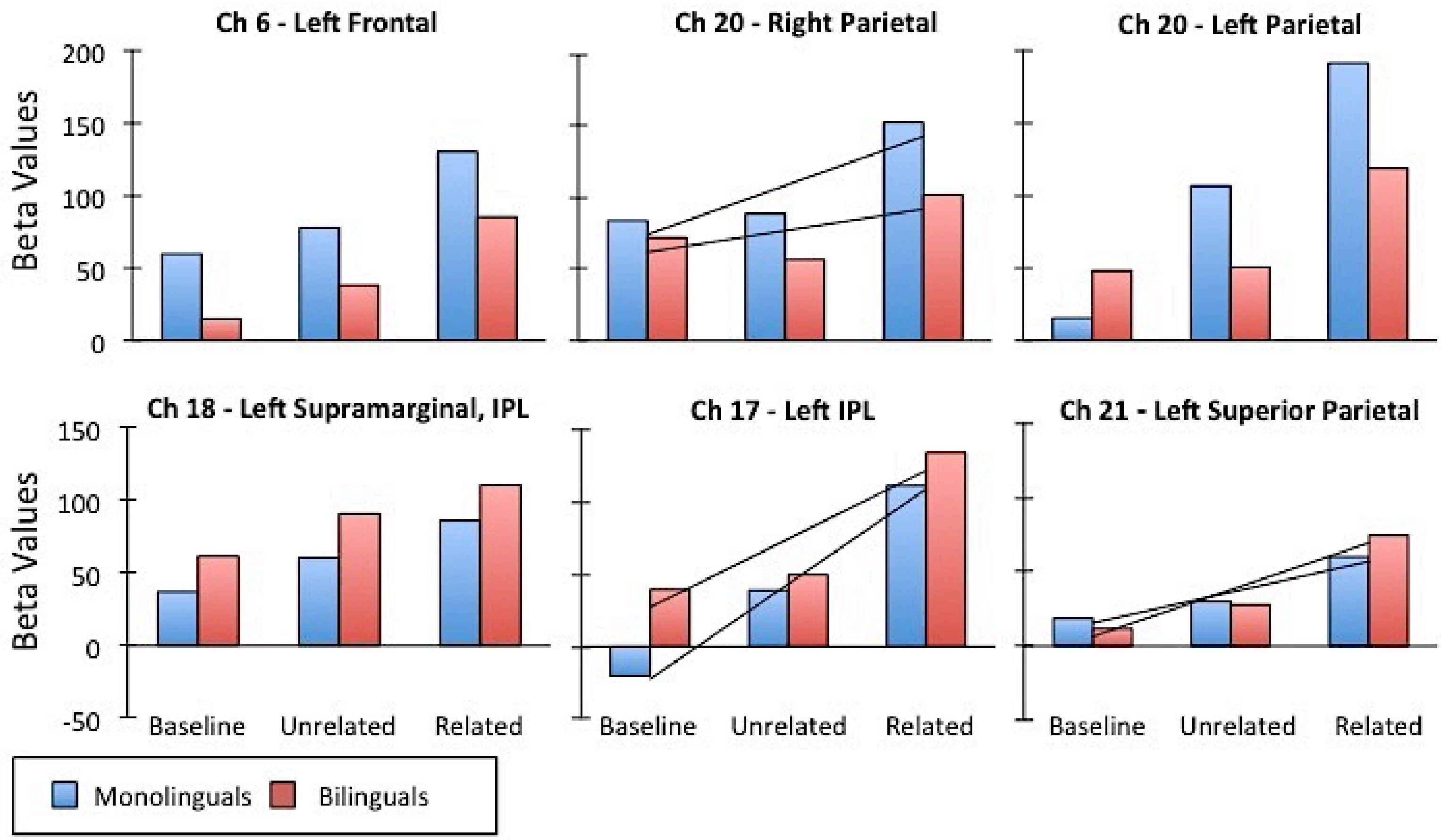


Figure 3. Bar graphs on brain activity effects during the linguistic competition task. Bar graphs represent monolinguals' (blue bars) and bilinguals' (red bars) beta values that represent brain activation during baseline, phonologically unrelated, and phonologically related conditions. Left frontal (channel [Ch] 6) revealed a main effect of group, in which monolingual children showed greater activation than bilinguals. Left frontal (Ch 6), two bilateral parietal channels (Ch 20) and two other left parietal channels (Ch 18 and 21) revealed main effects of conditions, in which there was increasing activity across the conditions. Group by condition interactions manifested in bilateral (right: Ch 20, left: Ch 17 and 21) parietal regions revealing diffences in brain activity among bilinguals and monolinguals across the control conditions (baseline and phonologically unrelated).

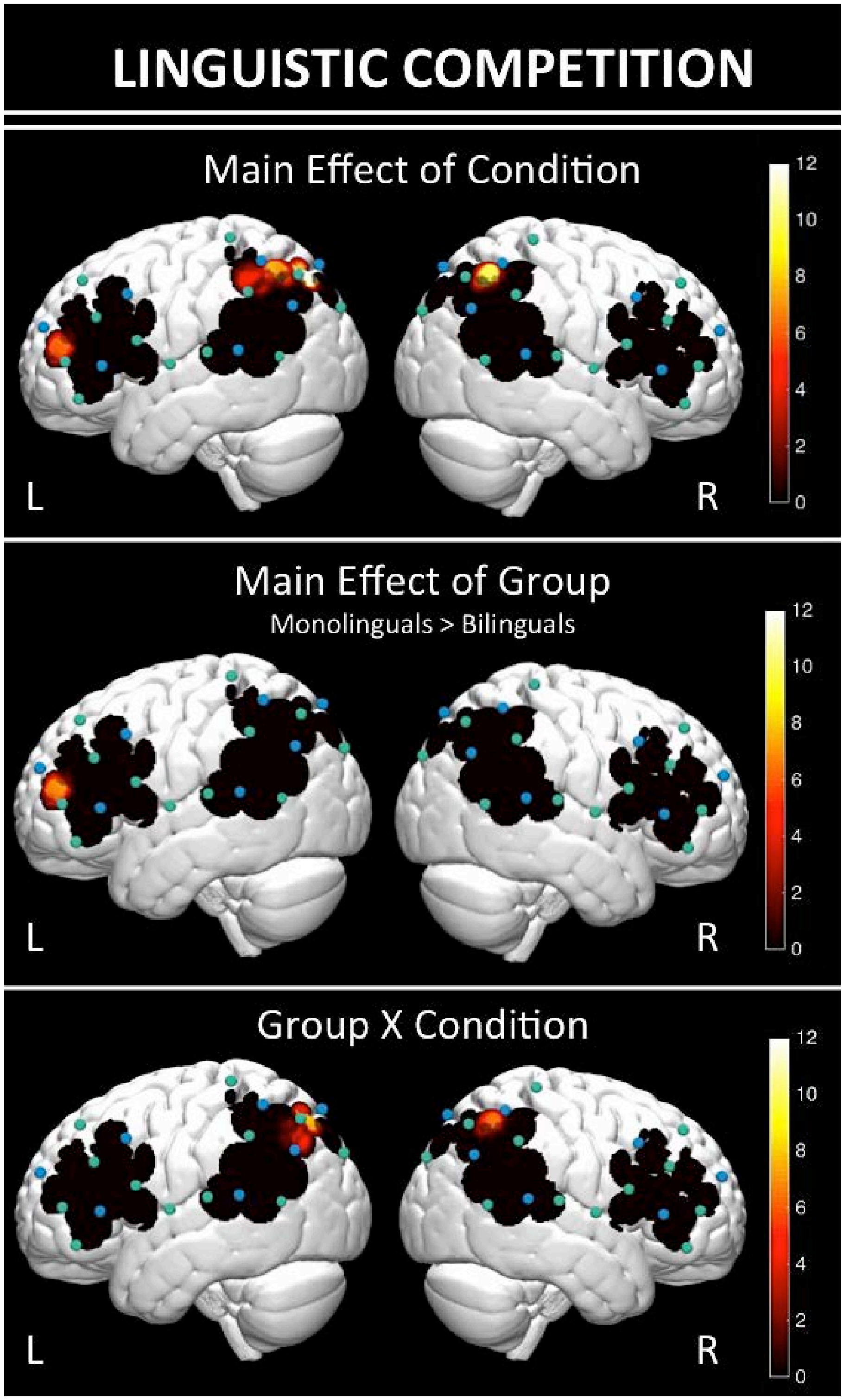


Figure 4. 3D-brain activity during the linguistic competition task. Color bar reflects F-values mapped for comparison of brain activation on approximate regions covered by the fNIRS probeset in the present study; see Table 2.

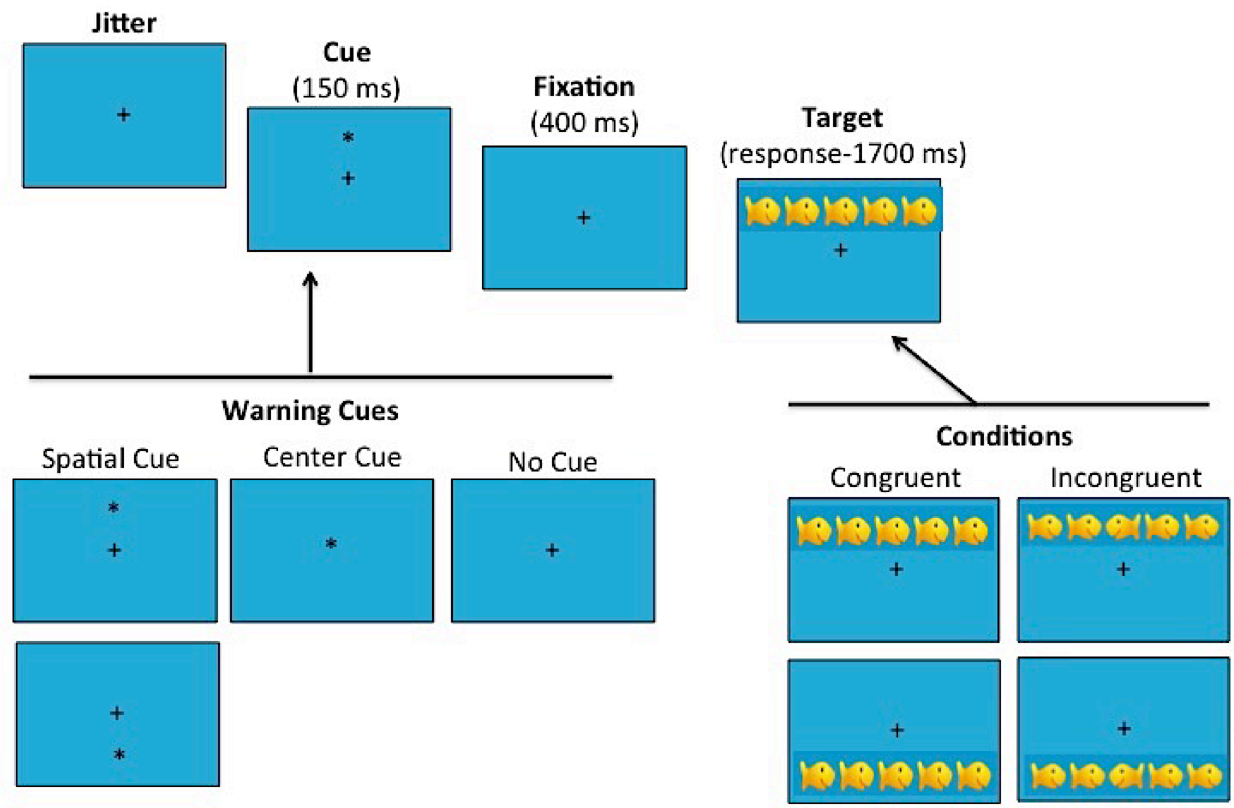


Figure 5. Example trials for the Attentional Network task.

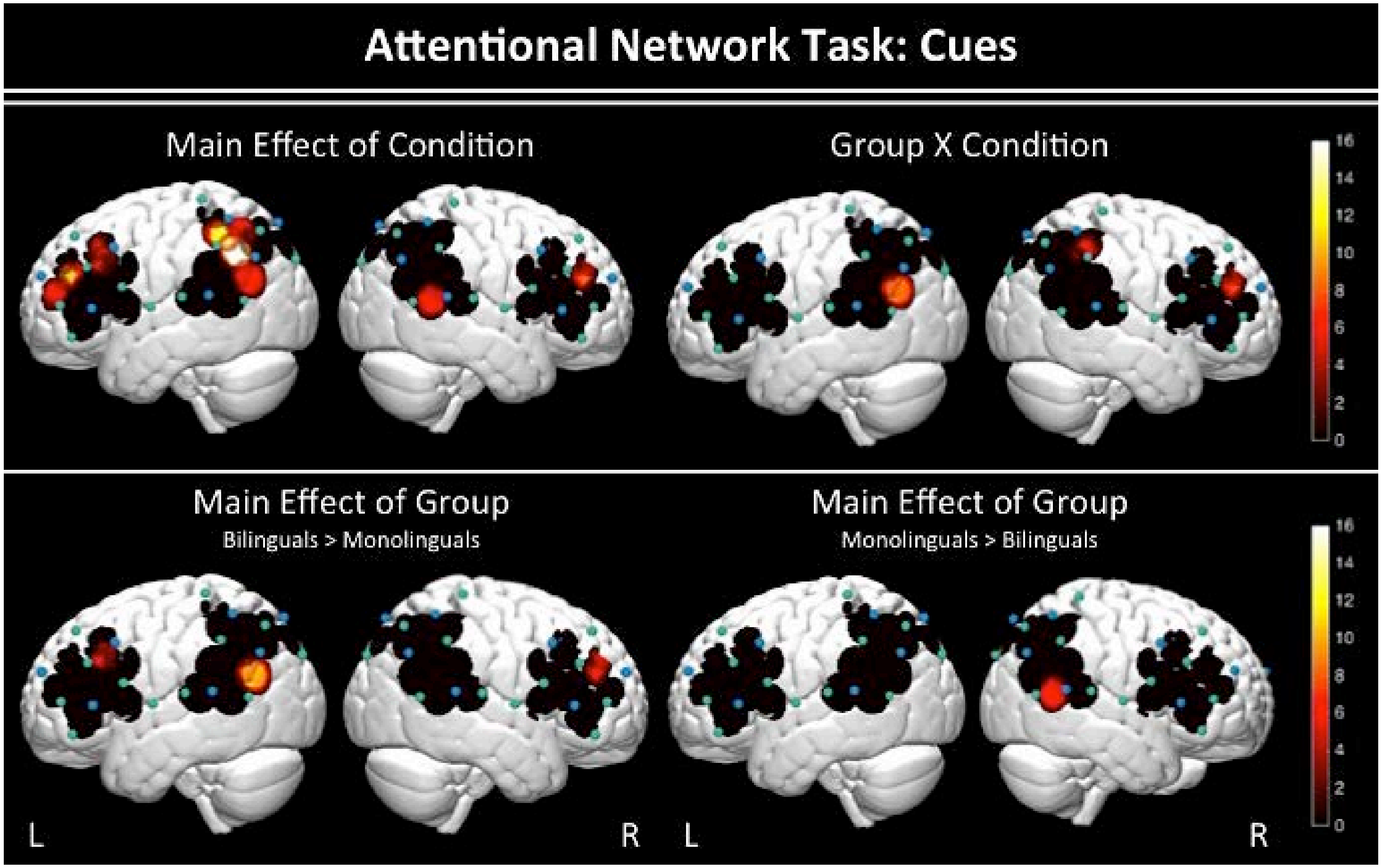
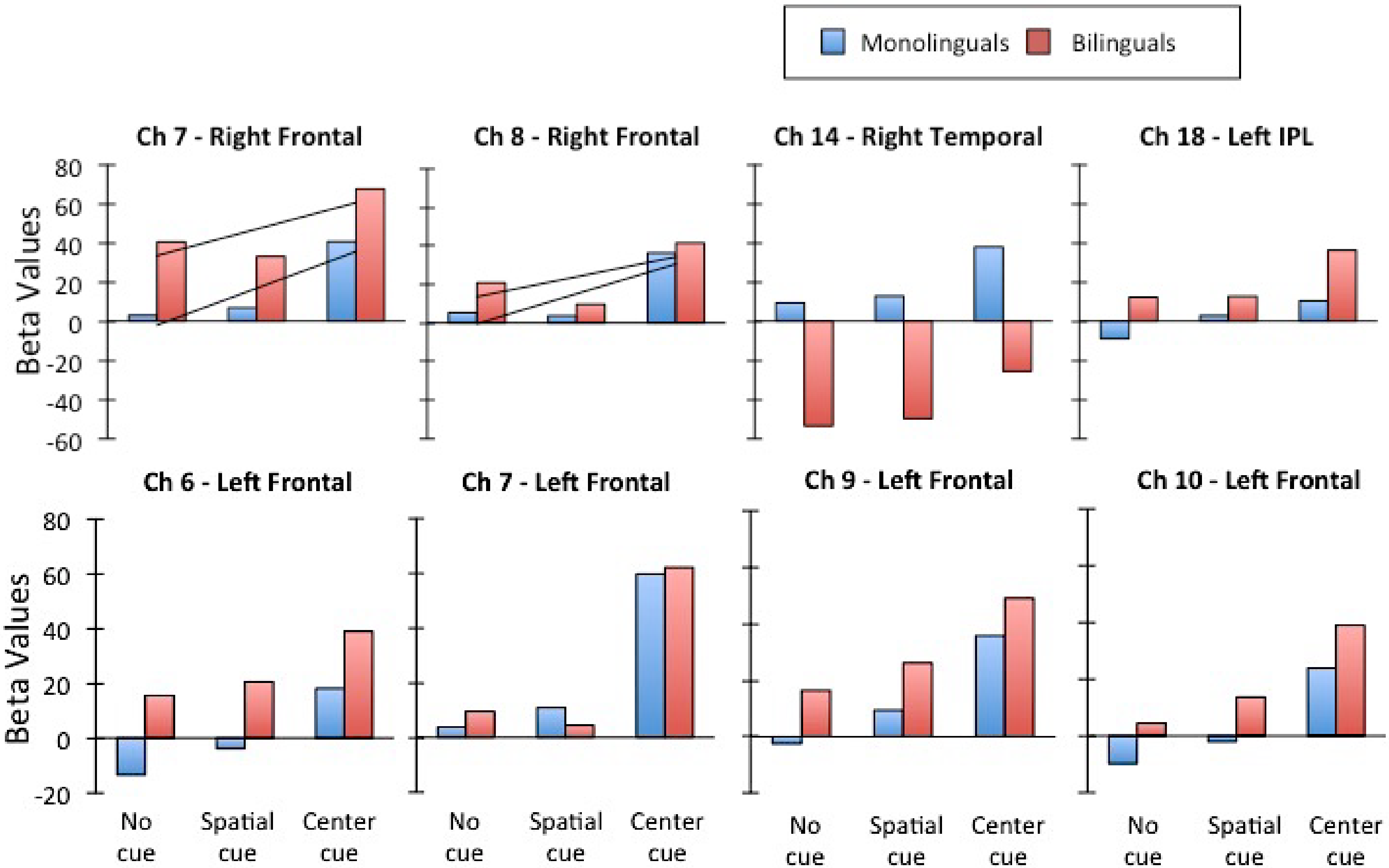


Figure 6. 3D-brain activity effects during the ANT cue conditions. Color bar reflects F-values mapped for comparison of brain activation during the ANT tasks across the cue conditions (No cues, Center cues, and Spatial cues) for monolingual and bilingual children; see Table 5.



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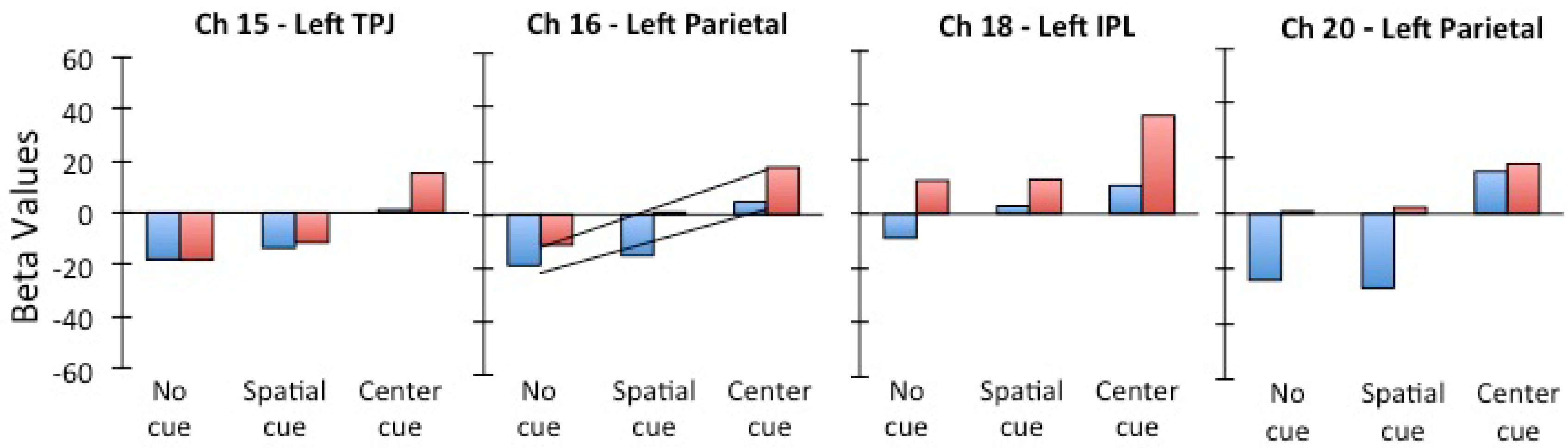


Figure 7. Bar graphs on brain activity effects during the ANT cue conditions. Bar graphs represent monolinguals' (blue bars) and bilinguals' (red bars) brain activation during Cue conditions: No cues, Spatial cues, and Center cues. Bilateral frontal (right: Ch 7 and 8; left: Ch 6, 7, 9 and 10) and left posterior temporal and parietal regions (Ch 15, 16, 18 and 20) revealed main effects of condition. One right temporal channel (Ch 14) revealed a main effect of group, in which monolingual children showed greater activation than bilinguals. Bilateral frontal (right: Ch 7 and 8; left: Ch 10) and one parietal channel (Ch 16) revealed a main effect of group, in which bilingual children showed greater activation than monolinguals. Group by condition interactions manifested in right frontal (Ch 7 and 8) and bilateral parietal regions (right: Ch 18, left: Ch 16) revealed differences in brain activity among bilinguals and monolinguals across No cues and Spatial cues.

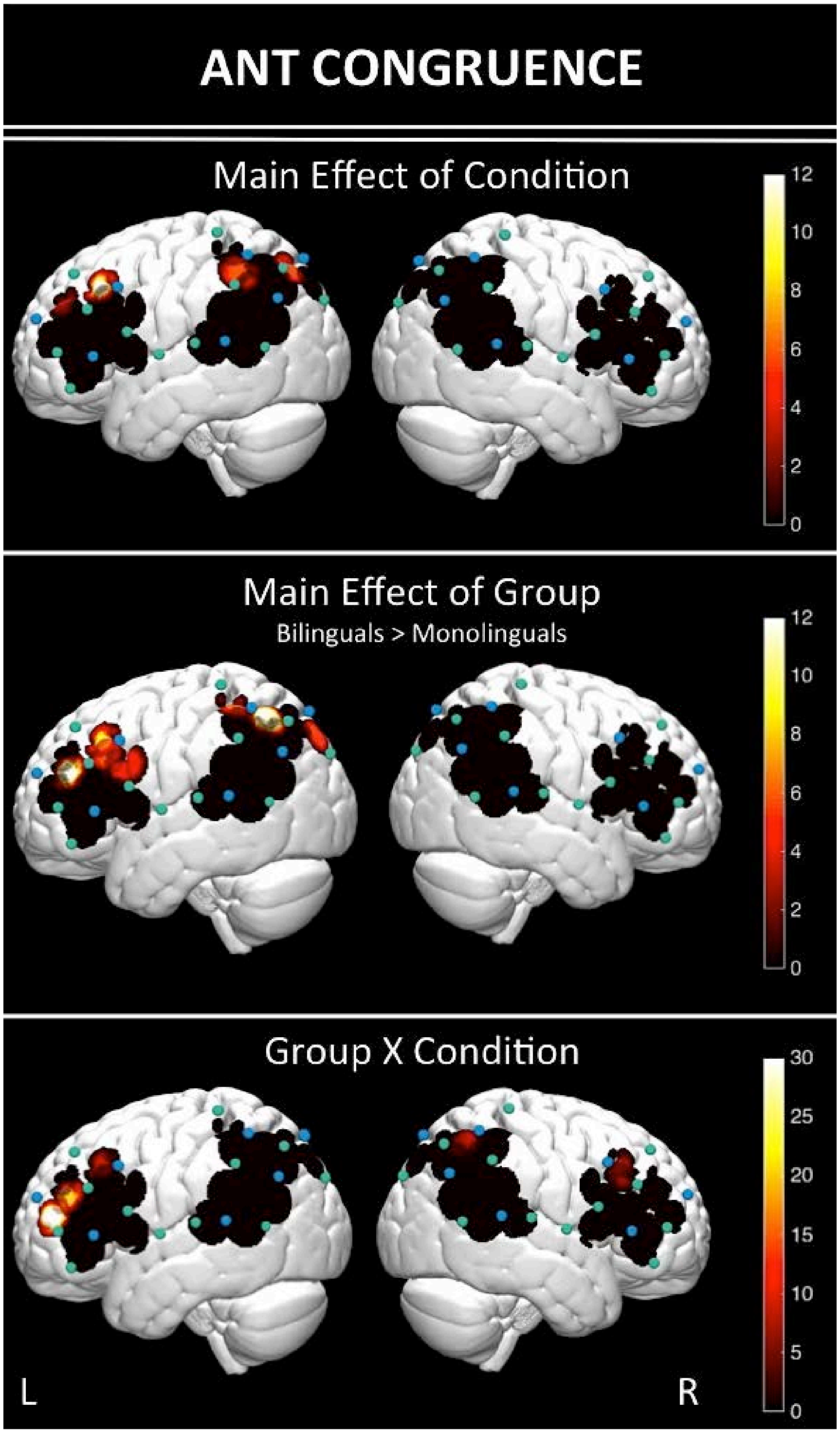
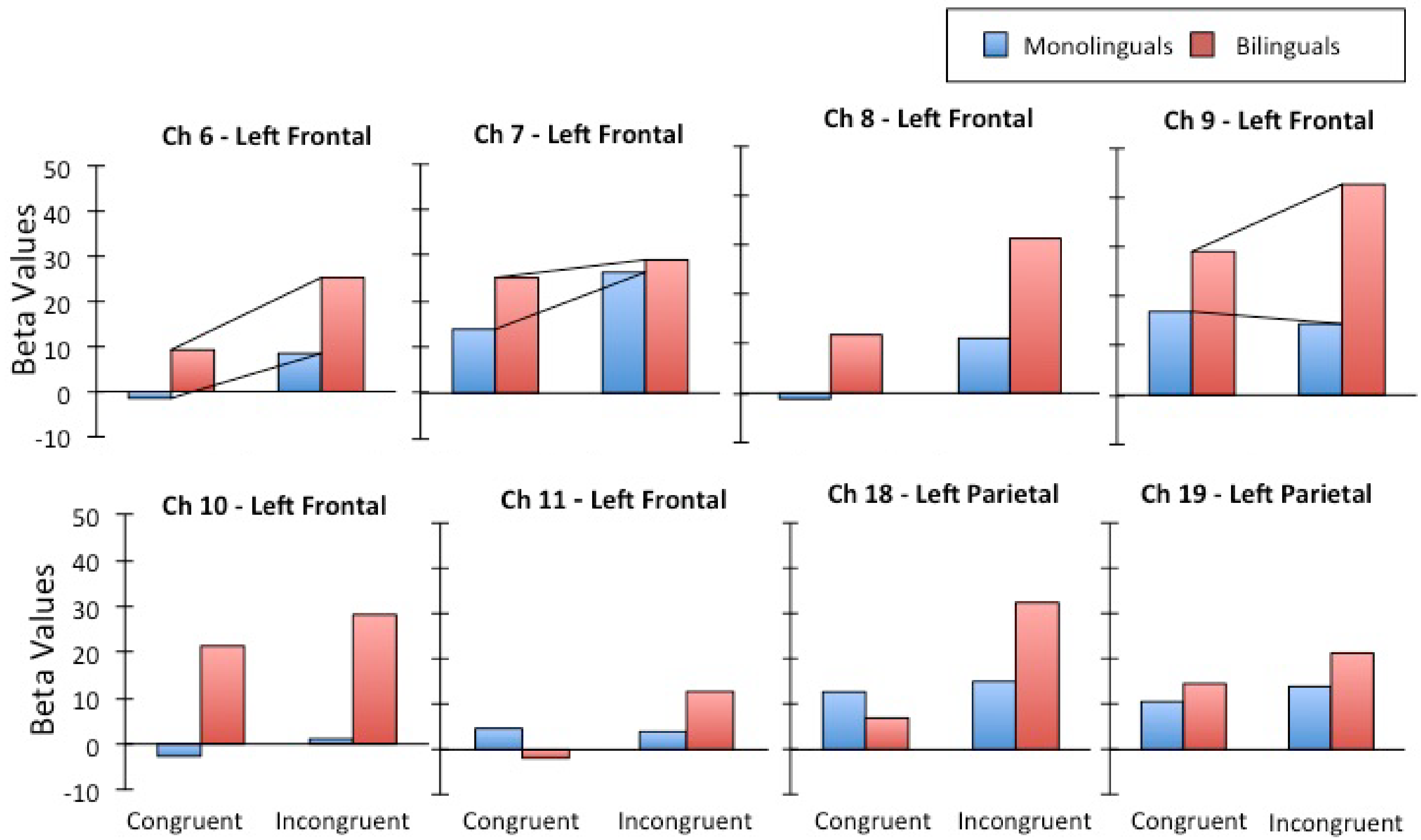


Figure 8. 3D-brain activity effects during the ANT congruence conditions. Color bar reflects F-values mapped for comparison of brain activation during the ANT tasks across the Congruence conditions (Congruent and Incongruent) for monolingual and bilingual children; see Table 6.



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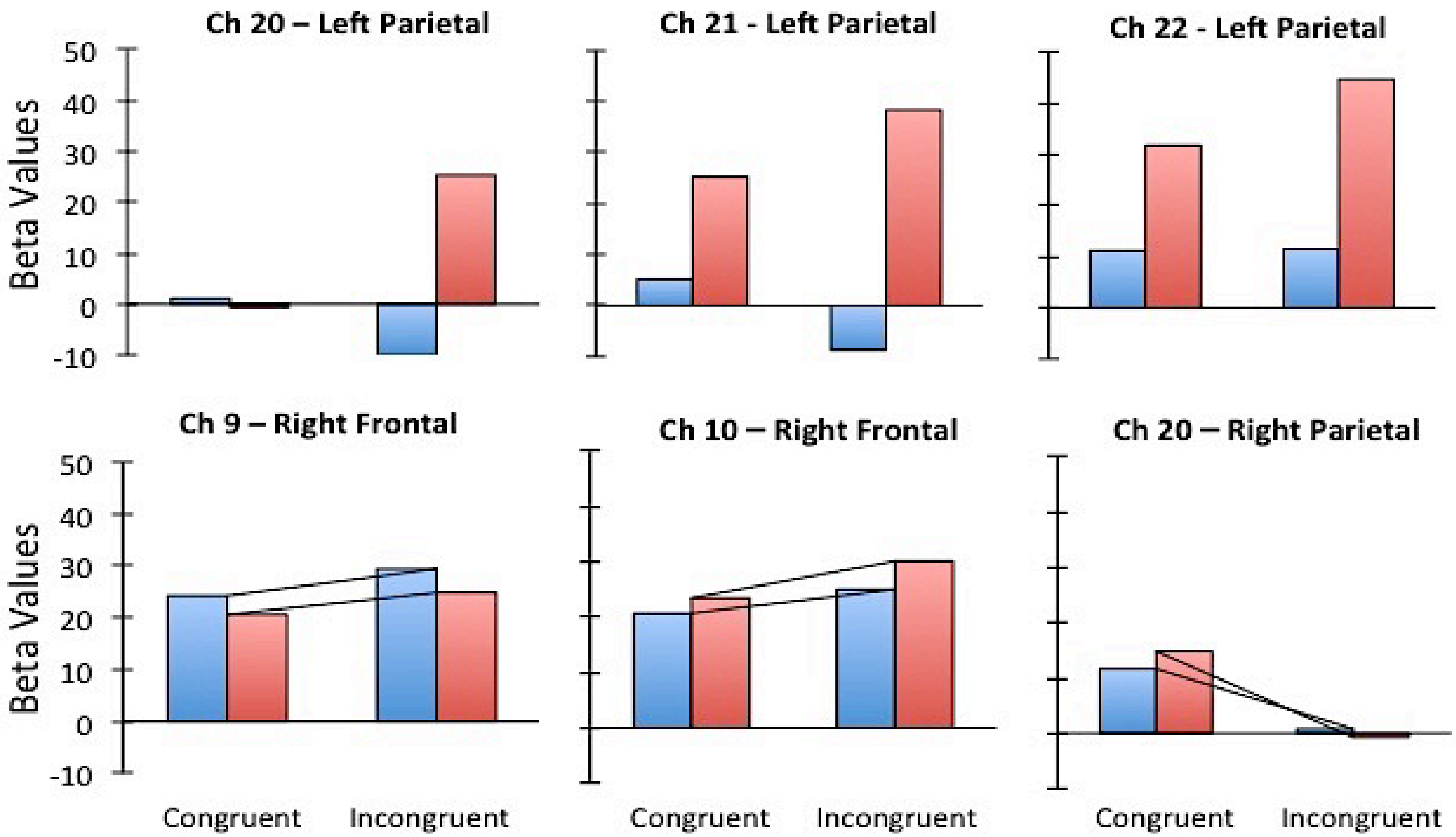


Figure 9. Bar graphs on brain activity effects during the ANT congruence conditions. Bar graphs represent monolinguals' (blue bars) and bilinguals' (red bars) brain activation during Congruence conditions, Congruent and Incongruent trials. Left frontal (Ch 8 and 11) and parietal regions (Ch 18 and 21) revealed main effects of condition. Left frontal (Ch 7, 9-11, 19, 20 and 22) revealed a main effect of group, in which bilingual children showed greater activation than monolinguals. Group by condition interactions manifested in bilateral frontal regions (right: Ch 9 and 10; left: Ch 6, 7 and 9) and one parietal channel (Ch 20) and revealed differences in brain activity among bilinguals and monolinguals across conditions.

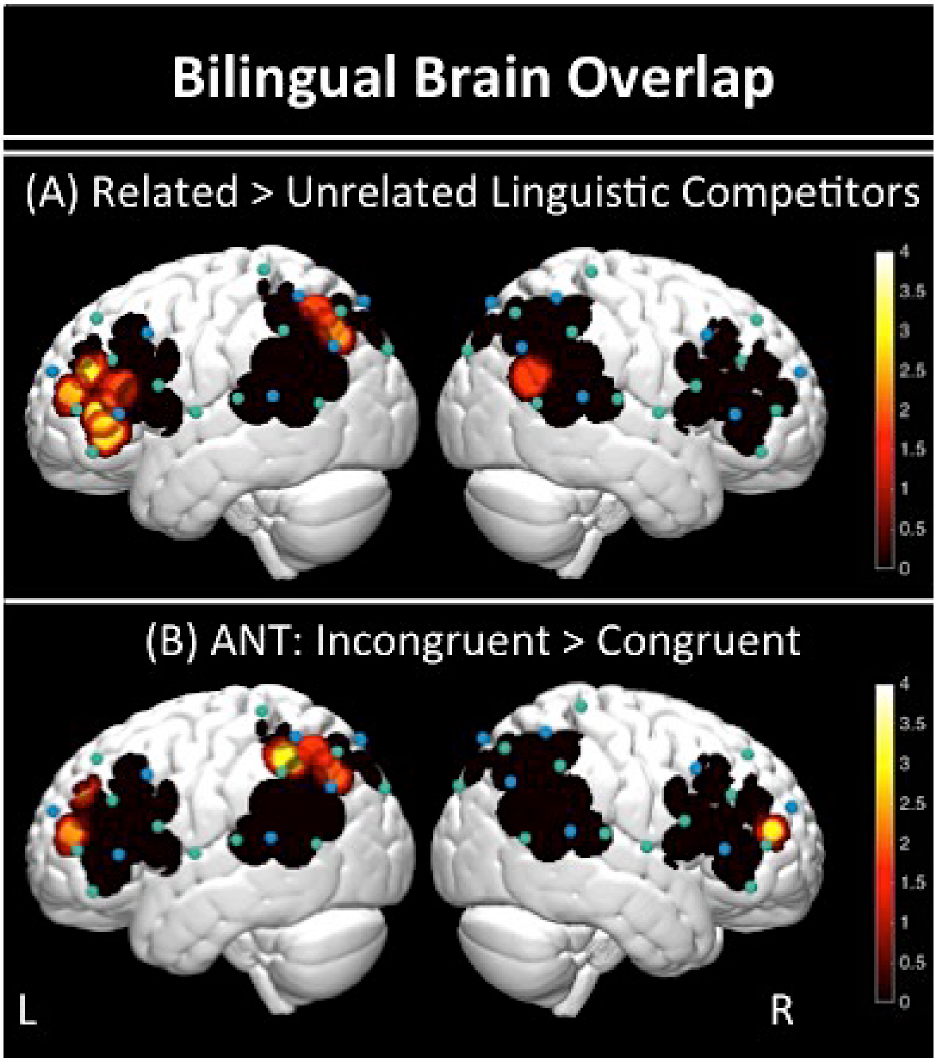


Figure 10. Bilingual brain overlap activity for the linguistic competition task and ANT. T-values mapped for comparison of brain activation for bilingual children in (A) the Linguistic Competition task [Study 1, Chapter 2] for the phonologically Related condition in comparison to the phonologically Unrelated condition, as well as (B) the Executive Attentional Network in the ANT [Study 2, Chapter 3] for the Incongruent condition in comparison to the Congruent condition. Higher values on the scale indicate greater brain activity. Bilingual children show overlapping brain activity in left frontal (Ch 6) and parietal (Ch 17 and 20) among the tasks.

APPENDIX A: Parent questionnaire—bilingual English version

Child's Date of Birth (Month/Day/Year) ___________________

Child's Gender
- ❍ Male
- ❍ Female

Child's Grade in School
- ❍ Grade 1
- ❍ Grade 2
- ❍ Grade 3
- ❍ Grade 4
- ❍ Grade 5

Was your child carried full term or born prematurely?
- ❍ Full Term
- ❍ Prematurely

Is your child taking any medication? (e.g. for attention difficulties or other)? If yes, please list the medication(s) and reason.
- ❍ Yes (Please specify) ___________________
- ❍ No

Where was your child born?
- ❍ In the United States
- ❍ Outside the United States (Please specify) ___________________

How much education do you expect your child to complete?
- ❍ Up to 11th grade
- ❍ High School Diploma or Equivalent (GED)
- ❍ Vocational Training/Certification
- ❍ Some College
- ❍ Associate's Degree
- ❍ Bachelor's Degree
- ❍ Master's Degree
- ❍ Doctorate (PhD) or Professional Degree (ex. MD, JD, DDS, etc.)

Parents' (or guardians') Information

Please specify **your** racial background (ex: White, Black, Asian etc.): ___________________

Please specify **your** ethnic background OR country of origin (ex: Hispanic/Latino, Mexican, South American, etc.): ___________________

Where were **you** born?

- ❍ In the United States
- ❍ Outside the United States (Please specify) ___________________

Please select the languages **you** speak (you may select more than one answer if appropriate):

- ❑ English
- ❑ Spanish
- ❑ Other (Please specify) ___________________

How often do **you** speak **English** with your child? (Please select one):

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often do **you** speak **Spanish** with your child? (Please select one):

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

Please indicate **your** level of education:

- ❍ Primary School
- ❍ Some Secondary School
- ❍ High School Diploma or Equivalent (GED)
- ❍ Some College
- ❍ Associate's Degree
- ❍ Bachelor's Degree
- ❍ Master's Degree
- ❍ Ph.D. (Doctorate Degree)
- ❍ Professional Degree (MD, JD, DDS, etc.)
- ❍ Other. Please specify: ___________________
- ❍ None of the above

Please specify the **other** parent's racial background (ex: White, Black, Asian etc.): _______________

Please specify the **other** parent's ethnic background OR country of origin (ex: Hispanic/Latino, Mexican, South American, etc.): ___________________

Where was the **other** parent born?

- ❍ In the United States
- ❍ Outside the United States (Please specify) ___________________

Please select the languages the **other** parent speaks (you may select more than one answer if appropriate):

- ❑ English
- ❑ Spanish
- ❑ Other (Please specify) ___________________

How often does the **other** parent speak **English** with your child? (Please select one):

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does the **other** parent speak **Spanish** with your child? (Please select one):

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

Please indicate the **other** parent's level of education:

- ❍ Primary School
- ❍ Some Secondary School
- ❍ High School Diploma or Equivalent (GED)
- ❍ Some College
- ❍ Associate's Degree
- ❍ Bachelor's Degree
- ❍ Master's Degree
- ❍ Ph.D. (Doctorate Degree)
- ❍ Professional Degree (MD, JD, DDS, etc.)
- ❍ Other. Please specify: ___________________
- ❍ None of the above

Child's Language Development

<u>What languages were spoken to your child? (Select all that apply):</u>

	In the home (by your family)		Outside the home (by others)	
	English	Spanish	English	Spanish
At birth	❑	❑	❑	❑
1 year old	❑	❑	❑	❑
2 years old	❑	❑	❑	❑
3 years old	❑	❑	❑	❑
4 years old	❑	❑	❑	❑
5 years old	❑	❑	❑	❑

<u>Does your child receive formal instruction in Spanish?</u>

❍ Yes

❍ No

If yes, where does your child receive formal instruction in Spanish? Please specify:

____

<u>If yes, how many hours a week does your child receive formal instruction in Spanish?</u>

❍ 0-5

❍ 5-10

❍ 10-15

❍ 15-20

❍ 20+

<u>If yes, how many weeks of the year does your child receive formal instruction in Spanish?</u>

❍ 0-10

❍ 10-20

❍ 20-30

❍ 30-40

❍ 40+

What region/dialect of Spanish is your child exposed to? What type of Spanish are his/her family members, teachers, friends or other's speaking? Please provide the names of the Latin American or European countries it pertains to (ex: Chicano, Mexican, Central American, South American etc):

____

____

____

How often does your child speak **English** with other family members (e.g. aunts, uncles, cousins etc.)?

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always
- ❍ N/A

How often does your child speak **Spanish** with other family members (e.g. aunts, uncles, cousins etc.)?

- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always
- ❍ N/A

Does your child have any siblings?

- ❍ Yes
- ❍ No

If yes, please list first names, ages, and gender, and whether they're older or younger than your child participating in the study.

First Name	Age	Gender	Younger or older than child participating

How often does your child speak **English** with their **older** sibling(s)?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does your child speak **Spanish** with their **older** sibling(s)?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does your child speak **English** with their **younger** sibling(s)?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does your child speak **Spanish** with their **younger** sibling(s)?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does your child speak **English** when playing with friends outside of school?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

How often does your child speak **Spanish** when playing with friends outside of school?
- ❍ Never
- ❍ Rarely
- ❍ Sometimes
- ❍ Quite Often
- ❍ Always

If your child needed to follow specific instructions, which language would be easiest for them to understand?

❍ English

❍ Spanish

❍ Other (specify) ___________________

Which language does your child feel most comfortable speaking?

❍ English

❍ Spanish

❍ Other (specify) ___________________

If your child is playing alone or talking to him/herself, what language would he/she use?

❍ English

❍ Spanish

❍ Other (specify) ___________________

How do your family and friends perceive your child?

❍ English speaker

❍ Spanish speaker

❍ Bilingual

Which of the following does your child do at least once in a typical week? (Check all that apply):

	In English	In Spanish	Neither
Listen to music	❍	❍	❍
Watch cartoons or TV shows	❍	❍	❍
Read magazines or books	❍	❍	❍
Watch movies	❍	❍	❍
Play games	❍	❍	❍
Talk with friends	❍	❍	❍

Please indicate whether any family members of your child have any identified difficulties in the following areas:

	Dyslexia or Reading Difficulty	Language Difficulties	ADHD or Attention Difficulties	Autism Spectrum Disorder	Hearing Impairment	Other
Mother	❑	❑	❑	❑	❑	❑
Father	❑	❑	❑	❑	❑	❑
Siblings 1	❑	❑	❑	❑	❑	❑
Siblings 2	❑	❑	❑	❑	❑	❑
Siblings 3	❑	❑	❑	❑	❑	❑
Paternal Uncle	❑	❑	❑	❑	❑	❑
Maternal Uncle	❑	❑	❑	❑	❑	❑
Paternal Aunt	❑	❑	❑	❑	❑	❑
Maternal Aunt	❑	❑	❑	❑	❑	❑
Other (Please specify)	❑	❑	❑	❑	❑	❑
Paternal Grand-father	❑	❑	❑	❑	❑	❑
Paternal Grand-mother	❑	❑	❑	❑	❑	❑
Maternal Grand-father	❑	❑	❑	❑	❑	❑
Maternal Grand-mother	❑	❑	❑	❑	❑	❑

Child's Early Development

Did your child attend day care?

- ❍ Yes
- ❍ No

If yes, when did your child start attending day care?

- ❍ Birth - 1 year
- ❍ 1 - 2 years
- ❍ 2 - 3 years
- ❍ 3 - 4 years
- ❍ 4 - 5years

What language was spoken at day care?

- ❍ English
- ❍ Spanish
- ❍ Other (Please specify) ____________________

How many hours per week did your child go to day care?

- ❍ 0 - 10
- ❍ 10 - 20
- ❍ 20 - 30
- ❍ 30 - 40
- ❍ 40+

Out of the 52 weeks of the year, how many weeks did your child attend day care?

- ❍ 0 - 10
- ❍ 10 - 20
- ❍ 20 - 30
- ❍ 30 - 40
- ❍ 40 - 52

When did your child start attending school (kindergarten)?

- ❍ 4 - 5 years
- ❍ 5 - 6 years
- ❍ Other (Please specify) ____________________

How many weeks of the year does your child spend in school?

- ❍ 20 - 30
- ❍ 30 - 40
- ❍ 40+

To the best of your knowledge, did your child experience any delays in motor development (e.g. sitting-up, making first steps, holding objects)? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

Your child started walking independently (8 or more steps) at age:

- ❍ 6-12 months
- ❍ 1-1.5 years
- ❍ 1.5-2 years
- ❍ 2-2.5 years
- ❍ 2.5-3 years

Please indicate which hand your child typically uses to do the following:

	Always Left	Usually Left	No Preference	Usually Right	Always Right
To draw pictures	❍	❍	❍	❍	❍
To throw a small ball	❍	❍	❍	❍	❍
To hold scissors to cut paper	❍	❍	❍	❍	❍
To hold a toothbrush while cleaning teeth	❍	❍	❍	❍	❍

To the best of your knowledge, when did your child produce his or her first word in English?

- ❍ 6-8 months
- ❍ 8-10 months
- ❍ 10-12 months
- ❍ 12-15 months
- ❍ 15-18 months
- ❍ 18-21 months
- ❍ 21-24 months
- ❍ 24-30 months
- ❍ Other, please specify ____________

To the best of your knowledge, when did your child produce his or her first word in Spanish?

- ❍ 6-8 months
- ❍ 8-10 months
- ❍ 10-12 months
- ❍ 12-15 months
- ❍ 15-18 months
- ❍ 18-21 months
- ❍ 21-24 months
- ❍ 24-30 months
- ❍ Other, please specify ____________

When did your child produce his or her first sentence (3 or more words) in English?

- ❍ Less than 1 year
- ❍ 1-1.5 years
- ❍ 1.5-2 years
- ❍ 2-2.5 years
- ❍ 2.5-3 years
- ❍ 3-3.5 years
- ❍ 3.5-4 years
- ❍ 4-4.5 years
- ❍ Other, please specify ______________

When did your child produce his or her first sentence (3 or more words) in Spanish?

- ❍ Less than 1 year
- ❍ 1-1.5 years
- ❍ 1.5-2 years
- ❍ 2-2.5 years
- ❍ 2.5-3 years
- ❍ 3-3.5 years
- ❍ 3.5-4 years
- ❍ 4-4.5 years
- ❍ Other, please specify ______________

To the best of your knowledge, did or does your child experience any speech difficulties (e.g. stuttering)? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

To the best of your knowledge, did or does your child experience any delays in language development? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

To the best of your knowledge, did or does your child experience any delays in reading development? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

Has your child been officially diagnosed with specific language impairment? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

Has your child been officially diagnosed with dyslexia or learning disabilities? If yes, please explain.

- ❍ Yes (Please specify) ____________________
- ❍ No

Has your child been officially diagnosed with autism or attention deficits? If yes, please explain.

❍ Yes (Please specify) ___________________

❍ No

Has your child been officially diagnosed with a mood disorder? If yes, please explain.

❍ Yes (Please specify) ___________________

❍ No

To the best of your knowledge, did or does your child experience any hearing problems? If yes, please explain.

❍ Yes (Please specify) ___________________

❍ No

When did your child start learning to read in English?

❍ 3-4 years

❍ 5-6 years

❍ 7-8 years

❍ 9-10 years

❍ Other, please specify _____________

Where did your child start learning to read in English?

❍ At home

❍ In daycare/kindergarten

❍ At school (Kindergarten/ grade 1/ after)

❍ Other, please specify _____________

If your child reads in Spanish, when did your child start learning to read in Spanish?

❍ 3-4 years

❍ 5-6 years

❍ 7-8 years

❍ 9-10 years

❍ Other, please specify _____________

If your child reads in Spanish, where did your child start learning to read in Spanish?

❍ At home

❍ In daycare/kindergarten

❍ At school (Kindergarten/ grade 1/ after)

❍ Other, please specify _____________

How often do you *currently* tell stories (not using a book) to your child (e.g. fairy tales)?

	Never	Once a week	Twice a week	3 or more times a week
In English	❍	❍	❍	❍
In Spanish	❍	❍	❍	❍

Was there a time when you used to do it more often?

- ❍ Yes
- ❍ No

If so, at what age did you **start** telling your child these stories (e.g. verbal fairy tales)?

- ❍ 2-3 years
- ❍ 3-4 years
- ❍ 5-6 years
- ❍ 7-8 years
- ❍ Other, please specify:

At what age did you **stop** telling your child these stories (e.g. verbal fairy tales)?

- ❍ 2-3 years
- ❍ 3-4 years
- ❍ 5-6 years
- ❍ 7-8 years
- ❍ Other, please specify:

How often do you *currently* read books to your child at home?

	Never	Once a week	Twice a week	3 or more times a week
In English	❍	❍	❍	❍
In Spanish	❍	❍	❍	❍

Was there a time when you used to do it more often?

- ❍ Yes
- ❍ No

If so, at what age did you **start** reading books to your child?

- ❍ 2-3 years
- ❍ 3-4 years
- ❍ 5-6 years
- ❍ 7-8 years
- ❍ Other, please specify:

At what age did you **stop** reading books to your child?

- ❍ 2-3 years
- ❍ 3-4 years
- ❍ 5-6 years
- ❍ 7-8 years
- ❍ Other, please specify:

<u>*Currently*, how often does your child read books at home on his or her own?</u>

	Never	Once a week	Twice a week	3 or more times a week
In English	❍	❍	❍	❍
In Spanish	❍	❍	❍	❍

If your child is learning another language, please indicate the age and environment (home, daycare, school) in which your child started learning this other language:

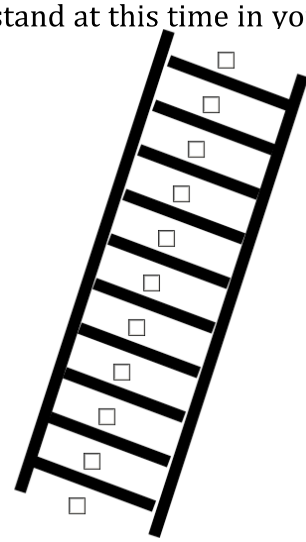
____

____

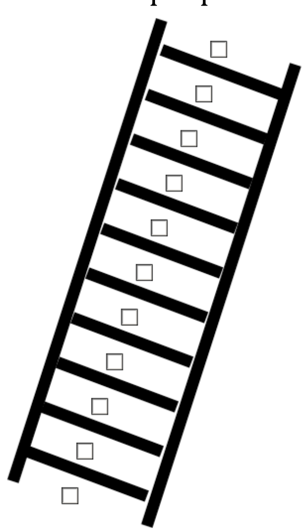
____

Demographics Information

COMMUNITY SCALE: Think of this scale as representing where people stand in their communities. People define community in different ways; please define it in whatever way is most meaningful to you. At the top of the scale are the people who have the highest standing in their community. At the bottom are the people who have the lowest standing in their community. Where would you place yourself on this scale? Please slide the bar to the number where you think you stand at this time in your life, relative to other people in your community.



NATIONAL SCALE: Think of this scale as representing where people stand in the United States. At the top of the scale are the people who are best off- those who have the most money, the most education, and the most respected jobs. At the bottom of the scale are the people who are worst off- who have the least money, least education, and least respected jobs or no job. The higher you are on this scale, the closer you are to the people at the very top; the lower you are, the close you are to the people at the very bottom. Where would you place yourself on this scale? Please slide the bar to the number where you think you stand at this time in your life, relative to other people in the United States.



Which of the following best describes **your** current main daily activities and/or responsibilities?

- ❍ Working full time
- ❍ Working part time
- ❍ Unemployed or laid off
- ❍ Looking for work
- ❍ Keeping house/raise children full-time
- ❍ Retired

Which of the following best describes the **other** parent current main daily activities and/or responsibilities?

- ❍ Working full time
- ❍ Working part time
- ❍ Unemployed or laid off
- ❍ Looking for work
- ❍ Keeping house/raise children full-time
- ❍ Retired

Which of these categories best describes your total combined household (family) income for the past 12 months? *

- ❍ Less than $5,000
- ❍ $5,000 through $11,999
- ❍ $12,000 through $15,999
- ❍ $16,000 through
- ❍ $50,000 through $74,999
- ❍ $75,000 through $99,999
- ❍ $100,000 and greater
- ❍ Don't know
- ❍ No response

*This should include income (before taxes) from all sources, wages, rent from properties, social security, disability and/or veteran's benefits, unemployment benefits, workman's compensation, help from relatives (including child payments and alimony), and so on.

Please provide us with any additional information that will help us to better understand your child's development, including how your child learned his or her languages (any other language exposure, language learning difficulties...etc.)

Parental Academic Socialization

Instructions: Please mark the answer that most applies to you for each statement.

Please note: This questionnaire refers to your child who is participating in this study.

	Never (1)	Seldom (2)	Sometimes (3)	Usually (4)	Always (5)
I put pressure on my child to do well in school.	☐	☐	☐	☐	☐
I force my child to get involved with school activities, even if he or she doesn't want to.	☐	☐	☐	☐	☐
I worry that my child can't do as well in school as I expect him/her to.	☐	☐	☐	☐	☐
I am understanding when my child doesn't do well in school.	☐	☐	☐	☐	☐
I am more concerned that my child does his or her best in school than that he/she get a particular grade.	☐	☐	☐	☐	☐
It is as important to me for my child to be happy as it is for my child to do well in school.	☐	☐	☐	☐	☐
I have very high standards for my child's school performance.	☐	☐	☐	☐	☐
I give my child extra problems the teacher hasn't yet.	☐	☐	☐	☐	☐
I tell my child that he/she could do better in school if he/she worked harder.	☐	☐	☐	☐	☐
I tell my child that he/she can get smarter as long as he/she tries hard.	☐	☐	☐	☐	☐
I tell my child that if he/she doesn't do well on a test, it's probably because he/she didn't study hard enough or long enough.	☐	☐	☐	☐	☐
I tell my child that he/she can get good grades in school as long as he/she always tries hard.	☐	☐	☐	☐	☐
I make my child feel ashamed if he/she does badly in school.	☐	☐	☐	☐	☐
I punish my child when he/she doesn't do well in school.	☐	☐			

Parental Ethnic Socialization

Instructions: The next set of questions is about things that parents sometimes do to help their child understand their ethnic background. For the next few statements, please indicate how important you think each statement is.

How important is it for you ….

	Not at all important (1)	Not very important (2)	Somewhat important (3)	Very important (4)
… that your child speaks English proficiently?				
… that your child reads and writes in English proficiently?				
… that your child speaks Spanish proficiently?				
… that your child reads and writes in Spanish proficiently?				
… that your child understands the history and traditions of your family's ethnicity?				
… that your child experiences things that reflect your family's ethnicity, such as eating food, listening to music, and/or watching movies?				
… that your child understands the history and traditions of American (U.S.) culture?				
… that your child experiences things that reflect American (U.S.) culture, such as eating food, listening to music, and/or watching movies?				

APPENDIX B:

Pilot results for the linguistic competition task: picture naming and response times

*Trials for Phonological Priming task, including picture naming performance and trial responses by 7- to 9-year old children, for phonologically related (experimental condition), phonologically unrelated (control condition) and word-picture matching baseline. *Target word is in **bold**.*

Target and Competitors for Phonologically Related Condition

	Picture Naming			*Trial Response*	
Word	N	Age Range	Accuracy (%)	Average RT	SD
Bed	10	5.19 - 9.01	100	1.4018	0.35
Bell	10	5.61 - 9.92	100		
Belt	10	5.19-9.01	90	1.7417	0.34
Bear	10	5.19-7.92	100		
Brick	10	5.19-7.92	90	1.9487	0.75
Bridge	10	5.19-9.01	100		
Candle	10	7.09 - 9.75	100	2.0226	0.61
Candy	10	7.09 - 9.75	100		
Cane	10	5.61 - 9.92	90	2.0453	0.71
Cake	10	5.19 - 9.01	100		
Card	9	5.19 - 9.01	100	1.5810	0.28
Car	10	5.19-9.01	100		
Cheek	10	5.61 - 9.92	100	1.6239	0.25
Cheese	10	5.19 - 9.01	100		
Cloud	10	5.19 - 9.01	100	1.5898	0.60
Clown	10	5.61 - 9.92	100		
Couch	10	5.19-9.01	90	1.5771	0.26
Cow	10	5.19-7.92	100		
Doll	10	5.19-7.92	100	2.0359	1.90
Dog	10	5.19-9.01	100		
Fork	10	5.19-9.01	100	1.9888	0.73
Four	10	5.19-7.92	100		
Goat	10	5.61 - 9.92	90	1.6905	0.30
Ghost	10	5.19 - 9.01	100		
Hanger	10	7.09 - 9.75	80	1.8663	0.67
Hammer	10	7.09 - 9.75	100		
Horn	10	5.19-9.01	80	1.8439	0.22
Horse	10	5.19-7.92	100		
Key	10	5.19 - 9.01	100	1.8412	0.62
King	10	5.61 - 9.92	100		
Knob	10	5.19-7.92	80	2.3447	0.87
Knot	10	5.19-9.01	80		

Moose	10	5.61 - 9.92	90	1.7899	0.33
Moon	10	5.19 - 9.01	100		
Mouse	10	5.19 - 9.01	100	1.7653	0.57
Mouth	10	5.61 - 9.92	100		
Onion	10	7.09 - 9.75	80	1.6128	0.36
Oven	10	7.09 - 9.75	90		
Swing	10	5.61 - 9.92	100	2.2946	0.74
Swim	10	5.19 - 9.01	100		
Wash	10	5.19-7.92	100	1.8308	0.31
Watch	10	5.19-9.01	90		

Target and Competitors for Phonologically Unrelated Condition

	Picture Naming			*Trial Response*	
Word	N	Age Range	Accuracy (%)	Average RT	SD
Ant	10	5.19 - 9.01	100	1.5820	0.63
Tie	10	5.61 - 9.92	90		
Bread	10	5.19 - 9.01	100	1.6235	0.36
Star	10	5.61 - 9.92	100		
Carrot	10	7.09 - 9.75	100	1.6339	0.43
Pillow	10	7.09 - 9.75	100		
Tooth	10	7.09 - 9.75	100	1.4066	0.42
Chair	10	7.09 - 9.75	100		
Clock	10	5.19 - 7.92	100	1.5159	0.31
Ice	10	6.08 - 9.92	100		
Leaf	10	5.19 - 9.01	100	1.3426	0.14
Deer	10	6.08 - 9.92	90		
Desk	10	5.19 - 9.01	100	1.6650	0.35
Girl	10	5.61 - 9.92	100		
Dress	10	5.19 - 9.01	100	1.7288	0.47
Eye	10	5.61 - 9.92	100		
Flag	10	6.08 - 9.92	100	1.7147	0.40
Cat	10	5.19-7.92	100		
Spoon	10	5.19 - 9.01	100	1.4818	0.54
Frog	10	5.19 - 7.92	100		
Grape	10	6.08 - 9.92	90	1.7340	0.66
Bus	10	5.19 - 7.92	100		
Hat	10	5.19 - 9.01	100	1.6233	0.48
Ball	10	5.61 - 9.92	100		
Mop	10	7.09 - 9.75	90	1.5730	0.40
Head	10	7.09 - 9.75	90		
Jar	10	5.19 - 7.92	90	1.7573	0.54
Shoe	10	6.08 - 9.92	100		

Nail	10	6.08 - 9.92	80	1.5875	0.23
Bone	10	5.61 - 9.92	100		
Pencil	10	7.09 - 9.75	100	1.3849	0.17
Box	10	5.61 - 9.92	100		
Pig	10	5.19 - 7.92	100	1.5688	0.38
Two	10	7.09 - 9.75	100		
Purse	10	7.09 - 9.75	90	1.5244	0.37
Juice	10	5.61 - 9.92	100		
Shark	10	7.09 - 9.75	100	1.4926	0.41
Door	10	6.08 - 9.92	100		
Sock	10	5.19 - 7.92	100	1.3612	0.21
Bat	10	7.09 - 9.75	100		
Worm	10	6.08 - 9.92	100	1.4865	0.38
Duck	10	5.19 - 7.92	100		

Baseline Condition

	Picture Naming		
Word	N	Age Range	Accuracy (%)
Ear	10	5.19 - 7.92	100
Bunny	10	7.09 - 9.75	80
Truck	10	6.08 - 9.92	100
Hand	10	5.19 - 7.92	100
Fish	10	6.08 - 9.92	100
Eight	9	5.19 - 9.01	100
Foot	10	5.19 - 9.01	100
Boy	10	5.61 - 9.92	80
Apple	10	7.09 - 9.75	100
Whale	10	5.61 - 9.92	100
Bow	10	5.61 - 9.92	100
Knight	10	6.08 - 9.92	100
Soap	10	5.19 - 9.01	100
Sled	10	7.09 - 9.75	100
Cage	10	6.08 - 9.92	100
Book	10	5.19-7.92	100
Brush	10	5.61 - 9.92	100
Wood	10	7.09 - 9.75	100
Boot	10	5.19-9.01	100
Egg	10	5.61 - 9.92	100
Cup	10	5.19 - 9.01	100

APPENDIX C

Deoxyhemoglobin (HbR) linear mixed model results for the Linguistic Competition task (ME=main effects, X=interactions), F-values

	Left Hemisphere			Right Hemisphere		
Channel	ME Condition	ME Group	Condition X Group	ME Condition	ME Group	Condition X Group
1	4.21*	0.01	3.23*	1.23	0.13	0.13
2	1.46	0.00	2.40	0.58	1.33	0.39
3	0.99	0.01	0.69	0.84	0.87	0.20
4	0.09	0.01	0.05	1.99	4.10*	2.54
5	1.56	0.07	0.53	0.07	1.54	0.21
6	0.42	1.57	2.54	1.87	0.33	0.18
7	0.26	0.01	1.20	0.30	0.61	0.35
8	1.37	0.05	2.13	0.21	1.89	1.36
9	2.90	0.24	0.77	1.25	0.50	0.40
10	0.40	0.02	0.12	0.29	0.00	0.45
11	7.70***	2.57	0.57	0.28	0.08	0.05
12	0.01	0.05	0.25	0.60	0.05	0.43
13	1.13	0.18	7.32***	0.00	0.63	0.50
14	0.16	1.09	1.65	0.51	0.28	0.27
15	1.06	0.01	0.10	0.34	0.01	0.04
16	2.60	0.04	1.43	0.76	0.32	0.03
17	12.19***	1.40	8.14***	1.96	0.04	0.26
18	0.08	0.01	0.05	0.09	0.00	0.04
19	9.26***	16.22***	9.79***	0.64	0.20	0.67
20	0.30	2.49	1.33	9.57***	2.99	6.06**
21	0.98	0.03	2.13	0.82	0.12	0.41
22	2.15	0.92	0.62	4.51*	2.94	3.77*

Left hemisphere channels—Betas and *t*-values

Left	Monolinguals						Bilinguals					
Channel	Baseline		PhU		PhR		Baseline		PhU		PhR	
	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value
1	5.77	.30	-26.88	-1.38	-36.62	-1.89	8.46	0.44	-2.81	-0.15	-8.01	-0.42
2	-3.55	-.20	-20.82	-1.16	-40.00	-2.25*	5.79	.31	-10.05	-.55	-40.24	-2.2
3	-9.44	-.66	-23.51	-1.66	-41.54	-2.98**	2.95	.19	6.63	.43	-23.88	-1.55
4	-3.71	-.19	-14.75	-.76	-34.74	-1.82	23.54	1.18	15.53	.79	-29.85	-1.55
5	17.20	.55	-.85	-.03	.59	.02	12.27	.41	-10.91	-.37	-58.83	-2.02*
6	-22.14	-1.51	-37.25	-2.56*	-65.69	-4.56***	7.59	.58	-25.21	-1.96*	-57.62	-4.52***
7	-20.96	-.93	-54.04	-2.42*	-99.03	-4.50***	-5.5	-.25	-40.75	-1.89	-83.97	-3.97***
8	.62	.04	-10.95	-.69	-31.79	-2.05*	14.41	.92	-28.69	-1.84	-49.89	-3.25**
9	-16.34	-1.13	-17.29	-1.21	-51.40	-3.63***	-6.44	-.42	-8.83	-.58	-36.46	-2.42*
10	-15.19	-1.14	-17.74	-1.34	-42.70	-3.26**	-1.51	-.1	-16.51	-1.06	-43.66	-2.86**
11	-26.07	-1.78	-23.42	-1.61	-61.85	-4.32***	5.36	.29	-1.38	-.08	-22.42	-1.25
12	-26.16	-1.70	-23.53	-1.54	-36.68	-2.42*	-8.65	-.4	-19.8	-.93	-7.97	-.38
13	3.76	.28	8.14	.61	.40	.03	-2.45	-.12	-16.45	-.85	6.65	.35
14	13.30	.85	8.20	.53	-7.13	-.46	29.34	1.50	27.95	1.45	44.73	2.36*
15	6.33	.43	-5.23	-.36	-1.66	-.12	14.79	.64	1.45	.06	1.55	.07
16	-.13	-.01	-6.98	-.60	-8.49	-.73	17.30	.82	23.77	1.14	24.60	1.19
17	11.56	.84	8.49	.62	16.53	1.23	-5.20	-.20	.62	.02	16.28	.66
18	-2.76	-.22	-24.87	-1.99	-42.71	-3.46***	13.74	1.00	-.22	-.02	-6.35	-.48
19	-4.13	-.40	-26.33	-2.54*	-33.64	-3.29**	-1.97	-.15	-22.68	-1.79	-9.72	-.77
20	2.04	.11	-9.71	-.51	-11.47	-.62	13.18	.48	10.79	.40	10.60	.40
21	15.58	.94	-9.60	-.58	-18.99	-1.17	-15.65	-.48	16.40	.52	34.55	1.12
22	2.27	.14	-14.53	-.90	-12.64	-.79	-10.93	-.37	40.39	1.42	55.91	2.02

Right hemisphere channels—Betas and *t*-values

Right	Monolinguals						Bilinguals					
Channel	Baseline		PhU		PhR		Baseline		PhU		PhR	
	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value
1	-16.40	-1.11	-19.63	-1.33	-22.05	-1.52	-18.99	-1.05	-54.07	-3.02**	-92.56	-5.22***
2	-5.96	-.38	-27.51	-1.77	-46.89	-3.06**	-13.63	-.86	-45.06	-2.88**	-96.35	-6.23***
3	-4.37	-.33	-15.14	-1.16	-30.30	-2.35*	3.7	.24	-44.59	-2.89**	-94.01	-6.18***
4	-17.22	-1.14	-25.88	-1.72	-34.33	-2.31*	-23.51	-1.17	-37.16	-1.88	-43.81	-2.25*
5	-2.48	-.13	-30.35	-1.59	-19.32	-1.02	11.81	.47	-4.9	-.2	-30.83	-1.25
6	1.56	.11	-8.02	-.57	-16.19	-1.16	-17.45	-1.19	-37.87	-2.61**	-57.41	-4.00***
7	-9.64	-.53	-22.74	-1.25	-36.45	-2.04*	1.31	.09	-42.77	-2.84**	-65.7	-4.43***
8	1.32	.10	-3.15	-.24	-3.31	-.25	10.78	.9	-9.79	-.86	-7.15	-.64
9	5.45	.36	-18.77	-1.25	-37.05	-2.50*	8.62	.6	-11.94	-.83	-37.08	-2.62**
10	-8.82	-.71	-13.80	-1.26	-32.89	-3.05**	12.86	1.14	-17.03	-1.51	-35.64	-3.21**
11	-10.62	-.83	-25.72	-2.03*	-55.13	-4.40***	-6.17	-.46	-22.84	-1.73	-48.02	-3.69***
12	-11.68	-.72	-35.50	-2.18*	-57.33	-3.56***	-15.7	-.97	-25.11	-1.58	-57.49	-3.67***
13	-1.83	-.10	-2.25	-.12	-16.65	-.91	17.31	.65	-11.13	-.43	9.68	.38
14	-13.57	-.76	-11.09	-.63	-19.21	-1.10	-7.6	-.43	-10.17	-.58	-19.02	-1.11
15	-35.12	-2.51*	-34.10	-2.46*	-25.40	-1.86	2.61	.14	-12.08	-.67	-23.12	-1.30
16	-10.49	-.57	-15.86	.86	-12.83	-.71	-7.38	-.38	-22.32	-1.18	-37.34	-2.00*
17	-15.79	-1.00	-23.29	-1.49	-37.98	-2.48*	-20.29	-1.00	-25.54	-1.26	-13.02	-.66
18	-7.41	-.64	-11.44	-1.00	-22.49	-1.99*	7.43	.49	-8.75	-.58	-.52	-.04
19	2.56	.24	-15.45	-1.44	-20.79	-1.96*	8.85	.81	-7.48	-.69	-13.26	-1.25
20	-14.35	-.72	-40.10	-2.03*	-59.56	-3.06**	-25.23	-.57	-61.88	-1.42	-67.15	-1.57
21	6.67	.43	-2.10	-.14	-8.83	-.59	4.88	.21	4.73	.20	23.31	1.00
22	.30	.02	-3.63	-.28	-8.59	-.66	-3.64	-.22	-5.83	-.36	1.32	.08

APPENDIX D

Deoxyhemoglobin (HbR) linear mixed model results for the ANT Cue conditions (ME=main effects, X=interactions), F-values

	Left Hemisphere			Right Hemisphere		
Channel	ME Condition	ME Group	Condition X Group	ME Condition	ME Group	Condition X Group
1	3.22*	0.48	5.10**	1.17	0.03	0.11
2	4.67**	0.06	0.55	3.35*	1.38	10.58***
3	1.38	2.15	1.01	5.16**	1.16	0.10
4	2.95*	3.95*	1.70	8.19***	21.67***	26.10***
5	14.11***	0.18	0.04	1.29	0.17	0.06
6	1.12	12.94***	13.71***	2.23	13.59***	6.86**
7	10.11***	0.20	0.30	4.13*	1.41	0.08
8	4.16*	3.97*	5.54**	1.78	0.20	0.30
9	1.75	0.12	4.05*	1.93	1.50	1.92
10	0.10	0.88	2.62	0.31	0.59	0.60
11	6.38**	3.80*	4.13*	2.87	0.03	0.17
12	2.87	3.00	4.53*	3.11*	0.17	1.01
13	23.33***	37.38***	30.13***	4.11*	1.40	1.98
14	3.12*	2.59	4.20*	4.84**	0.84	1.33
15	12.08***	3.12	14.06***	2.04	0.02	0.69
16	2.63	0.00	1.09	0.93	0.91	0.52
17	0.19	2.84	2.02	1.74	0.70	3.24*
18	2.73	4.23*	2.66	2.10	3.81	2.11
19	11.04***	0.21	10.25***	15.07***	7.49**	6.32**
20	26.54***	0.01	39.54***	1.05	0.37	1.06
21	8.97***	0.55	1.63	1.03	5.44*	2.46
22	4.12*	0.02	6.06**	4.84**	0.78	3.10*

Left hemisphere channels—Betas and *t*-values

Left	Monolinguals						Bilinguals					
Channel	No Cue		Spatial Cue		Center Cue		No Cue		Spatial Cue		Center Cue	
	4.87	.60	11.55	1.41	3.60	.45	29.94	3.27***	46.89	5.1***	40.48	4.50***
1	1.90	.26	.60	.08	.59	.08	14.30	1.70	5.38	.63	-.73	-.09
2	2.44	.41	2.44	.29	-2.45	-.42	12.46	1.67	9.03	1.21	2.55	.35
3	13.72	1.87	20.76	2.81**	8.63	1.20	28.24	3.11**	26.62	2.91**	25.89	2.90**
4	12.15	1.14	23.31	2.16*	4.49	.43	27.68	2.30*	43.63	3.61***	33.83	2.89**
5	-.62	-.12	-7.18	-1.33	-8.76	-1.68	-3.33	-.52	-14.31	-2.22*	-23.80	-3.75***
6	1.91	.23	2.44	.29	-20.04	-2.50*	5.07	.53	-15.79	-1.66	-27.20	-2.94
7	6.03	1.09	8.57	1.52	-6.86	-1.26	2.01	.27	-3.08	-.41	-9.14	-1.23
8	5.21	.87	.57	.09	-12.99	-2.22*	-3.84	-.44	-11.89	-1.35	-29.60	-3.44***
9	-3.47	-.62	-3.63	-.64	-16.92	-3.09**	1.78	.19	-11.68	-1.27	-14.71	-1.63
10	5.34	.90	12.36	2.06*	-4.28	-.74	13.70	1.45	3.14	.33	-7.79	-.84
11	5.50	.93	-7.55	-1.27	-16.62	-2.89**	15.45	1.68	16.16	1.75	10.24	1.13
12	7.76	1.40	3.70	.66	-1.47	-.27	15.36	1.64	13.48	1.43	6.69	.73
13	9.86	1.48	-2.20	-.33	-10.50	-1.61	22.88	2.12*	20.65	1.91	29.28	2.77**
14	10.60	1.62	5.60	.85	.12	.02	.001	.001	-13.06	-1.19	-18.55	-1.72
15	-.94	-.19	-6.57	-1.31	-16.85	-3.44***	9.47	.96	.90	.09	-1.64	-.17
16	16.42	2.53*	13.93	2.12*	7.15	1.13	-21.86	-1.85	-22.21	-1.86	-24.26	-2.08*
17	9.00	1.72	4.69	.88	2.24	.44	11.55	1.39	2.20	.26	-.30	-.04
18	2.70	.60	-.77	-.17	-1.54	-.35	-2.36	-.31	-4.57	-.61	-6.87	-.92
19	24.98	2.93**	15.13	1.75	17.87	2.15*	-4.68	-.31	8.76	.58	-23.49	-1.61
20	-1.40	-.20	3.50	.49	-1.98	-.29	-4.29	-.30	-7.78	-.54	-7.65	-.55
21	-12.48	-1.79	-9.87	-1.39	-20.08	-2.93**	10.68	.69	21.10	1.36	-2.70	-.18
22	4.87	.60	11.55	1.41	3.60	.45	29.94	3.27***	46.89	5.1***	40.48	4.50***

Right hemisphere channels—Betas and *t*-values

Right	Monolinguals						Bilinguals					
Channel	No Cue		Spatial Cue		Center Cue		No Cue		Spatial Cue		Center Cue	
	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value
1	7.47	1.25	11.81	1.96*	6.52	1.19	29.35	3.81***	27.76	3.59***	25.20	3.31***
2	7.70	1.37	6.42	1.13	.37	.07	4.22	.57	7.25	.97	3.21	.44
3	-1.97	-.39	3.89	.77	-5.22	-1.06	5.55	.74	-.28	-.04	-6.90	-.94
4	9.82	1.55	20.17	3.14**	8.09	1.30	25.72	3.16**	28.97	3.54***	24.51	3.06**
5	11.66	1.41	21.37	2.58**	9.42	1.17	35.55	3.79***	44.67	4.73***	36.00	3.89***
6	-1.43	-.26	-3.26	-.58	-12.05	-2.23*	-14.73	-2.24*	-4.35	-.66	-15.52	-2.40*
7	-11.34	-1.75	-7.54	-1.14	-24.57	-3.88***	-8.42	-1.19	-1.69	-.24	-18.11	-2.59**
8	2.49	.47	10.48	1.96*	-3.33	-.65	-1.79	-.27	-.24	-.04	-7.80	-1.20
9	-6.89	-1.20	-.04	-.01	-8.37	-1.50	-1.88	-.23	-1.49	-.18	-17.72	-2.19*
10	-6.54	-1.48	-1.44	-.32	-11.35	-2.61**	-3.22	-.49	-5.98	-.91	-12.18	-1.88
11	-7.96	-1.54	-7.04	-1.35	-14.41	-2.85**	-2.03	-.29	-1.12	-.16	-13.50	-1.95
12	-5.77	-.92	3.04	.48	-5.88	-.96	-22.92	-2.58**	-32.66	-3.67***	-33.68	-3.85***
13	-8.44	-1.17	-5.94	-.82	-8.90	-1.27	1.48	.11	-15.28	-1.17	-26.72	-2.11*
14	-1.82	-.28	-5.22	-.80	-1.32	-.21	-18.31	-1.92	-26.92	-2.81**	-30.38	-3.23***
15	-2.52	-.45	1.71	.30	-3.48	-.64	-.59	-.06	-8.29	-.87	-17.38	-1.86
16	-2.92	-.40	-13.34	-1.82	-21.12	-2.99**	-6.40	-.58	-24.18	-2.19*	-22.60	-2.09*
17	4.25	.66	.12	.02	-.65	-.10	-1.02	-.09	-11.35	-1.01	-17.71	-1.61
18	1.09	.22	5.67	1.14	-4.02	-.84	-4.76	-.51	-9.58	-1.03	-16.62	-1.82
19	-3.49	-.79	-.22	-.05	-6.40	-1.47	-1.42	-.21	-.34	-.05	-6.73	-1.01
20	5.93	.73	4.11	.49	4.93	.62	-3.01	-.16	-8.51	-.44	-25.63	-1.39
21	8.85	1.35	-5.69	-.85	-2.37	-.37	4.28	.37	-5.94	-.51	-16.18	-1.42
22	6.07	1.09	-9.27	-1.64	-8.22	-1.50	-11.73	-1.21	-17.95	-1.84	-24.21	-2.53*

APPENDIX E

Deoxyhemoglobin (HbR) linear mixed model results for ANT Congruence conditions (ME=main effects, X=interactions), F-values

	Left Hemisphere			Right Hemisphere		
Channel	ME Condition	ME Group	Condition X Group	ME Condition	ME Group	Condition X Group
1	26.52***	3.14	1.76	12.73***	0.49	5.06*
2	0.16	2.15	0.69	0.00	2.18	0.01
3	1.85	0.15	0.02	8.48**	28.54***	8.75**
4	0.03	2.67	9.17**	1.70	3.70	0.00
5	3.92*	13.55***	11.02***	0.49	0.22	2.45
6	1.40	0.18	0.01	1.04	0.02	0.21
7	0.44	1.79	8.93**	18.56***	3.04	2.25
8	0.01	1.89	0.02	4.94*	0.78	8.81**
9	0.64	0.55	0.51	15.37***	2.60	8.37**
10	8.86**	2.78	0.08	0.04	2.08	0.75
11	3.99*	2.64	0.99	2.16	0.19	0.27
12	1.14	15.46***	27.59***	0.98	5.35*	2.48
13	0.21	0.00	0.94	2.05	0.16	0.00
14	3.74	0.64	0.77	5.00*	0.00	1.48
15	21.07***	7.08**	11.37***	4.91*	2.55	3.15
16	1.75	0.20	0.09	0.26	0.21	0.31
17	0.23	4.32*	4.97*	0.56	0.24	0.12
18	0.21	0.08	0.45	0.27	3.90*	8.63**
19	0.36	2.89	5.51*	10.93**	1.70	0.91
20	17.70***	8.97**	0.67	0.89	0.22	0.38
21	0.08	0.04	0.25	2.23	0.38	0.14
22	0.12	6.58*	6.07*	43.22***	12.05***	50.36***

Left hemisphere channels—Betas and *t*-values

Left H.	Monolinguals				Bilinguals			
	Congruent		Incongruent		Congruent		Incongruent	
Channel	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value
1	16.62	2.23*	24.59	3.33***	50.11	5.76***	54.93	6.37***
2	2.91	0.44	8.82	1.35	21.69	2.67**	15.45	1.91
3	5.07	0.89	4.86	0.86	15.22	2.01*	12.96	1.71
4	18.06	2.63**	21.53	3.17**	41.42	4.83***	35.44	4.16***
5	32.67	3.36***	36.06	3.74***	56.46	5.30***	46.93	4.46***
6	-0.34	-0.07	-2.50	-0.50	-9.11	-1.37	-11.37	-1.71
7	2.03	0.27	0.20	0.03	-9.40	-1.06	-13.78	-1.56
8	2.59	0.49	4.62	0.89	0.66	0.09	-1.22	-0.16
9	-1.13	-0.20	2.43	0.44	-5.47	-0.64	-14.26	-1.66
10	-2.90	-0.55	-2.73	-0.52	-2.91	-0.32	-3.28	-0.37
11	5.55	1.00	13.13	2.39*	6.07	0.68	7.59	0.85
12	0.93	0.17	-6.14	-1.11	14.50	1.63	10.73	1.22
13	0.40	0.07	-0.78	-0.15	11.98	1.30	5.09	0.56
14	-4.41	-0.71	-2.92	-0.48	23.08	2.23*	20.18	1.96*
15	1.74	0.29	7.27	1.21	-7.06	-0.66	-9.46	-0.88
16	-5.05	-1.03	-6.58	-1.35	4.25	0.44	2.01	0.21
17	2.63	0.43	7.04	1.16	-23.65	-2.11*	-29.47	-2.64**
18	4.56	0.91	9.57	1.92	6.96	0.82	1.46	0.17
19	-1.49	-0.34	0.88	0.20	-7.23	-0.92	-5.25	-0.67
20	1.45	0.19	16.87	2.21*	-4.27	-0.32	-17.90	-1.35
21	-6.86	-1.06	-2.71	-0.43	0.45	0.04	-4.86	-0.39
22	-9.44	-1.46	-11.47	-1.79	21.32	1.53	14.14	1.02

Right hemisphere channels—Betas and *t*-values

Right H.	Monolinguals				Bilinguals			
	Congruent		Incongruent		Congruent		Incongruent	
Channel	Beta	t-value	Beta	t-value	Beta	t-value	Beta	t-value
1	9.64	1.72	12.31	2.22*	30.03	3.93***	29.79	3.92***
2	6.63	1.24	6.75	1.28	16.78	2.26*	6.41	0.87
3	2.55	0.52	0.57	0.12	8.92	1.18	-1.27	-0.17
4	10.37	1.74	21.06	3.56***	33.64	4.23***	30.39	3.84***
5	28.87	3.78***	25.94	3.44***	46.59	5.23***	51.52	5.83***
6	-8.38	-1.61	0.61	0.12	-4.00	-0.59	-8.26	-1.23
7	-6.76	-1.15	-17.27	-1.60	-2.15	-0.30	-4.21	-0.59
8	-0.81	-0.16	5.02	1.01	1.71	0.25	3.98	0.59
9	-5.63	-1.05	-2.23	-0.42	0.05	0.01	-3.37	-0.42
10	-3.45	-0.79	-2.82	-0.65	0.91	0.13	-2.78	-0.41
11	-6.75	-1.37	-3.44	-0.70	0.85	0.12	-0.86	-0.12
12	9.96	1.65	9.44	1.57	-21.38	-2.41*	-28.83	-3.26**
13	1.87	0.28	4.12	0.62	-5.41	-0.45	-19.72	-1.65
14	2.46	0.41	8.60	1.43	-23.26	-2.42*	-27.56	-2.87**
15	-3.21	-0.61	1.55	0.29	4.05	0.43	-5.18	-0.55
16	-12.19	-1.84	-9.93	-1.51	-4.51	-0.42	-6.74	-0.62
17	-3.15	-0.53	-0.05	-0.01	-5.70	-0.53	-9.80	-0.92
18	-2.98	-0.63	6.14	1.30	-4.71	-0.52	-6.86	-0.76
19	-5.82	-1.33	-0.53	-0.12	-2.96	-0.41	0.22	0.03
20	-1.76	-0.24	5.76	0.79	-15.79	-0.97	-19.59	-1.22
21	-4.28	-0.70	0.21	0.04	-9.68	-0.86	-3.23	-0.29
22	-8.08	-1.53	-2.05	-0.39	-15.86	-1.63	-12.87	-1.32

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