8-2022

Executive Functioning and Brain Activation in Young Monolingual and Bilingual Children: An fNIRS Study

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Recommended Citation

Cook, Matthew L., "Executive Functioning and Brain Activation in Young Monolingual and Bilingual Children: An fNIRS Study" (2022). *All Graduate Theses and Dissertations*. 8568.
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EXECUTIVE FUNCTIONING AND BRAIN ACTIVATION IN YOUNG MONOLINGUAL AND BILINGUAL CHILDREN: AN fNIRS STUDY

by

Matthew L. Cook

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

In

Human Development and Family Studies

Approved:

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Logan, Utah

2022

ABSTRACT

Executive Functioning and Brain Activation in Young Monolingual and Bilingual Children: An fNIRS Study

by

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Utah State University, 2022

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The current study examines brain activation and executive functioning skills (inhibitory control, cognitive flexibility, working memory) in young monolingual and bilingual children. Data was collected from a sample of five monolingual and six bilingual children aged three to five who were recruited from an on-campus childcare and the surrounding community. The parents of the participants were highly educated. Brain activation was measured using oxygenated, deoxygenated, and total hemoglobin levels that were collected using the NIRSport2 fNIRS system. Executive functioning skills were measured using five tasks from the EF Touch computerized battery. The results suggest a trend of better executive functioning skills for the bilingual children although, the differences did not reach statistical significance. There was also a pattern of brain activation differences with the monolingual group showing more deactivation in the medial (middle) cortex than the bilingual group and similar levels of activation in the dorsolateral (sides) cortex for both groups. The higher activation in the medial cortex for the bilingual group could potentially serve as a catalyst for a bilingual advantage in executive functioning skills as that area of the prefrontal cortex is responsible for higher-level executive functions. Future research should continue to explore this trend of differences in locations of brain activation to determine if the neural recruitment of the medial cortex aids in the processing of executive functioning tasks.

(120 pages)

PUBLIC ABSTRACT

Executive Functioning and Brain Activation in Young Monolingual and Bilingual Children: an fNIRS Study

Matthew L. Cook

Over the past 40 years, the prevalence of bilingualism in the United States has increased. As bilingualism is increasing, it is important to examine potential benefits or drawbacks that early household bilingual exposure has on child development and how bilingualism may facilitate those benefits or drawbacks. This study included 5 monolingual and 6 bilingual children and compared differences in brain activation location and executive functioning skills. Results from this project show a trend of activation differences where the monolingual children had less activation of the middle area of the prefrontal cortex while there was similar activation in both the left and right side of the prefrontal cortex for both groups. Also shown is a pattern of better performance on the executive functioning tasks for the bilingual group. This could potentially be explained by the greater use of that middle area of the prefrontal cortex for the bilingual group compared to the monolingual group. The implications of this project suggest that there may be differences in abilities between bilingual and monolingual children and warrant further exploration of these trends.

ACKNOWLEDGMENTS

I am grateful for the support that everyone has shown me throughout the completion of this program and thesis. First, I would like to thank my wonderful mentors, Drs. Boyce, Bradshaw, and Yan for all their support in helping me complete my thesis project and surviving my master’s program. I would also like to thank my wonderful cohort without whom this would have been impossible. I am especially grateful to my best friends Dylan and Maggie for all their love and support they have shown me, especially for the late-night food runs and vent sessions.

I would also like to thank the College of Education and Department of Human Development and Family Studies for the thesis funding assistance they generously provided.

Matthew L. Cook

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

This chapter introduces and provides a brief overview of the overall project and each main subcategory.

Bilingualism in the United States

Bilingualism has been on a steady increase in the U.S. The percentage of the individuals in the United States who speak a language other than English at home has risen from 11% in 1980 to 21.9% in 2018 (Zeigler & Camarota, 2019). According to Pew Research Center (2020), the number of second language speakers and immigrants is projected to continue increasing with over 1 million immigrants entering the United States each year. Historically, bilingualism has been looked at as a negative trait (Goodenough, 1926). Peal and Lambert (1962) challenged this notion when they found results that supported the possibility of a bilingual advantage in mental flexibility. This groundbreaking discovery shifted the notion surrounding bilingualism from a negative to a positive, creating a concept called the bilingual advantage in executive functioning (EF), which gained increasing support in research and literature.

Executive Functioning and Why it Matters

EF has become an umbrella term for various cognitive processes performed by the prefrontal areas of the frontal lobes (Goldstein & Naglieri, 2014). It includes aspects like working memory, attention shifting, inhibitory control, and planning. Lezak (1995) said,

> Executive functions refer to a collection of interrelated cognitive and behavioral skills that are responsible for purposeful, goal-directed activity, and include the highest level of human functioning, such as intellect, thought, self-control, and social interaction. (p. 42)

The importance of EF is highlighted in this quote when he states that the highest level of human functioning is controlled by EF. Therefore, the development of EF should be prioritized and supported throughout the lifespan. This is especially prevalent during the preschool years (3-5 years old), where EF develops most rapidly (Center on the Developing Child, n.d.; Moriguchi, 2014; Zelazo & Carlson, 2012). Research has shown that adverse experiences (e.g., abuse and neglect) in childhood have a negative effect on the development of EF (e.g., Ji & Wang, 2018) which makes promoting early positive experiences, such as a second language, important in the normative development of EF.

Brain Scanning and Functional Near-Infrared Spectroscopy

Use of cerebral blood flow (CBF) to measure brain activation and EF, through both functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS), has been utilized for decades but has mainly been utilized with adults and clinical patients (Joanette et al., 2008). In the study of bilingualism this method of measurement has also been utilized to a great extent, but it has focused on the processes of language development and language processing (e.g., Jasinka & Petitto, 2013; Kovelman et al., 2008). In recent years, there has been an uptick in researcher utilizing fNIRS to study components of EF with preschool age children (e.g., H. Li, Wu, Yang, & Luo et al., 2021; Y. Li et al., 2017) but the inclusion of bilingualism is not as widespread.

Decline Effect

There has also been a decline effect in published research supporting the bilingual advantage with 80% of research between 2011 and 2015 showing null results (Paap et al., 2015). Possible explanations for this decline effect are that researchers may have been using suboptimal measurement tools which do not accurately isolate the construct or that potential confounding variables were not accurately accounted for. Despite these null results, there is still potential for a bilingual advantage in specific circumstances or components of EF (Gunnerud et al., 2020; Paap et al., 2015).

The novel method in this study of using fNIRS to measure brain activation in conjunction with EF measurements with bilingual and monolingual preschoolers may give insights into what circumstances facilitate a bilingual advantage in EF and lay a groundwork for future bilingual fNIRS research. It may also provide insight into which aspects or components (e.g., attention shifting, inhibitory control) of EF benefit from the experience of exposure to a second language.

CHAPTER II

LITERATURE REVIEW

This chapter delves into the literature including the theoretical framework for this study, executive functioning literature (including bilingual executive functioning), the predictors of executive functioning skills, as well as brain imaging techniques including, functional magnetic resonance imaging, electroencephalography, and functional near-infrared spectroscopy

Theoretical Framework

The developmental cascades theoretical framework refers to the cumulative influences on development resulting from the many different interactions and transactions that are experienced across domains and systems (Bornstein et al., 2006; Marchman & Fernald, 2008; Masten & Chiccheti, 2010; Smith & Thelen, 2003). This theory suggests that the early experiences of children will have a cascading effect on their development over multiple domains and over time. These cascades can theoretically be directly related uni- or bidirectionally and even indirectly related through multiple paths. Therefore, it is possible to understand how early bilingual experiences via second language exposure and culture can have an effect on EF in early childhood and even later in life. It also accounts for the other factors (e.g., parenting interactions, socioeconomic status [SES]), which can influence the development of the child.

One example of a commonly studied cascade is the influence of internalizing and externalizing behaviors on academic success in childhood and adolescence. Greater levels of internalizing and externalizing behaviors are often associated with lower academic achievement (Masten et al., 2005; Vaillancourt et al., 2013; van Lier et al., 2012). Van Lier et al. found that children who expressed externalizing behaviors were more likely to experience peer victimization and lower academic achievement and subsequently express more externalizing behaviors at later time-points. This supports the bidirectional, longitudinal nature of cascades and shows how multiple experiences (i.e., peer victimization and lower academic achievement) can compound and cascade to a child expressing more externalizing behaviors. Additional support for the bidirectional and compounding nature of cascades is provided by Vaillancourt et al. They found similar results where internalizing behaviors predicted higher rates of peer victimization which further led to lower grades and higher levels of externalizing behaviors.

Cascading interactions of EF skills and development on language development have also been observed. Fuhs et al. (2014) conducted a longitudinal study looking at the associations between EF and various academic skills. They found that in a sample of 562 children, EF and language development had a bidirectional association in preschool but that in kindergarten EF was a moderate predictor of language development with no bidirectional association. Support for the unidirectional influence of EF on language development is provided by Weiland et al. (2014), who found that EF skills predicted later vocabulary and receptive language skills in a sample of 400 preschoolers. Potential pathways for this cascading relation could be that children who exhibit EF problems experience less maternal bonding (de Cock et al., 2017), which then leads to lesser language skills through less interactive parent-child relationships (Safwat & Sheikany, 2014).

Executive Functioning

Three main constructs are typically proposed as the core of EF (Diamond, 2006; Miyake et al., 2000): (1) inhibitory control, (2) working memory or updating, and (3) cognitive flexibility (Barac et al., 2014). Every day, people are required to make decisions, solve problems, and complete complex tasks correctly. Important processes like these occur in and develop parallel to the prefrontal cortex of the brain and are often referred to executive control skills. However, EF skills are not always utilized fully when completing complex or difficult tasks (Diamond, 2006). For example, an intricate task or activity such as playing an instrument may require a large amount of concentration and heavy use of your EF skills if you are a novice, but if you are a professional musician doing that same task will require much less cognitive effort and less executive function use. Regardless of if EF skills are fully utilized once you have mastered a task, they are a very important developmental steppingstone to get to that point.

Each aspect of EF facilitates different cognitive tasks, and everyone accesses them to some degree. However, cognitive deficiencies in an individual and adverse life experiences can make it much more difficult to fully utilize or develop certain EF skills. In a study of 700 Chinese college students, Ji and Wang (2018) found that adverse childhood experiences (ACEs; i.e., abuse, neglect, familial chronic alcoholism) and negative life experiences were positively correlated with inhibitory control. However, the existence of ACEs led to significantly longer reaction times for attention switching (cognitive flexibility) tasks when compared to the non-ACEs group. The students reporting fewer negative life experiences had significantly faster reaction times than their higher scoring counterparts. These results show the negative effect that poor life experiences can have, and that cognitive flexibility, specifically, is influenced heavily by ACEs. These negative experiences can potentially have lasting impacts on the individuals leading to deficits in academic and social competencies which shows the necessity of promoting positive life experiences.

Inhibitory Control

Inhibitory control is the ability to inhibit thought processes or physical actions that are irrelevant to the goal or task (Rothbart & Posner, 1985). Both parts of inhibitory control can be tested using various common methods such as the common Stroop color and word task (Stroop, 1935) and the go no-go task (Durston et al., 2002). The Stroop task measures the participant's ability to ignore irrelevant information such as the physical color of a word while stating which color the word says (i.e., a red text that says blue). The go no-go task is also designed to measure inhibitory motor control by having two or more stimuli with one being the "go" response and the second being the "no-go" response. The participant must react each time the "go" stimuli is presented and must inhibit that response whenever the "no-go" stimuli is presented. This gets more difficult as a greater number of "go" stimuli are presented in a row.

This aspect of EF is very important as it has also been linked to the emotional regulation of preschool aged children. In a study looking at 53 preschool children ages 4-

and 5-years-old, Carlson and Wang (2007) found that in tasks designed to measure inhibitory control and delay of gratification children who scored higher had a better emotional understanding while also displaying fewer negative expressions when presented with a disappointing gift. These results are supported by Hudson and Jacques (2014) who conducted a study with 107 children ages 5 to 7 years old. They found that inhibitory control and age were significant predictors of the effort that was put in to regulating emotion and whether or not a child was able to successfully regulate their emotions.

The development of inhibitory control and emotional regulation at this age also has lasting impacts on the social success of children as those with higher inhibitory control and emotional regulation skills are more likely to be preferred by their peers. Nakamichi (2017) conducted two studies using Stroop-like tests that demonstrated how those with high inhibitory control or emotional regulation had better peer relationships. In their first study, they looked at 66 children who were approximately 6 years of age and found that when children were rated with higher scores in either inhibitory control or emotional regulation, they were more popular with their peers than those children who had lower scores. The second study ($N = 43$) showed that those with higher inhibitory control/emotional regulation were able to select appropriate responses to a situation even when it was disappointing or there was a negative emotion introduced and tended to have more mutual friendships than the children who had low inhibitory control or emotion regulation. However, these two studies may not generalize to other cultures. All participants in these studies were middle-class Japanese children whose cultural experiences are very different from western countries and even other Asian countries.

Working Memory

Working memory is also a very important aspect of EF. It is the ability to hold information in your mind and mentally manipulate it (Barac et al., 2014). This aspect of EF plays key roles in learning and developing academic skills, such as reading and math (Gathercole et al., 2016). One very common test that is used to measure an individual's working memory is the self-ordered pointing test (SOPT; Cragg & Nation, 2007; Petrides & Milner, 1982). A SOPT generally consists of a grid of pictures with familiar objects or symbols of which the participant points at one of them. Each subsequent trial, the pictures are the same, but they are in a different spot on the grid and the participant must point to a different picture from the ones previously selected. This is a good test of one's working memory as it requires the participant to organize and carry out a sequence of responses as well as retain and monitor previous responses. It is also flexible in difficulty by lowering or raising the number of picture choices, so you can adjust for different ages and cognitive developmental levels.

There are many benefits to aiding the development of working memory, including helping groups such as children who have attention-deficit/hyperactivity disorder (ADHD) or pediatric bipolar disorder, two groups who tend to have significant working memory deficits (Passarotti et al., 2016), improve their cognitive performance. In a recent study conducted by Passarotti et al. (2020), they found that in their sample of 29 children ages 10–19, all of whom were diagnosed with either pediatric bipolar disorder, ADHD, or both, cognitive working memory training helped to improve their performance on several different tasks. Both groups improved on the Cogmed working memory tasks and the digit span task which also measures working memory. The pediatric bipolar group also improved in several subscales of the parent report version of the Behavior Rating Inventory of Executive Function (BRIEF) including the inhibition scale, behavior regulation index, and global executive functioning composite. However, they did not significantly improve on the stop signal task which is specifically designed to test inhibition. These conflicting results are interesting and suggests that there may be an underlying reason which would cause the parent to see an improvement in inhibition but for it not to show up in the inhibition task. The ADHD group significantly improved on different tasks including the spatial spans task and the reading fluency task which lends support to working memory being associated with academic skills and how the reading skills improved after doing the working memory training. This demonstrates the importance of supporting the working memory development in children in order to facilitate success in academics and social situations.

Cognitive Flexibility

Cognitive flexibility is the ability for an individual to adjust to changes in demands or priorities and to switch between goals (Barac et al., 2014). One common task used to test the development of cognitive flexibility is the flexible item selection task (Jacques & Zelazo, 2001). In this task, the participants are first required to select two cards out of a possible three. The two cards must match each other on one dimension. This first section measures the ability for abstract thought. Second, the participants are asked to select two more cards that match on a different dimension which requires one card to be reused. This second section measures the cognitive flexibility of the participant because it requires them to use the same card but flex their thinking to a different aspect of that card.

Much like the other components of EF, improved cognitive flexibility can lead to improved performance in academics. In a study examining cognitive flexibility and reading comprehension, Colé et al. (2014) found that flexibility significantly predicted reading comprehension skills in a sample size of 60 second-grade French children. They also noted that cognitive flexibility is especially critical when tasked to read an isolated word. This study shows how important promoting cognitive flexibility is to the development of academic skills like reading. However, their measures of flexibility were limited to matrix classification tasks, which requires the participant to simultaneously process two different dimensions. There could potentially be stronger support for the association between cognitive flexibility as a whole and reading comprehension skills if the research were to include a task that tested the ability to switch between two different criteria such as a card sort task. This would allow any differences to be measured and show if there is a difference in reading skills between those two different measures of cognitive flexibility.

In a meta-analysis conducted by Yeniad et al. (2013), it was found that cognitive shifting ability was significantly associated with both math ($k = 18$, $N = 2{,}330$) and reading ($k = 16$, $N = 2{,}266$). Intelligence however, measured using both verbal (e.g., Peabody Picture Vocabulary) and nonverbal (e.g., Raven's Metrics) tasks, was found to have a stronger association with both math and reading abilities than shifting ability. This is understandable as Yeniad et al. also found a strong, significant association between cognitive shifting ability and intelligence, meaning that those children who performed better on the shifting tasks tended to also perform better on the intelligence tasks and vice versa.

Bilingualism and Executive Functioning

Bilingualism can be a very complex construct and is not always clearly defined. Definitions of what constitutes being bilingual can change depending on age. For example, very young children may be considered as bilingual if they receive an appropriate amount of exposure to a second language whereas more weight would be given to level of fluency including receptive language, expressive language, reading and writing skills for older youth and adults. One common conceptualization of bilingualism is that it is on a spectrum (Beardsmore, 1986). On one end, you have a monolingual individual who has very limited to no exposure or experience with a second language, and at the other end you have a synchronous bilingual who grew up with equal exposure to both languages and is considered to have native-like fluency in both languages. Similarly equal exposure to both languages is the best way to assure that a child will successfully acquire both languages (Thordardottir, 2011). However, attaining this perfect balance is very difficult due to the tendency for more exposure to one language from the primary caregiver, or limited exposure to the adults who are providing second language exposure (e.g., grandparents, childcare).

Children who are classified as bilingual generally receive this classification based on parents' report of their children's use and exposure to both languages. The questions parents are asked focus on what language(s) a child uses in what contexts and which family members typically speak to the child in each language (Anderson et al., 2018; Singh et al., 2015). Parents are often asked about outside exposure such as at school or childcare and media exposure such as through social media, television, and books (Anderson et al., 2018). These parent report questionnaires can be useful in learning about the language exposure of a child especially if multiple language pairings are present; however, these types of questions do not assess the actual language skills of children.

Support Against a Bilingual Advantage in Executive Functioning

While bilingualism is a heavily studied and growing field, evidence for an effect of bilingualism on cognition has been seen (see Bialystok, 2017, for a review). In contrast, some research has documented null effects or even an advantage for monolingual children. The results from a recent study conducted by Dick et al. (2019) suggest that there was little to no evidence of a bilingual advantage in the EF skills of inhibitory control, attention shifting, and cognitive flexibility. Furthermore, their research suggests potential disadvantages in English vocabulary for bilinguals. The large sample (*N* = 4,524) of 9- and 10-year-old children and inclusion of multiple EF measures (i.e., Dimensional Change Card Sort task (DCCS), Flanker task, and Stop signal task) are strengths of this study. Dick et al. found a significant bilingual advantage in bilingual status predicting the scores on the Flanker task which tests the child's ability to ignore irrelevant information, however when English vocabulary and demographic variables were controlled for, they failed to find any significant advantage and even found disadvantages for bilinguals in the reaction time of the stop signal task which is designed to measure inhibitory control.

A second study, conducted by Arizmendi et al. (2018) used a smaller sample (*N* = 247) with a similar age group of children 7 to 9 years of age. The bilingual group were all Spanish-English bilinguals. Similar to Dick et al. (2019), they also found null results in their battery of seven executive functioning tasks, with two tasks designed to test updating skills showing a significant advantage for the monolingual participants. This study shows that if there is a bilingual advantage in EF it is not found across all circumstances and that there may even be factors of EF that monolinguals have advantages when compared to bilinguals. However, there are potential explanations for their lack of finding an advantage for bilinguals. The Arizmendi et al. sample was from southern Arizona where part of the bilingual group came from a community where over 70% spoke Spanish primarily and the other part came from a community where just over 20% spoke Spanish primarily. These differences could contribute to a lack of opportunities for children to practice shifting between their two languages. However, the authors did not report within group differences among participants from the two different locations.

A third study supporting a lack of bilingual advantage in EF was conducted by Loe and Feldman (2016) who examined preschoolers born preterm (*n* = 82) and full term (*n* = 79). The preschoolers in their study were rated as bilingual or monolingual based on their language exposure. Loe and Feldman (2016) used both parent report and objective tasks to measure child inhibition, working memory, and cognitive flexibility. Preterm children had significantly higher parent-rated EF scores and performed poorer on the objective EF tasks than their full-term peers, both of which indicated more struggles with EF skills. However, they did not find significant effects of language status (monolingual or bilingual) on EF skills, including birth group by language status interactions suggesting that bilingualism may not have as strong of an impact on child EF as originally thought, especially when compared to the impact on cognitive development that shorter gestation periods may have. However, the researchers operationalized bilingualism as having at least 10 hours of cumulative exposure to two languages at home. Using a more robust measure of bilingualism may have differing results.

Support for a Bilingual Advantage in Executive Functioning

As mentioned previously, there is much support for the existence of the bilingual advantage in preschoolers. Castillo et al. (2020) conducted a study examining the developmental trajectories of EF with 7,846 children who were split into three categories, monolingual (*n* = 7,095), bilingual (*n* = 522), and English language learners (*n* = 229), They used the numbers reversed task to test child working memory and the Dimensional Change Card Sort task to test cognitive flexibility along with teacher report of children’s self-control, attention level, and inhibitory control. Latent growth curve models indicated that those who were English language learners start off with lower initial EF skills but had steeper growth curves than monolingual children. Bilingual children started off similarly to the monolingual children but also had steeper growth curves. The teachers rated the bilingual children as having higher perceived EF skills than the monolingual and English language learner children. This study suggests that there are differences between groups of children who grew up being exposed to multiple languages, monolingual children, and those who are learning a second language at an older age.

A second study, conducted by Tran et al. (2019), also provides evidence for a bilingual advantage in EF while also including a cultural component. They studied 96 children who were 3 years old from three different countries (United States, Argentina, and Vietnam) and six different language categories (Spanish, English, or Vietnamese monolingual or Spanish/English, Vietnamese/English, and Vietnamese/Cantonese). Tran et al. used four different tasks to measure the inhibition, working memory, behavioral regulation, and cognitive flexibility aspects of EF. Their results suggest a bilingual advantage for the cognitive processes that involve selective attention, switching, and inhibition. The effect of culture was most pronounced on the EF skills related to behavioral regulation and response inhibition. The authors point out the cultural difference and suggest that “response inhibition processes may be more sensitive to ‘tightly integrated’ collectivistic qualities” (Tran et al., 2019, p. 727). Even though they share similar collectivistic qualities, this would be more apparent in Eastern cultures compared to Latin cultures because of the influence of individualism in Latin cultures.

A third, interesting longitudinal study on the effect that growth in bilingualism has on EF was conducted by Crivello et al. (2016). They tested a total of 92 bilingual (French/English; 24 months at time 1) and monolingual (English; 23.18 months at time 1) on executive functioning (2nd time point) and language (both time points). The executive functioning measures included the Reverse Categorization task and Shape Stroop task designed to test inhibitory control and cognitive flexibility, the Gift Delay task which tests delay, and the Multilocation task which tests response control and working memory. The language task tested expressive vocabulary and transition equivalents between French and English. Bilingual children performed significantly better than the monolingual children after the switch between task rules for the Reverse Categorization task indicating that bilingual children are better able to shift their thought processes. No differences were found between monolingual and bilingual children on either the delay or working memory/response inhibition tasks. Within the bilingual group, larger increases in translation equivalents significantly predicted better performances on the conflict tasks but not the delay tasks. These findings lend support to the idea that an EF advantage for bilinguals may not be encompassing of every aspect of EF.

A lack of bilingual advantage on the delay and working memory EF tasks is, however, not consistent across the research literature. Morales et al. (2013) found that bilingual children outperformed monolingual children in a Simon-type task that manipulated the working memory demands. This study was followed up by a second larger study using a visuospatial span task that also found a bilingual advantage in working memory. For both studies, Morales et al. found that bilinguals outperformed the monolinguals overall but that for the tasks that required activation of additional aspects of EF they performed even better. This suggests that there can be an advantage for working memory but that it is more evident when the tasks require more than just working memory. A bilingual advantage in working memory was also not found by De Cat et al. (2018). In their study, short term memory was the only significant predictor for working memory and bilingualism and SES were not related to working memory. Therefore, it may be that there is not a bilingual advantage in working memory.

However, bilingualism has been shown to have an effect on the executive function of preterm born children (Baralt & Mahoney, 2020). This is in opposition to the previously mentioned study conducted by Loe and Feldman (2016) who found no evidence for a bilingual advantage in their sample of pre- and full-term children. Baralt and Mahoney utilized two tasks of EF, the Flanker task and Simon task which measure response inhibition and conflict resolution respectively. They found that the preterm bilingual children scored significantly better than their preterm monolingual counterparts on the Flanker task and were also faster and more accurate on the Simon task. However, those differences were not statistically significant. All bilingual children were Spanish/English bilingual and categorized as simultaneous bilinguals, meaning they learned both languages concurrently. This measure of bilingualism is more direct than the one used by Loe and Feldman, which lends greater support for these results. Because of the significant advantage for the bilingual population found in this study, it is plausible that bilingualism may be a protective factor and help with the development of EF in at risk populations such as those born preterm.

In the study of bilingualism, tests have generally been of a visual picture-based nature. However, the bilingual advantage in EF may not be limited to verbal auditory or picture tasks only. In a study conducted by Foy and Mann (2014), they found that young

Spanish/English bilinguals had faster reaction times than the English monolingual counterparts in additional blocks of a nonverbal, auditory go/no-go task which was designed to measure cognitive flexibility after switching targets. However, there were no significant differences between the groups when the task was a verbal auditory go/no-go task. This suggests that early bilingualism may assist in completing non-verbal auditory tasks which require the use of cognitive flexibility. It also suggests that while there may or may not be a bilingual advantage in EF when visual stimuli are used, there could potentially be a different area in the brain connected to auditory processing that may contribute to a possible bilingual advantage in EF.

Predictors of Executive Functioning

When studying EF, it is important to control for various factors that may influence the acquisition or level of EF skills in early childhood. If left unaccounted for, there is the potential for confounds that are not conducive of a direct bilingual advantage on EF. Presented below are known predictors of child EF including SES, level of parent education, child sex and age.

Family Factors

Socioeconomic Status

SES is one of the few known predictors of child EF. In a sample of 114 middle class Canadian mother-child dyads, Rochette and Bernier (2014) found a positive correlation between familial SES and two aspects of EF, impulse control, and conflict EF. This shows that children from higher SES homes are better able to control impulsive reactions and manage salient conflicting items in order to respond appropriately than children from lower SES homes. Rochette and Bernier also looked at maternal parenting quality and its effect on child EF. They found that many domains of maternal behaviors were significantly related to conflict EF but had no significant or marginal relations with impulse control. These results are supported by Bernier et al. (2010) who also found that maternal parenting behaviors were significantly related to conflict EF but not impulse control. Interestingly, Rochette and Bernier found that high quality maternal behaviors were a protective factor for children's EF in lower SES households but that maternal behaviors were not significantly related to child EF in higher SES households.

Additional support for the impact of SES on child EF is provided by Sarsour et al. (2011) who found that in their sample of 60 families, SES was a positively correlated with and a significant predictor of all three components of EF, inhibitory control, cognitive flexibility, and working memory. After controlling for single parenthood and child age, SES was still a modest predictor of child EF skills. Single parenthood was not a significant predictor for child EF after controlling for age and SES. However, when included in analyses as a moderating factor, single parenthood affected the associations between SES, inhibitory control, and cognitive flexibility but not working memory. This effect between lower SES, inhibitory control, and cognitive flexibility was exacerbated by single parenthood meaning that children with one parent who were from lower SES homes performed significantly worse than the children of one parent who were from higher SES homes. This is understandable as parents from lower SES homes and especially single parents may be more focused on providing for their family rather than optimizing child development when compared to parents of a higher SES.

Parent Education

Apart from its inclusion in SES, parent education individually is also a known predictor of child EF. In a sample of 186 third through sixth graders, van Tetering & Jolles (2017) found that children who had at least one parent with a high level of education (i.e., above vocational school) had significantly better planning and initiative taking skills as reported by parents and teachers on the Amsterdam Executive Functioning Inventory (AEFI; Van der Elst et al., 2012). However, there were no significant differences between groups on the other two sections of the AEFI; attention and self-control/self-monitoring. The total scores for the AEFI were approaching statistical significance with a p-value of .04, but due to the use of the modified Hochberg correction to correct for Type-1 errors, the level of significance was set to a p-value of .03. This study shows that there can be differences between levels of parents' education and children's EF, however, including objective tasks designed to measure EF (e.g., Stroop color and word task, SOPT) rather than solely relying on parent/teacher report measures may provide a stronger basis of support or show other areas of child EF that differ based on parent education.

Parent education and child EF associations were also found in a study conducted by Ardila et al. (2005). In their sample of 622 children, the type of school that each child attended (i.e., private or public) was significantly related to the level of parent education. In turn, level of parent education was significantly correlated with six out of eight EF subtests for both age groups tested (i.e., 5-6 and 13-14). These subtests measured verbal and graphic fluency, cognitive flexibility, inhibitory control, and working memory. Of the two uncorrelated tasks, both groups showed no association with the Mexican pyramid task, testing problem solving ability, but differed on the second task they were not associated with. For the younger group, the task that parents' education was not correlated was a matrix classification type task testing cognitive flexibility which is understandable as they tend to be more difficult for younger children. However, the task that the older group was not correlated with was the card sorting task, testing working memory, which is also understandable as that task tends to be less difficult for older children which would suggest that education would not factor into those results. The type of school was also significantly associated with scores on the EF tests where children who attended private schools tended to score higher on all tasks except for the card sorting measure. However, age was significantly associated with all eight tasks which suggests that age may be a more important factor in determining skills in cognitive flexibility than type of school.

A third study, conducted by Schady (2011), also provides support for the influence of maternal education on the cognitive development of children using a sample of 2,118 children from rural Ecuador. They also included the father's education level which significantly predicted children's visual integration. Mother's education significantly predicted all parts, vocabulary, memory, and visual integration when only the sample without any missing data was included in the analyses. Mother's vocabulary, measured by the Spanish version of the Peabody Picture Vocabulary task, was also a significant predictor of all the cognitive function tasks. Mothers' schooling also significantly predicted children's performance on various academic achievement tests which include letters and words, math, and numeric series.

Sex

Sex is a third predictor of executive functioning skills. In a sample of 237 children and young adults ages 7–18 with autism spectrum disorder, White et al. (2017) found that parents, using the BRIEF, rated their female children as having more executive functioning problems than male children. The female children also exhibited more difficulties on the daily living scales domain on the Vineland adaptive behavior scales. While the sample in this study was non-normative, it shows that there can be sex differences with executive functioning skills. However, the measure of EF used in this study was a parent report survey which may be more subjective than other measures of EF.

Van Tetering and Jolles (2017) also found sex related differences in the self-control and self-monitoring scale of their EF inventory. However, their results differed from the previous study in that the female participants scored significantly higher on that section than the male participants did. The inconsistency between studies suggests that there may be other factors outside of child sex that moderate or mediate the influence of sex on executive functioning. A recent review by Grissom and Reyes (2019) suggests that there may not be differences in EF skills based on sex. However, much of the research reviewed was conducted on males which potentially fails to adequately identify circuitry or brain chemistry differences that are unique to females and may account for some differences in EF based on sex. They also suggest that while there may not be performance differences in EF between the sexes, there could potentially be differences in structural brain development or pathways in which EF is developed or used. Overall, more research is needed to determine if there are EF differences between males and females.

Age

Age is very relevant to EF skills, especially in young children. In their sample of 60 families with children ages 8–12, Sarsour et al. (2011) found that there was a significant age-related difference in inhibitory control capabilities. The older children were more able to control their dominant response. Inhibitory control was measured using the classic Stroop color and word test which is a very common and recognized task of inhibitory control. There were no correlations between age and working memory and cognitive flexibility, however, a small sample size and the range of ages may be a contributing factor to not seeing differences.

There is much more support for age related differences provided by van Tetering and Jolles (2017). They found that on two out of the three scales on the EF inventory, there were significant improvements from third to fourth grade and from fifth to sixth grade. This was also supported by a significant improvement between grades for the total EF score. There is however a limit to how much people improve in EF skills as they age. As people reach older age, cognitive functions begin to slow leading to decreased performance in EF skills. This is shown in a longitudinal study conducted by Fjell et al. (2017), who found that in their sample of 119 young, middle-aged, and older adults that there were unique age-related reductions in EF over and above the changes in basic cognitive functions. Longitudinal declines in EF can be contributed to both functional and structural changes in brain connectivity, however only the structural changes can be attributed to the specific age-related declines in EF (Fjell et al., 2017). Taken together, these studies suggest that age should be accounted for when examining EF skills in children.

Functional Magnetic Resonance Imaging and Electroencephalography

Functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) are two different ways in which brain activation is measured. fMRI uses a static magnetic field which allows for the changes in cerebral blood flow to be measured. EEG uses electrodes to measure the electrical activity in the brain. However, both methods have been used extensively in research surrounding bilingualism and the bilingual advantage in EF. Presented below are studies which have used fMRI or EEG to explore bilingualism and EF.

fMRI

In a study conducted by Coderre et al. (2016), they found that in their sample of 15 monolingual and 14 bilingual young adults there were differences between groups in areas of activation during a linguistic and nonlinguistic flanker type task testing inhibitory control. Participants first completed a digit span task measuring working memory where there was a slight monolingual advantage. This is consistent with previous literature suggesting that bilingualism may not facilitate an advantage in working memory. However, after a conjunction between fMRI brain activation data from the flanker tasks and a semantic categorization task bilinguals showed an overlap in activation in the left inferior frontal gyrus whereas monolinguals did not. This suggests that learning a second language may selectively alter brain regions involved in language processing, linguistic, and non-linguistic control allowing for joint activation during executive control tasks.

A second study conducted by de Bruin et al. (2014) found that in their sample of 27 trilingual university students, language switching caused activation in the right inferior frontal gyrus and pre-supplementary motor area which are two regions associated with domain-general inhibitory control. These activations were more pronounced when each participant was required to use their second or third language compared to no-switching or switching to their first language. These results suggest that switching languages recruits brain regions related to general inhibition and that multilinguals use inhibitory control when switching languages. This may help explain a potential bilingual advantage in inhibitory control.

Electroencephalography

Differences in brain activation between monolinguals and bilinguals have also been seen in studies utilizing EEG. In a study conducted by Grundy et al. (2017), they found that their bilingual participants ($n = 20$) had more complex EEG brain signals in their occipital regions than their monolingual participants ($n = 20$). Both groups performed similarly on the switching task, which measured cognitive flexibility, however the multiscale entropy, derived from EEG measures, show that the bilingual group have more complex activations than the monolingual group. These results suggest that bilinguals may be more reliant on automatic resources and less reliant on frontal resources than monolinguals. Greater brain signal complexity is also believed to allow for faster switching of brain states which may facilitate a bilingual advantage in cognitive flexibility.

Functional Near-Infrared Spectroscopy

When compared to adults, the study of children is much more difficult. This is especially true with brain imaging as many of the previously available methods required minimal movement which is difficult for young children. The creation and subsequent development of fNIRS has helped to alleviate some of these concerns. fNIRS as a method of studying brain activation has been around since 1992, however it has undergone many different changes in its functionality (Ferrari & Quaresima, 2012). The first fNIRS studies in 1992, conducted independently by Chance, Kato, Hoshi, and Villringer, were completed using a device that was able to only collect one channel of data (Ferrari & Quaresima, 2012). By 1999, the amount of channels was 64 in a device used for adult optical tomography and the first commercially available units were released (Ferrari & Quaresima, 2012). In 2011, NIRx Medical Technologies released a commercially available wireless unit for adult frontal cortex imaging that allows for 256 channels of data collection. This advancement from one channel to 256 channels has allowed for imaging larger areas of the brain as well as how different areas of the brain work together helping to further develop our understanding of cognitive activation.

In brain imaging, fNIRS is preferential for use with young children because it is fairly inexpensive, does not have an operating noise and is less intrusive than other methods such as fMRI and EEG (Karmiloff-Smith et al., 2014; Quaresima & Ferrari, 2019). Aside from less operating noise and intrusiveness, fNIRS has other advantages over fMRI including portability, due to advances in technology where devices have become battery operated, and being less susceptible to movement which has allowed for outdoor studies and studies involving movement and brain activation (Ayaz et al., 2013; Balardin et al., 2017; McKendrick et al., 2016, 2017). There is also the capability for fNIRS to be used with other imaging modalities such as fMRI and EEG. However, there are also some disadvantages with fNIRS. One main issue is that fNIRS is limited in the amount of cortical information it can provide compared to fMRI which can measure the whole brain (Scarapicchia et al., 2017). These same limitations apply to the depth into the brain that fNIRS devices are capable of measuring. To date, a small number of studies have looked at prefrontal activation during EF tasks with children. However, it is a growing field of study with greater interest being shown. Presented below is some of the more recent literature examining fNIRS imaging and different components of EF in children.

fNIRS and Executive Functioning in Children

In a study conducted by H. Li, Wu, Yang, and Luo et al. (2021), they found that children who did not use tablets scored a significantly higher correct rate on the Dimensional Change Card Sort task (DCCS), which is designed to test working memory and cognitive flexibility, than those who had heavy tablet use. They also found that the groups differed significantly in the activation of Brodmann area 9, which is one of the areas that has previously been linked to EF in preschool children (H. Li, Wu, Yang, & Xie et al., 2021; Xie et al., 2020). This is interesting because it suggests that there may be a difference in brain activation based on tablet use. Their sample consisted of 38 preschool children aged 4 to 6. The children were split into three groups, non-user (*n* = 8), low-user (*n* = 14), heavy-user (*n* = 16) based on the parent responses for the Home Learning Environment and Practice Survey that was modified for Chinese contexts (H. Li, 2013). For their analyses, they did not include the low-user group and only compared results from the non-user and heavy-user groups. This is the most likely comparison that would show differences; however, it would be ideal to see if any sort of tablet use in early childhood affects EF and brain activation or if it is associated specifically with heavy usage.

A second, longitudinal study conducted by McKay et al. (2021) provides fNIRS evidence for age and schooling related increases in EF skills. In their sample of 80 children with an average age of four and a half at time point one, they found that one year later, those who moved from kindergarten to formal schooling (*n* = 40) showed a greater change over time in the bilateral frontal cortex activation for response monitoring compared to those who stayed in kindergarten (*n* = 40). They also found fNIRS evidence for a change in left frontal activation which was positively associated with increased performance in math. The task used for EF was a Go/No-Go task designed to test response inhibition and response monitoring. There was no evidence for group specific differences on performance and blood flow for response inhibition, however both groups did improve between time points. This is interesting as it suggests that response inhibition develops more with age as opposed to level of schooling.

Creativity has also been linked neurologically to executive functioning in early childhood. Wang et al. (2021) found that in their sample of 26 preschool children, those who had strong recruitment of their ventrolateral prefrontal region during the post-switch phase of the DCCS (i.e., switching from matching based on one criterion to matching based on a different criteria) also had heavy activation on the Unusual Box Test which is designed to test creativity. They however did not find any significant associations between scores on the two tasks. This suggests that even if creativity and EF skills as a whole are not related, developing cognitive flexibility may help to support creativity and vice versa because they activate the same area in the brain.

Bilingualism and fNIRS

Even fewer studies have used fNIRS with bilingual children. These studies will be reviewed below. In a study conducted in China, Xie et al. (2021) found that English ability in Chinese preschoolers was significantly correlated with their working memory and cognitive flexibility performance on the DCCS and also predicted their grouping (pass or perseverate) category. The pass group included 25 children who passed all testing items while the perseverate group included 20 children who missed at least two consecutive items during the test. The group placement along with English ability was also significantly correlated with prefrontal activation (fNIRS data) during the DCCS task where more activation was present in the pass group. An additional finding from Xie et al. is that the ages between groups were significantly different. Those in the pass group were significantly older than in the perseverate group which is consistent with previous literature (e.g., Sarsour et al., 2011) showing that age is associated with EF skills.

The second study, conducted by Moriguchi and Lertladaluck (2020), looked at a sample of 24 preschoolers who attended an international nursery school in Japan. The children's first language was Japanese, however most schooling was conducted in English. All children were given the English and Japanese fourth edition of the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007) as measures of receptive vocabulary in order to calculate the child's verbal age. EF skills were measured using a modified version of the DCCS. The DCCS included 3 different phases, pre-switch (one category), post-switch (opposite category), and mix (both categories). fNIRS data was collected during the task. Japanese verbal age was marginally correlated with the post-switch phase and significantly correlated with the mix phase. It was not correlated with the pre-switch phase. English verbal age was significantly correlated with correct performance on the pre-switch phase but not the other two. The fNIRS data shows that the right lateral prefrontal region was activated during the DCCS task however, no significant correlations between English verbal age and brain activation were found. This suggests that second language exposure may not necessarily be associated with activation in that particular region of the brain.

A third study conducted by C. Li et al. (2019) looked at differences in performance and brain activation between English as a foreign language bilingual (*n* = 25) and Chinese monolingual (*n* = 66) kindergarten children (about 74 months of age). Language proficiency was measured using the PPVT Revised and general intelligence was measured using the Combined Raven's Test-the-City in China. EF skills were measured using the Head-Toes-Knees-Shoulders task (HTKS) which measures inhibitory control, cognitive flexibility, and working memory. They used a classical flanker task that measures attentional control during the fNIRS imaging where the experimental condition required the children to ignore irrelevant stimuli. There were not between group differences on the HTKS. However, the bilingual children performed more accurately on the attentional control measure and also showed greater left prefrontal cortex activation when compared to the monolingual children. The balance in languages for the bilingual children was also correlated with the accuracy and activation. These results support the notion that there may be a bilingual advantage in tasks that require inhibitory control, especially if the bilingual is balanced.

The final study examined alterations in frontal lobe functioning for attentional control due to bilingualism. Arredondo et al. (2017) conducted a study comparing brain activation in Spanish-English bilinguals (n = 13) with age matched English monolinguals (n =14) in a nonverbal attentional control task. English vocabulary was assessed using the Kaufman Brief Intelligence Test (KBIT-2) Verbal Knowledge subtest and Spanish vocabulary was assessed using the Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition. EF skills were tested using the HTKS and attentional control was measured using a similar flanker task as C. Li et al. (2019). There were no differences between groups on language, EF, or attentional control. However, brain activation differed between groups. Bilinguals showed greater activation in the left hemisphere of the prefrontal cortex than monolinguals whereas the monolinguals showed greater activation in the right hemisphere of the prefrontal cortex for tasks requiring selective attention. This is interesting and suggests that there may be some sort of physical changes or different developmental pathways brought on by learning a second language.

The following section includes information on the connection between cerebral blood flow and its relation to EF capabilities. Locations of brain activation during EF tasks can also potentially be seen due to localized spikes in oxygenated hemoglobin, which is recorded with fNIRS.

Cerebral Blood Flow and Executive Functioning

Higher concentrations of oxygen in the brain are key for promoting optimal brain functioning (Amir et al., 2020). Oxygen is transported throughout the body via hemoglobin in red blood cells. Heavy cognitive loads are accompanied by an increase in oxygenated hemoglobin being transferred to the region of the brain that helps facilitate the action being completed (Amir et al., 2020; Techayusukcharoen et al., 2019). Increases in cerebral blood flow may also contribute to an improvement in EF skills. A study conducted by Tari et al. (2020) found that in their sample of 16 college age students, experiencing a 10-minute session of moderate to heavy aerobic exercise as well as a second condition of a hypercapnic environment (i.e., 5% CO_2) for 10 minutes lead to increases in cerebral blood flow. Both conditions also improved participant EF skills for a period of time after completion. EF was measured using the Antisaccades task, which measures inhibitory control, working memory, and cognitive flexibility through tracking eye movements. Results suggest that increases in cerebral blood flow may be a facilitator for increased capabilities of EF skills and that further research should be conducted.

Summary

Developmental cascades iterate that different experiences influence and cumulate to drive development. This theoretical perspective is especially relevant when discussing bilingual exposure in early childhood. Bilingualism and bilingual exposure have been shown to alter brain activation and have also been associated with differences in EF skills between monolingual and bilingual children. One potential cascading influence of early bilingual exposure is the need for a child to constantly inhibit one or more languages. The cumulative experience of this inhibitory action could potentially be an explaining reason as to why a bilingual advantage over monolingual children has been seen in inhibitory control. Similarly, the cumulative experiences of having to cognitively shift between different languages could explain why there may also be a bilingual advantage in cognitive flexibility skills. These connections suggest that there should be a focus on supporting synchronous first and second language development and that there are potential benefits for children who have this support. A second potential cascading influence is that as a child is continuously exposed to a second language, there may be a physical or synapse-based change in the brain resulting in differences in efficiency or location of activation between monolingual and bilingual individuals.

Previous research has shown a positive link between bilingualism and EF. However, there has been recent evidence showing no association. Therefore, the role that bilingualism plays on the development of EF is still unclear and more research needs to be conducted. It is especially important that as new methods of study are introduced and developed, they are utilized in the study of bilingualism and EF development. Thus, the current study will test an underutilized method of study, fNIRS, and look to explore any known and unknown connections between bilingualism, prefrontal cortex activation, and EF skills in order to further the current understanding of bilingualism and EF.

Research Questions and Hypotheses

1. What are the executive functioning abilities of the bilingual and monolingual children in the sample?
2. Is executive functioning related to children's cerebral blood flow (CBF) as measured by oxy-Hb (oxygenated hemoglobin) and deoxy-Hb (deoxygenated hemoglobin)?
3. Is there an advantage in executive functioning skills for bilingual children over monolingual children?
4. Are there differences between young bilingual and monolingual children's cerebral blood flow (CBF) as measured by oxy-Hb (oxygenated hemoglobin) and deoxy-Hb (deoxygenated hemoglobin)?

H1. Bilinguals will show an advantage in some executive functioning skills (inhibitory control, cognitive flexibility) and no advantage in others (working memory) consistent with previous literature.

H2. There will be differences in CBF between young monolingual and bilingual children, specifically bilingual children will have greater activation in the left hemisphere of the prefrontal cortex and monolingual children will have greater activation in the right hemisphere during EF tasks requiring selective attention.

CHAPTER III

METHODS

Participants

Eleven study participants, ages 3-5 were recruited at an on-campus preschool at Utah State University (USU) and within surrounding communities. Five monolingual and six bilingual children and their parents were recruited. This USU preschool program agreed to help with the recruitment for this study and has a relatively high percentage of bilingual language users. The average age at the assessment was 58.5 months (*SD* = 10.6) and 36% of the children were female. The average age of the bilingual group (*n* =6) was 61 months and 55.4 months for the monolingual group (*n* = 5). The difference in ages between groups was not significant. The majority of participating parents had either a masters or doctorate degree (72.6%). Second languages spoken at home include Mandarin (*n* = 3), Portuguese (*n* = 2), and Korean (*n* = 1)

The sample is both homogenous with the majority of parents being very highly educated (i.e., masters or doctorate level) and heterogeneous because of the wide variety of languages and cultures present within the bilingual sample of families. Due to the wide variety of language pairings at this location we have elected to select our sample based on exposure to a second language rather than proficiency with precedence provided in previous research (Loe & Feldman, 2016; Singh et al., 2015; Valicenti-McDermott et al., 2013). For this study, bilingualism is defined as having at least 25% exposure to a second language and monolingualism is defined as having at least 90% exposure to a first language (Pearson et al., 1993).

Procedure

Prior to arriving on campus for the assessment portion of the study, parents completed several surveys at home via REDCap, including demographic information and a language background questionnaire of their children. Upon arrival to USU's campus, the children and their parents were brought to a laboratory setting where the participating children completed a battery of computer-based tasks that are designed to measure EF. A cap with attached electrodes was fitted to the head of the participant who was then assessed with the battery of EF tasks administered by a trained undergraduate research assistant following the protocol laid out by the Frank Porter Graham Child Development Institute. The order the tasks were completed is as follows: spatial conflict arrows, animal Go/No-Go, silly sounds Stroop, something's the same, and pick the picture. Trained fNIRS technicians were present to oversee data collection. After completion of this battery, the children had a short break where they receive a snack of their parents' choice and water. After the short break, children's English receptive vocabulary was assessed. Participating parents received a $50 gift certificate and children received a book valued at $16 for their time.

Measures

Demographics

Demographic data were collected from all parents regardless of child bilingual status. This included child information such as date of birth, gestation period, and the age at which they were enrolled in the on-campus preschool. Parent information included their level of education, language(s) spoken between parents, and information about which language(s) each parent speaks and understands.

Language Background Questionnaire

This language background questionnaire (LBQ) was adapted from a phone-based questionnaire (Singh et al., 2015) and administered over REDCap allowing for easier completion by parents. Only parents of bilingual children were asked to complete the LBQ. The LBQ includes three sections with questions about: child languages, exposure to those languages from family and teachers, and which language(s) a child uses when speaking to different people (i.e., parents vs. teachers). These questions were either short answer or scale-based questions for the parents. Child exposure was based off of the response of the bilingual parent and how much interaction they have with the child. Monolingual children were marked as zero exposure.

Executive Function

The EF touch battery is a computerized battery of tasks designed to test EF in children aged 3-5 years. It was developed at the Frank Porter Graham Child Development Institute at the University of North Carolina. It is composed of seven tasks testing EF and two tasks that are meant as a warm-up/orientation and a gauge of simple reaction time. The entire battery is expected to take between 45-60 minutes to complete with the child. However, we have opted to include only the five tasks described below that are appropriate for the 3-year-old participants. Criterion validity has been established through correlations between a child's performance on the battery and parent-reported ADHD behaviors and the child's performance on two screening indicators of IQ (Willoughby et al., 2010). The individual tasks have a moderate retest reliability of .60 but the full test battery has a strong retest reliability of .95 (Willoughby & Blair, 2011). The names and descriptions for the included tasks are introduced below.

Spatial Conflict Arrows

This is a Simon task that is used to measure a child's ability to inhibit a dominant response. The child is instructed to press the button in the direction that the arrow is pointing. This task begins easily then continuously gets more difficult as the child progresses through the task.

Silly Sounds Stroop

This task is designed to measure inhibitory control in children. It is a sound-based Stroop test where the child is presented with images of a cat and a dog side by side and are instructed to touch the opposite picture to the animal sound that they heard (i.e., when they hear a cat meow they press on the picture of the dog).

Something's the Same

This task is designed to measure attention shifting and requires flexible thinking from the child. The child is presented with two pictures that have similarities along a single dimension, either color, shape, or size. A third picture is then shown, and the child must point out how it is similar to one of the previous two. For the initial tests, the examiner points out the similarity in the first two pictures and the child is only required to do the third picture but as the test progresses the child must point out both the initial similarity and the secondary similarity after the third picture appears.

Animal Go/No-Go

This task is designed to measure inhibitory control and is a standard go/no-go task. The child is instructed to press a green button every time they see an animal, except when they see a pig. This gets more difficult the larger the number of "go" responses there are before a "no-go" response.

Pick the Picture

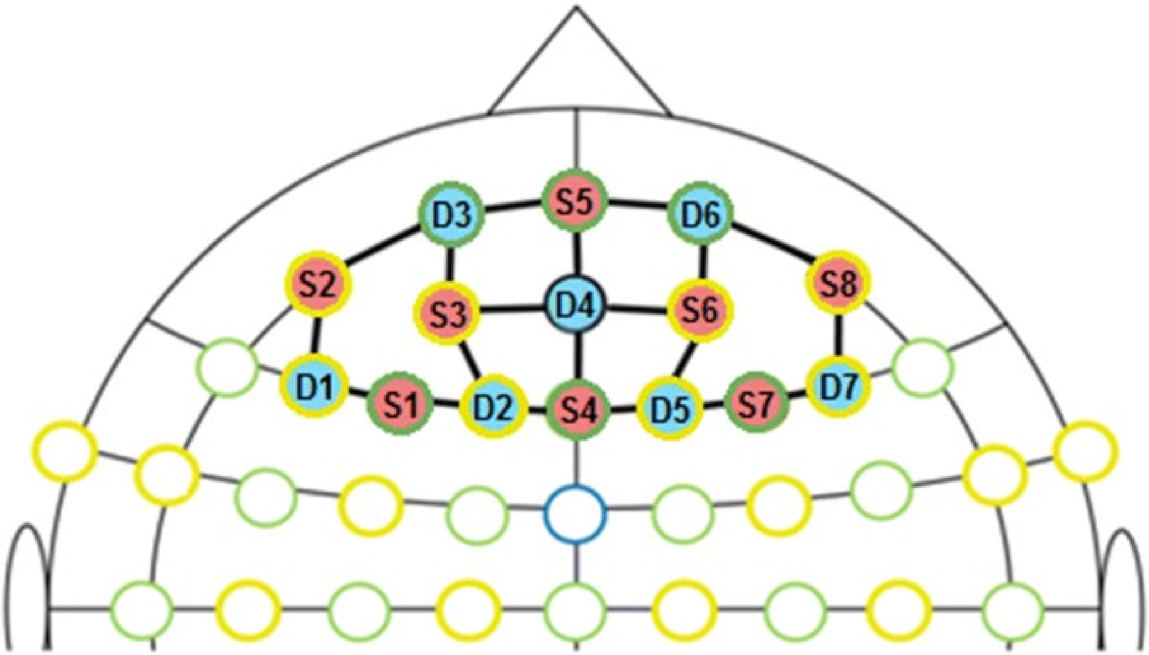
This task is designed to test working memory. Children are presented with a series of continuously larger sets of pictures (2, 3, 4, 6). For each set of pictures, they are instructed to press a picture of their choice. The set is then repeatedly presented with the location and order of the pictures changing each test. The children are instructed to continue touching a different picture each time until they have touched all the different pictures.

Functional Near-Infrared Spectroscopy

fNIRS data for this study were collected using the NIRSport 2 Core System Unit which has eight light sources and eight light detectors while the participants participate in the measures of EF described previously. Using Aurora, sources and detectors were arranged in a geographic montage over the frontal hemispheres (frontal-parietal network) of each participating child, similar to a montage that has been validated using both functional magnetic resonance imaging (Wijeakumar et al., 2015) and fNIRS imaging (Buss et al., 2014; Wijeakumar et al., 2019). The NIRSport 2 device was controlled via the Aurora software provided by NIRx technologies. The geographic montage over the frontal-parietal network is shown in Figure 1. The red circles are light sources, and the blue circles are light detectors. There were eight sources and seven detectors used in this study for a total of 20 channels.

Figure 1

fNIRS Montage



Note. Blue = light detector; Red = light source; Black line = pathway.

Analytic Plan

Outcome measures associated with fNIRS imaging used in analyses include oxy-Hb and deoxy-Hb measures of CBF, resulting from applying the modified Beer-Lambert law statistical algorithm (Ayaz et al., 2009) to the raw fNIRS data. These measures of CBF, especially the deoxy-Hb, are similar to the blood oxygen level diagnostic (BOLD) signal that is used in fMRI (Huppert et al., 2006). Visual representation for each channel of the data was also included for the Arrows and Animal Go/No-Go tasks.

All children who participated were included in the executive functioning analyses. However, one child in the bilingual group was excluded from the brain imaging analyses because they kept pushing the cap backwards causing a change in location of brain measurement.

CHAPTER IV

RESULTS

In this chapter, the results addressing the different research questions are reported. Pre-processing and transformation of the fNIRS data was completed in Homer3 (http://openfnirs.org/software/homer/), an opensource fNIRS toolbox. Block averages were completed in excel. All other analyses were completed using IBM SPSS Statistics for Windows, Version 28.0. Descriptive statistics were performed to examine the executive functioning skills of both groups. Next, bivariate correlations were performed between executive functioning and brain activation to answer research question two. Thirdly, *t* tests were performed on the executive functioning data to answer research question three. Finally, to answer research question four, *t* tests were performed on the brain activation data. For these questions, a *p* value of .05 was used to determine statistical significance.

Question 1

Descriptive statistics for the proportion correct on each task of the executive functioning battery for the full sample ($N = 11$) are found in Table 1. For timed tasks, the average reaction time was also included. However, the youngest participant was unable to complete all five tasks so only the data from the three completed tasks are included. This child was in the monolingual group. The Silly Sounds Stroop task was the task in which participants seemed to struggle the most as indicated by the low average score. This task also had the largest standard deviation of all the tasks. Data for the entire sample for each task, along with data for the monolingual and bilingual groups are pictured in Figure 2.

Table 1

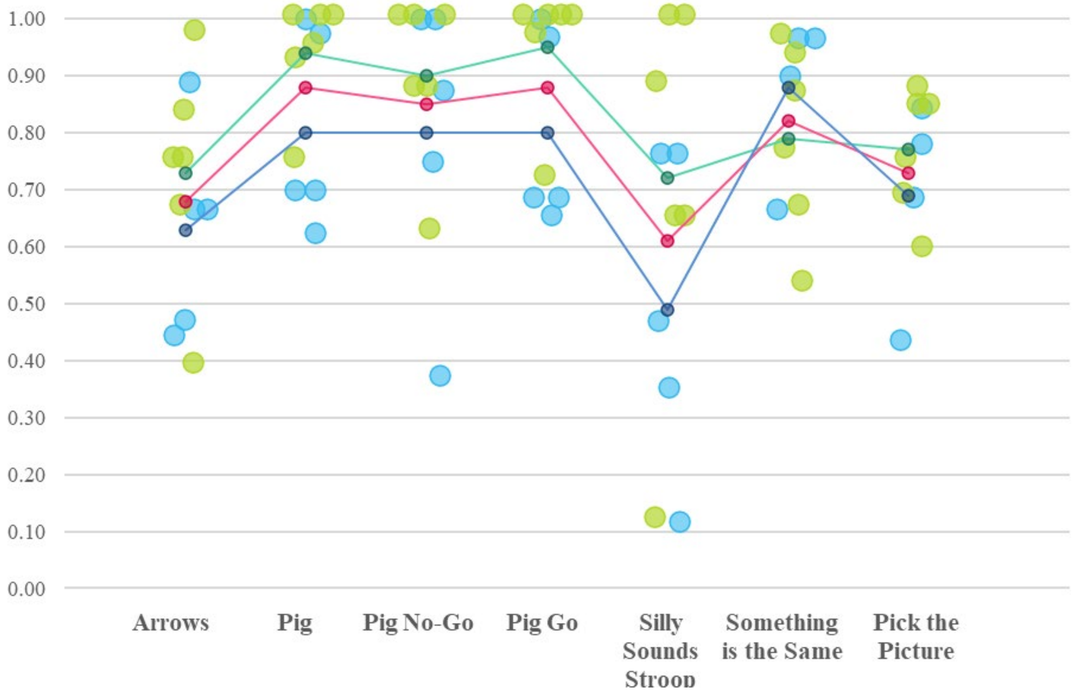
Executive Functioning Descriptive Statistics for Entire Sample

Task	*n*	Minimum	Maximum	Mean	*SD*
Arrow	11	0.39	0.97	0.68	0.19
Pig	11	0.63	1.00	0.88	0.15
Pig No-Go	11	0.38	1.00	0.85	0.20
Pig Go	11	0.66	1.00	0.88	0.15
Pick the Picture	10	0.44	0.88	0.73	0.14
Silly Sounds Stroop	11	0.12	1.00	0.61	0.32
Something's the Same	10	0.53	0.97	0.82	0.16

Note. Scores are a percentage out of 100.

Figure 2

Beeswarm Plot of Participant Executive Functioning Scores



Note. Green is Bilingual; Blue is Monolingual; Red is Total Sample.

Monolingual Group

Descriptive statistics for the monolingual sample (*n* = 5) are presented in Table 2. The participating child who was unable to finish all five tasks was in the monolingual sample so their data for the Something's the Same and Pick the Picture tasks are missing. Interestingly, the task that the monolingual group performed the best on was Something's the Same with a group average score of 88% correct. This is one of the tasks in which the youngest child did not participate which may have skewed the results causing a higher average than otherwise may have been.

Table 2

Executive Functioning Descriptive Statistics for Monolingual Sample

Task	*n*	Minimum	Maximum	Mean	*SD*
Arrow	5	0.44	0.89	0.63	0.18
Pig	5	0.63	1.00	0.80	0.17
Pig No-Go	5	0.38	1.00	0.80	0.26
Pig Go	5	0.66	1.00	0.80	0.17
Pick the Picture	4	0.44	0.84	0.69	0.18
Silly Sounds Stroop	5	0.12	0.76	0.49	0.28
Something's the Same	4	0.67	0.97	0.88	0.14

Note. Scores are a percentage out of 100.

Bilingual Group

Descriptive statistics for the bilingual sample (*n* = 6) are presented in Table 3. Each child was able to complete all five tasks resulting in complete executive functioning data. This group performed well on all five tasks; however, the Animal Go/No-Go task was by far the best. For both parts (Go/No-Go) and the total task, the group had an average score of at least 90% correct along with small standard deviations indicating a tight grouping of results.

Table 3

Executive Functioning Descriptive Statistics for Bilingual Sample

Task	*n*	Minimum	Maximum	Mean	*SD*
Arrow	6	0.39	0.97	0.73	0.20
Pig	6	0.75	1.00	0.94	0.10
Pig No-Go	6	0.63	1.00	0.90	0.15
Pig Go	6	0.72	1.00	0.95	0.11
Pick the Picture	6	0.59	0.88	0.77	0.11
Silly Sounds Stroop	6	0.12	1.00	0.72	0.33
Something's the Same	6	0.53	0.97	0.79	0.17

Note. Scores are a percentage out of 100.

Data Visualization

The descriptive statistics for each task were visualized in the form of a beeswarm plot. A beeswarm plot includes all data points for each measure allowing for the visualization of any potential clustering of groups, differences between groups, and the spread of results within the groups. For this project the green dots represent the scores of each bilingual participant. The blue dots represent the monolingual scores. The smaller dots of the same color that are connected with lines represent group averages.

Question 2

Intercorrelations for child executive functioning tasks are presented in Table 4. Many of the executive functioning battery subscales were significantly associated with each other. Age was also positively associated with three of the five executive functioning tasks, as well as reaction time for the Animal Go/No-Go task. Age was also positively associated with the specific “go” stimuli of that task.

Table 4

Intercorrelations for Executive Functioning Tasks

Task	1	2	3	4	5	6	7	8	9	10
1. Age	--									
2. Arrows	.47	--								
3. Arrows reaction time	-.32	-.05	--							
4. Pig	.78**	.73*	-.37	--						
5. Pig reaction time	-.73*	-.30	.16	-.58	--					
6. Pig no-go	.59	.31	-.58	.71*	-.77**	--				
7. Pig go	.75**	.78**	-.26	.97**	-.45	.52	--			
8. Silly sounds	.81**	.34	-.44	.68*	-.64*	.67*	.60	--		
9. Something’s the same	.60	.59	.21	.58	-.47	.43	.54	.63	--	
10. Pick the picture	.67*	.80**	.11	.86**	-.64*	.51	.83**	.62	.74*	--

* = $p < .05$.
**= $p < .01$.

Significant correlations between task performance and the block average of oxygenated, deoxygenated, and total hemoglobin for the Arrows and Animal go/no-go tasks presented in Tables 5 and 6, respectively, for the monolingual group and Table 7 for the bilingual group. Complete tables for all five tasks can be found in Appendices A–E. For both groups, every task except bilingual Arrows had at least one channel with significant activation or deactivation. However, the location of activation and deactivation occasionally differed between group averages on the tasks. For example, in the Animal Go/No-Go task the monolingual group had significant deactivation for both the oxygenated and total hemoglobin for channel 4-4. The bilingual group shows no activation/deactivation in that region of the brain. Alternatively, they show significant deactivation in channel 3-2 with the monolingual group not showing any activation/

Table 5

Monolingual Arrows

Channel	Arrows
HRFHbO21_Arrows	-.97**
HRFHbT21_Arrows	-.90*
HRFHbT42_Arrows	.93*

* = *p <.05.*
** = *p < .01.*

Table 6

Monolingual Animal Go/No-Go

Channel	Pig	Pig No-Go	Pig Go
HRFHbO42_Pig	-0.87	-0.57	-.91*
HRFHbO44_Pig	-.99**	-0.77	-.98**
HRFHbT44_Pig	-.94*	-0.77	-.92*
HRFHbT45_Pig	-.97**	-0.67	-1.00**
HRFHbO65_Pig	-0.76	-0.25	-.89*

* = *p <.05.*
** = *p < .01.*

Table 7

Bilingual Animal Go/No-Go

Channel	Pig	Pig No-Go	Pig Go
HRFHbR32_Pig	-.93*	-0.09	-.95*
HRFHbT45_Pig	-0.76	0.39	-.91*
HRFHbO54_Pig	0.42	.99**	0.13
HRFHbT54_Pig	0.57	.95*	0.3

* = *p <.05.*
** = *p < .01.*

deactivation there. Interestingly, for the Silly Sounds Game, both groups had significant associations in channel 1-1 but the directions were different. The monolingual group showed deactivation in that area, but the bilingual group showed activation in that area. There were also several channels that were very highly correlated but not statistically significant (i.e., $r > .8$ but $p > .05$).

Question 3

One-tail independent samples *t* tests for executive functioning tasks between both groups are presented in Table 8. There were no statistically significant group differences for any of the tasks. However, there were two tasks where the differences between the groups approached statistical significance. The bilingual group scored higher than the monolingual group on the Animal Go/No-Go ($p = .083$) and the specific Go portion of that task ($p = .058$). An *F* test was conducted to determine equality of variances with the

Table 8

Executive Functioning One-Tail Independent Samples t *Tests*

Task	*t*	*df*	*P* value
Arrows	-0.868	9	0.204
Arrows Reaction Time	0.727	5.002	0.25
Pig	-1.574	6.021	0.083^
Pig Reaction Time	0.812	9	0.219
Pig No-Go	-0.775	9	0.229
Pig Go	-1.736	9	0.058^
Pick the Picture	-0.867	8	0.206
Silly Sounds Stroop	-1.18	9	0.134
Silly Sounds Stroop Reaction	-0.544	9	0.3
Something’s the Same	0.844	8	0.212

^ = $p < 0.1$

reaction time for "Arrows" and the total proportion correct for the animal Go/No-Go having unequal variance between groups.

Question 4

Because 300 independent samples *t* tests were conducted, only the 31 tests that were approaching or statistically significant were presented in Table 9. The entire list can be found in Appendix F. The data used for these analyses were transformed to optical density from the raw fNIRS data, then underwent the targeted Principle Component Analyses (tPCA) movement artifact correction to account for participant movement during data collection (Reyes et al., 2018). Finally, the corrected data underwent the modified Beer-Lambert law statistical algorithm to convert the optical density data to numbers of oxygenated and deoxygenated hemoglobin. The activation for each stimulus (executive functioning task) was blocked together for that stimulus, which is known as block averaging. *F*-tests were conducted to determine equality of variance. The results of the t-tests indicate a trend of higher activation in the medial cortex for the bilingual group and similar activation in the dorsolateral cortex with the monolingual group having slightly more activation in those areas.

Data Visualization

Probe maps for both the Arrows and Pig tasks are presented in Figures 3 and 4, respectively. A probe map includes all fNIRS channels that were recorded and displays the data. The time length was 210 seconds for each task. For Arrows, the main channel that suggests a difference in hemoglobin concentration is 3-4 (source-detector). The

Table 9

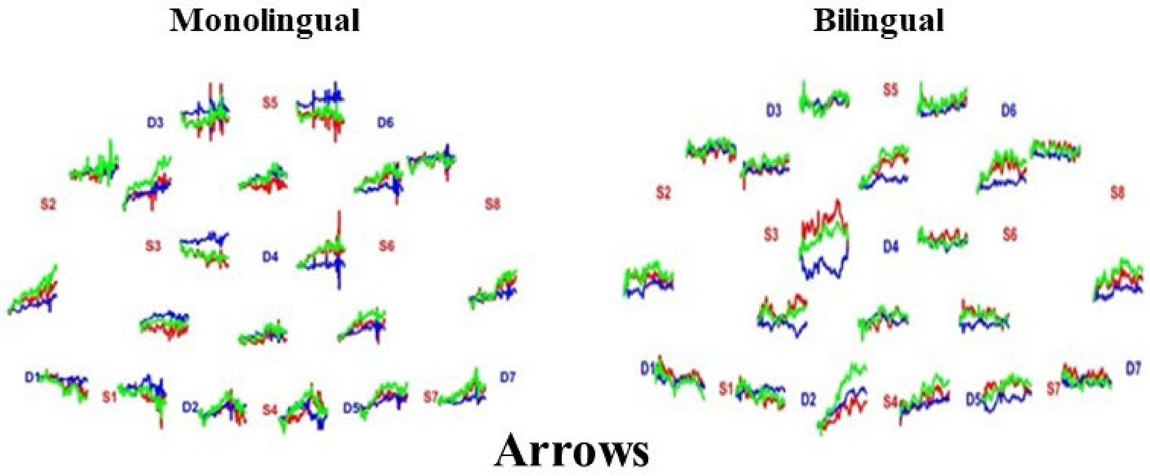
t *tests Among Oxy-, De-oxy, and Total Hemoglobin Levels*

Channels	*t*	*df*	Two-sided *p*
HbO32_Arrow	-1.9	8	0.09^
HbO34_Arrow	-3.59	8	0.01**
HbR34_Arrow	1.96	8	0.09^
HbT34_Arrow	-3.1	4.32	0.03*
HbO56_Arrow	-1.85	8	0.1^
HbR12_Pig	-3.18	8	0.01**
HbO21_Pig	2.06	8	0.07^
HbO23_Pig	2.23	4.57	0.08^
HbR34_Pig	-2.46	8	0.04*
HbR45_Pig	-2.7	8	0.03*
HbR53_Pig	-2.04	8	0.08^
HbO54_Pig	2.66	8	0.03*
HbT54_Pig	2.26	8	0.05*
HbO64_Pig	2.12	8	0.07^
HbO32_SSG	2.17	7	0.07^
HbT32_SSG	2.72	7	0.03*
HbO33_STS	1.97	7	0.09^
HbR33_STS	2.64	4.38	0.05*
HbT33_STS	2.27	7	0.06^
HbR34_STS	-2.05	7	0.08^
HbO77_STS	2.4	7	0.05*
HbT77_STS	2.24	7	0.06^
HbO42_PTP	-2.35	3.82	0.08^
HbR42_PTP	-3.37	7	0.01**
HbT42_PTP	-2.7	4.22	0.05*
HbR54_PTP	2.47	7	0.04*
HbR66_PTP	3.63	7	0.01**
HbO86_PTP	2.02	7	0.08^
HbR86_PTP	2.58	7	0.04*
HbT86_PTP	3.78	7	0.01**
HbR87_PTP	1.9	7	0.1^

^ = $p < .1$.
* = $p < .05$.
** = $p < .01$.

Figure 3

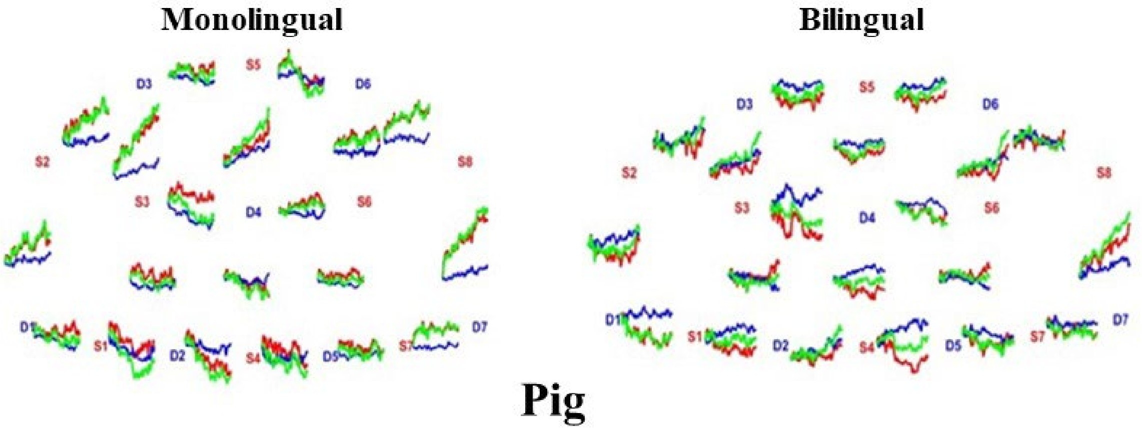
Probe Map for Mono- and Bilingual Performance on Arrows



Note. A positive slope for only the red and green lines show activation in that region.

Figure 4

Probe Map for Mono- and Bilingual Performance on Pig



Note. A positive slope for only the red and green lines show activation in that region.

monolingual group shows strong activation in that region (increase in red/green lines) whereas the bilingual group does not show activation there. Conversely, channel 5-4 for the bilingual group shows activation in that region with the monolingual group showing no activation. For Pig, more obvious differences can be seen. The monolingual group shows activation in channels 2-1, 2-3, 3-3, 6-6, 6-8, 7-7, and 8-7. The bilingual group only shows activation in channel 8-7. Deactivation for the monolingual group is seen in 4-2 and for bilinguals in channel 1-1.

CHAPTER V

DISCUSSION

The first purpose of the current study was to lay a groundwork for continued use of fNIRS as a brain imaging technique with bilingual children. As mentioned previously, the use of fNIRS with bilingual children is limited and further research utilizing the novel method could potentially inform differences in locations and pathways of activation between monolingual and bilingual individuals. The current study sought to further expand the research surrounding bilingual prefrontal cortex use during heavy executive function use. In addition, this study used a unique sample where most of the parents of participating children were very highly educated. This contrasts with most of the immigrant population in the U.S. who generally have lower education and income than the sample in the current study (Camarota & Zeigler, 2016).

The second purpose of the current study was to examine if there is a bilingual advantage in executive functioning with a sample of children who have highly educated parents. Studies on the bilingual advantage are contradictory with some results supporting an advantage and other results supporting a null effect of bilingualism with recent research showing no effect (Gunnerud et al., 2020; Paap et al., 2015). This study extends previous research in that it utilized a novel method with fNIRS while measuring executive functioning skills in groups of bilingual and monolingual children. This novel method allowed for the examination of brain activation during executive functioning tasks to better understand the process of how bilingualism may influence executive functioning.

Executive Functioning Scores and Group Differences

Children performed well on all five tasks. One task of interest, where two children (one in each group) answered only 12% correctly, was the Silly Sound Stroop task. This is interesting as this task also has the largest standard deviation of 0.32 which suggests that there is large variance in scores and that children either performed really well or really poorly on this task. One potential explanation for the low scores is that this task required both cognitive flexibility and working memory because children had to remember both the rule and mentally apply that rule to the activity. Reflecting previous literature, the increased use of those aspects of executive functioning, especially working memory, may have made the task more difficult for the younger participants resulting in a lower number of correct responses (Howard et al., 2015; Simmering, 2012). A second potential explanation for the low scores is that during the task children had to remember the rule which would cause them to hesitate on which choice they picked for the sound. By the time they decided, the next sound stimuli had played causing them to occasionally pick the wrong answer even if they knew the correct answer.

It was also interesting seeing the tendency in average scores between both groups. For all tasks except one, the mean score for the bilingual group tended to be higher than the score for the monolingual group, with the Animal go/no-go and specifically the "go" portion of that task approaching statistically higher scores for the bilingual group. This trend could be attributed to either bilingualism in the form of second language exposure or age differences as the bilingual sample was about six months older than the monolingual sample. The higher averages, however, were also accompanied by lower minimum scores and larger standard deviations on multiple executive functioning tasks. Overall, these base level observations suggest a potential bilingual advantage in executive functioning. However, as stated in hypothesis one, any advantage would not be all encompassing of executive functioning skills but that specific skills (e.g., inhibitory control) would show an advantage which is supported by the results of the Animal go/no-go task approaching significance.

Previous literature is mixed on the existence of a bilingual advantage in executive functioning. Recently, there has been literature showing a bilingual advantage in executive functioning skills (Grote et al., 2021; Grundy & Timmer, 2017; Nayak et al., 2020) as well as literature that has found mixed or null results (Blanco-Elorrieta & Pylkkänen, 2017; Lehtonen et al., 2018; Lowe et al., 2021; Naeem et al., 2018). For example, some research suggests that cognitive flexibility may be an area where a bilingual may have an advantage over a monolingual because of the constant nature of using and switching between both languages (Barbu et al., 2018; Marzecová et al., 2013). However, other research indicates a better performance by monolinguals than bilinguals (Haft et al., 2019; Shokrkon & Nicoladis, 2021). Both Haft et al. (2019) and Shokrkon and Nicoladis (2021) hypothesized that having a larger sample size would lead to a lack of bilingual advantage in cognitive flexibility. This is derived from Paap et al. (2015), who displayed that most studies who have shown a bilingual advantage had small sample sizes (< 30). Additionally, Haft et al. suggest that their method of measuring bilingualism could also affect the results. They used a continuous measurement of bilingualism as opposed to a dichotomous measurement. Overall, there needs to be more research conducted, with larger sample sizes and variability in how bilingualism is measured, to determine if or when a bilingual advantage is present in cognitive flexibility.

If a bilingual advantage is based solely on differences that are statistically significant, then the current study would be considered one of the 80% of recent studies Paap et al. (2015) that found null results for a difference in executive functioning skills between monolinguals and bilinguals. However, when scores between groups are examined visually on a beeswarm plot (see Figure 2), bilingual preschoolers' scores tended to appear higher on average than monolingual preschoolers' scores. There may be several reasons as to why no statistically significant advantage was found between the two groups. One potential reason is that the sample for the current study is too small resulting in an underpowered study and null results for a difference between groups. A second potential reason is that because the sample of parents in this study are more highly educated than typical samples in the existing literature there may be a reason such as better parent-child interactions or more family income influencing the results (Haft & Hoeft, 2017; Helm et al., 2020; Sosic-Vasic et al., 2017). This would be consistent with previous literature which suggests that the bilingual advantage is not all encompassing and that there needs to be specific situations, such as low-income/education, before an advantage is present (Gunnerud et al., 2020; Paap et al., 2015). Overall, more research needs to be conducted with a mix of high- and low-income participants as well as differing parenting styles in order to more fully understand potential situations or interactions where a bilingual advantage can be seen.

Differences in Location of Activation

As mentioned previously, one of the intended purposes of this study was to use fNIRS to look for potential differences in location of brain activation/deactivation between young monolingual and bilingual preschoolers. Previous literature has supported the idea that there may be differences in the location of the prefrontal cortex where activation occurs (Arredondo et al., 2017) during executive functioning tasks. The current study supports this hypothesis as the data suggests location differences in activation and deactivation in young bilinguals and monolinguals. Interestingly, there were some patterns that appeared when visually comparing the significant correlations between groups and tasks.

The main pattern that emerged is that the bilingual group tended to have less deactivation in the medial (middle) area of the prefrontal cortex whereas the monolingual group tended to have more deactivation in that area with similar activations for both groups in the dorsolateral (side) areas of the prefrontal cortex. This is interesting as the medial cortex is responsible for higher level executive functioning (i.e., planning and fluid intelligence) whereas the dorsal lateral area is responsible for lower-level executive functions (working memory, inhibition, cognitive flexibility). This does not support hypothesis two, which stated that bilinguals would have more activation in the left hemisphere of the prefrontal cortex and monolinguals would use more of the right hemisphere during selective attention tasks. This suggests that there could potentially be a reason related to bilingualism that influences where activation occurs. This pattern also provides a possible reasoning as to why there may be a bilingual advantage in executive functions. If bilinguals do recruit the medial cortex with lower-level executive functioning tasks, it may assist the dorsolateral cortex allowing for faster, more accurate processing skills. Overall, more research and a larger sample comparison should be conducted in order to more fully explore this possible pattern to see if there is a difference in brain activation/deactivation during executive functioning tasks and whether bilinguals do recruit more of the medial cortex even with lower-level executive functions.

Limitations

This study should be interpreted with some limitations in mind. First, the sample size is quite small resulting in an underpowered study which may contribute to the null results that were found. A larger sample size would be more ideal and lead to more reliable results. Increasing the sample size would also allow for the use of a general linear model (GLM) with the fNIRS data, which allows for more accurate activation data for variable length trials and allows for the ability to control for co-variates such as age. However, for the current sample size, block averaging is the better option as there is not enough data for a GLM to be accurate. Secondly, there is a six-month age difference on average between groups. Because a large proportion of cognitive development occurs during this time of development (Center on the Developing Child, n.d.), especially with working memory capabilities, this difference may potentially skew the results in the favor of the bilingual sample. Ideally participating children would be age matched in order to remove the confounding factor of age. Thirdly, for research question four, 300 *t* tests were conducted resulting in an increased chance of Type 1 error. To account for this, a statistical correction should be used, however this correction was not used due to the small sample size. There are many options specific to functional neuroimaging data available to correct for multiple comparisons. The method that would be best for this study when a larger sample size is available is a Threshold Free Cluster Enhancement as it has been found to have a better false alarm rate than Statistical non-Parametric Mapping and 3DClustStim (Han et al., 2019). Finally, when collecting the fNIRS data, triggers were only added at the beginning of each task. To make it more accurate a trigger would ideally be added for each stimulus in each task. This would allow for the removal of specific items if there was an issue during data collection on that question.

Strengths and Future Directions

This study is among the first to use fNIRS as a method with young monolingual and bilingual children while examining executive functioning. This novel method has the potential to further the field of bilingual research and provide insight into the reasoning of how and why there may be a bilingual advantage in executive functioning. Also, using fNIRS rather than a different method of imaging worked better with the children, who tended to move around more. This allowed us to get more accurate measurements of oxygenated, deoxygenated, and total hemoglobin levels during the tasks. Furthermore, the sample for this study included primarily highly educated parents, even with the bilingual group. This is an uncommon sample and allows for the ability to see how a higher level of education may influence child executive functioning, especially for the bilingual group.

As data collection continues for this study, a focus should be put on being more precise with the initial trigger placement, allowing for more detailed data and the ability to remove any trials where the child may have been distracted or touched the cap. Additionally, a larger sample size will provide sufficient power to extend the preliminary results from this study specifically in regard to a potential bilingual advantage on the working memory and inhibitory control tasks. Another focus should be placed on attempting to recruit younger children as the majority of the current sample are 5 years old.

Other directions include, examining the effect that cultural experiences have on the development of executive functioning rather than solely the aspect of being exposed to or speaking a second language. Using specific language pairings (e.g., Spanish-English) would allow for discovery of the specific effect that a particular language may have on executive functioning. Finally, future research using a mixed income sample (i.e., low and high income) should be done in order to look for potential differences in the effect that bilingualism has based on income and whether bilingualism may mediate the association between executive functioning development and poverty. Much of the research literature which has found a bilingual advantage was with low-income samples (e.g., Grote et al., 2021; Naeem et al., 2018). Testing bilingualism as a mediator of poverty on executive functioning may help explain why some research suggests a bilingual advantage other research does not.

Conclusion

This study sought to explore potential differences in executive functioning skills and locations of brain activation between young monolingual and bilingual children. The results of this study did not find a significant advantage in the executive functioning skills of the bilingual children over the monolingual children. However, the differences between the two groups on one of the inhibitory control tasks, the Animal Go/No-Go and specifically the Go portion of that task, approached statistical significance favoring the bilingual children. In addition, visual representations suggested a pattern of higher scores for most of the executive functioning tasks, as well as faster reaction times for the bilingual children. Group differences between locations of activation and deactivation in the prefrontal cortex during the executive functioning tasks were also present. This gives support to the possibility of bilingualism altering cognitive processes. Finally, it was shown that there are specific areas of the prefrontal cortex that are associated with the different aspects of executive functioning. Future research should continue to explore these trends suggesting potential differences in brain activation and executive functioning skills of young monolingual and bilingual children.

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APPENDICES

Appendix A

Arrows

Table A1

Monolingual Arrows Correlations

Channels	Arrows
HRFHbO11_Arrows	-0.3
HRFHbR11_Arrows	0.3
HRFHbT11_Arrows	-0.19
HRFHbO12_Arrows	-0.32
HRFHbR12_Arrows	0.3
HRFHbT12_Arrows	-0.3
HRFHbO21_Arrows	-.97**
HRFHbR21_Arrows	-0.51
HRFHbT21_Arrows	-.90*
HRFHbO23_Arrows	-0.15
HRFHbR23_Arrows	-0.04
HRFHbT23_Arrows	-0.35
HRFHbO32_Arrows	0.1
HRFHbR32_Arrows	-0.17
HRFHbT32_Arrows	0.05
HRFHbO33_Arrows	-0.08
HRFHbR33_Arrows	-0.15
HRFHbT33_Arrows	-0.12
HRFHbO34_Arrows	-0.26
HRFHbR34_Arrows	0.79
HRFHbT34_Arrows	0.01
HRFHbO42_Arrows	0.34
HRFHbR42_Arrows	0.48
HRFHbT42_Arrows	.93*
HRFHbO44_Arrows	-0.11
HRFHbR44_Arrows	0.69
HRFHbT44_Arrows	0.55
HRFHbO45_Arrows	0.16
HRFHbR45_Arrows	0.67
HRFHbT45_Arrows	0.31
HRFHbO53_Arrows	-0.33
HRFHbR53_Arrows	-0.58
HRFHbT53_Arrows	-0.41

(*table continues*)

Channels	Arrows
HRFHbO54_Arrows	-0.03
HRFHbR54_Arrows	0.79
HRFHbT54_Arrows	0.31
HRFHbO56_Arrows	-0.51
HRFHbR56_Arrows	-0.33
HRFHbT56_Arrows	-0.58
HRFHbO64_Arrows	-0.38
HRFHbR64_Arrows	-0.2
HRFHbT64_Arrows	-0.72
HRFHbO65_Arrows	-0.83
HRFHbR65_Arrows	0.05
HRFHbT65_Arrows	-0.57
HRFHbO66_Arrows	-0.22
HRFHbR66_Arrows	-0.41
HRFHbT66_Arrows	-0.4
HRFHbO75_Arrows	0.61
HRFHbR75_Arrows	0.73
HRFHbT75_Arrows	0.79
HRFHbO77_Arrows	0.17
HRFHbR77_Arrows	0.59
HRFHbT77_Arrows	0.39
HRFHbO86_Arrows	0.06
HRFHbR86_Arrows	-0.06
HRFHbT86_Arrows	0.01
HRFHbO87_Arrows	-0.47
HRFHbR87_Arrows	-0.24
HRFHbT87_Arrows	-0.42

* = $p < .05$.
** = $p < .01$.

Table A2

Bilingual Arrows Correlations

Channels	Arrow
HRFHbO11_Arrow	-0.43
HRFHbR11_Arrow	-0.24
HRFHbT11_Arrow	-0.39
HRFHbO12_Arrow	-0.82
HRFHbR12_Arrow	0.26
HRFHbT12_Arrow	-0.24
HRFHbO21_Arrow	0.12
HRFHbR21_Arrow	-0.38
HRFHbT21_Arrow	0.02
HRFHbO23_Arrow	0.11
HRFHbR23_Arrow	0.52
HRFHbT23_Arrow	0.38
HRFHbO32_Arrow	-0.63
HRFHbR32_Arrow	0.35
HRFHbT32_Arrow	0.17
HRFHbO33_Arrow	-0.07
HRFHbR33_Arrow	0.84
HRFHbT33_Arrow	0.32
HRFHbO34_Arrow	0.3
HRFHbR34_Arrow	-0.31
HRFHbT34_Arrow	0.21
HRFHbO42_Arrow	-0.16
HRFHbR42_Arrow	0.24
HRFHbT42_Arrow	0.04
HRFHbO44_Arrow	-0.24
HRFHbR44_Arrow	0.48
HRFHbT44_Arrow	0.49
HRFHbO45_Arrow	-0.13
HRFHbR45_Arrow	0.5
HRFHbT45_Arrow	0.04
HRFHbO53_Arrow	-0.82
HRFHbR53_Arrow	0.12
HRFHbT53_Arrow	-0.61

(*table continues*)

Channels	Arrow
HRFHbO54_Arrow	-0.13
HRFHbR54_Arrow	0.79
HRFHbT54_Arrow	0.17
HRFHbO56_Arrow	-0.31
HRFHbR56_Arrow	0.68
HRFHbT56_Arrow	-0.1
HRFHbO64_Arrow	-0.42
HRFHbR64_Arrow	0.3
HRFHbT64_Arrow	-0.18
HRFHbO65_Arrow	-0.61
HRFHbR65_Arrow	-0.4
HRFHbT65_Arrow	-0.63
HRFHbO66_Arrow	0.24
HRFHbR66_Arrow	0.64
HRFHbT66_Arrow	0.44
HRFHbO75_Arrow	-0.61
HRFHbR75_Arrow	-0.22
HRFHbT75_Arrow	-0.56
HRFHbO77_Arrow	-0.66
HRFHbR77_Arrow	-0.12
HRFHbT77_Arrow	-0.53
HRFHbO86_Arrow	-0.03
HRFHbR86_Arrow	-0.22
HRFHbT86_Arrow	-0.11
HRFHbO87_Arrow	-0.04
HRFHbR87_Arrow	0.43
HRFHbT87_Arrow	0.05

Appendix B

Pigs

Table B1

Monolingual Animal Go/No-Go Correlations

Channels	Pig	Pig No-Go	Pig Go
HRFHbO11_Pig	-0.75	-0.28	-0.86
HRFHbR11_Pig	-0.28	-0.19	-0.29
HRFHbT11_Pig	-0.77	-0.32	-0.87
HRFHbO12_Pig	-0.4	-0.1	-0.47
HRFHbR12_Pig	-0.48	-0.82	-0.3
HRFHbT12_Pig	-0.76	-0.73	-0.7
HRFHbO21_Pig	-0.16	0.15	-0.26
HRFHbR21_Pig	0.4	0.34	0.39
HRFHbT21_Pig	0.02	0.23	-0.06
HRFHbO23_Pig	-0.47	-0.13	-0.56
HRFHbR23_Pig	0.74	0.6	0.72
HRFHbT23_Pig	-0.15	0.1	-0.24
HRFHbO32_Pig	-0.25	0.09	-0.35
HRFHbR32_Pig	0.57	0.02	0.73
HRFHbT32_Pig	-0.1	0.12	-0.18
HRFHbO33_Pig	-0.02	0.1	-0.07
HRFHbR33_Pig	0.44	0.21	0.49
HRFHbT33_Pig	0.13	0.14	0.11
HRFHbO34_Pig	-0.69	-0.33	-0.77
HRFHbR34_Pig	0.03	-0.43	0.21
HRFHbT34_Pig	-0.58	-0.55	-0.53
HRFHbO42_Pig	-0.87	-0.57	-.91*
HRFHbR42_Pig	-0.16	-0.23	-0.11
HRFHbT42_Pig	-0.84	-0.56	-0.87
HRFHbO44_Pig	-.99**	-0.77	-.98**
HRFHbR44_Pig	-0.25	-0.36	-0.19
HRFHbT44_Pig	-.94*	-0.77	-.92*
HRFHbO45_Pig	-0.87	-0.8	-0.81
HRFHbR45_Pig	-0.42	0.03	-0.56
HRFHbT45_Pig	-.97**	-0.67	-1.00**
HRFHbO53_Pig	-0.35	-0.29	-0.34
HRFHbR53_Pig	-0.31	-0.49	-0.21
HRFHbT53_Pig	-0.35	-0.33	-0.32

(*table continues*)

Channels	Pig	Pig No-Go	Pig Go
HRFHbO54_Pig	-0.07	0.19	-0.17
HRFHbR54_Pig	0.29	0.03	0.37
HRFHbT54_Pig	0.07	0.15	0.04
HRFHbO56_Pig	-0.44	-0.13	-0.51
HRFHbR56_Pig	-0.41	-0.41	-0.37
HRFHbT56_Pig	-0.44	-0.23	-0.48
HRFHbO64_Pig	-0.72	-0.2	-0.85
HRFHbR64_Pig	-0.46	-0.23	-0.51
HRFHbT64_Pig	-0.73	-0.25	-0.84
HRFHbO65_Pig	-0.76	-0.25	-.89*
HRFHbR65_Pig	0.07	-0.13	0.14
HRFHbT65_Pig	-0.58	-0.3	-0.63
HRFHbO66_Pig	0.07	0.29	-0.02
HRFHbR66_Pig	-0.34	-0.55	-0.23
HRFHbT66_Pig	-0.1	-0.04	-0.11
HRFHbO75_Pig	-0.65	-0.1	-0.8
HRFHbR75_Pig	-0.56	-0.47	-0.54
HRFHbT75_Pig	-0.74	-0.26	-0.85
HRFHbO77_Pig	-0.32	-0.07	-0.39
HRFHbR77_Pig	-0.33	-0.35	-0.3
HRFHbT77_Pig	-0.34	-0.14	-0.39
HRFHbO86_Pig	0.09	0.11	0.07
HRFHbR86_Pig	0.35	0.04	0.43
HRFHbT86_Pig	0.17	0.1	0.18
HRFHbO87_Pig	-0.36	-0.01	-0.46
HRFHbR87_Pig	0.03	0.18	-0.03
HRFHbT87_Pig	-0.29	0.03	-0.38

* = $p < .05$.
** = $p < .01$.

Table B2

Bilingual Animal Go/No-Go Correlations

Channels	Pig	Pig No-Go	Pig Go
HRFHbO11_Pig	-0.02	0.33	-0.13
HRFHbR11_Pig	-0.45	-0.61	-0.29
HRFHbT11_Pig	-0.05	0.29	-0.14
HRFHbO12_Pig	-0.14	-0.68	0.06
HRFHbR12_Pig	-0.23	-0.24	-0.16
HRFHbT12_Pig	-0.24	-0.84	0.02
HRFHbO21_Pig	0.34	0.85	0.1
HRFHbR21_Pig	0	0.06	-0.02
HRFHbT21_Pig	0.15	0.43	0.03
HRFHbO23_Pig	0.19	-0.83	0.46
HRFHbR23_Pig	-0.08	0.75	-0.31
HRFHbT23_Pig	-0.02	0.61	-0.21
HRFHbO32_Pig	0.55	0.12	0.54
HRFHbR32_Pig	-.93*	-0.09	-.95*
HRFHbT32_Pig	0.05	0.08	0.03
HRFHbO33_Pig	0.25	0.01	0.25
HRFHbR33_Pig	0	0	0
HRFHbT33_Pig	0.15	0.01	0.15
HRFHbO34_Pig	0.07	0.15	0.03
HRFHbR34_Pig	-0.08	-0.19	-0.03
HRFHbT34_Pig	0.02	0.03	0.01
HRFHbO42_Pig	-0.14	-0.2	-0.08
HRFHbR42_Pig	0.27	0.05	0.26
HRFHbT42_Pig	0.09	-0.06	0.11
HRFHbO44_Pig	-0.03	0.58	-0.21
HRFHbR44_Pig	-0.23	-0.84	0.02
HRFHbT44_Pig	-0.19	0.35	-0.31
HRFHbO45_Pig	-0.25	0.63	-0.46
HRFHbR45_Pig	-0.32	-0.57	-0.15
HRFHbT45_Pig	-0.76	0.39	-.91*
HRFHbO53_Pig	0.09	-0.25	0.17
HRFHbR53_Pig	0.23	-0.6	0.43
HRFHbT53_Pig	0.2	-0.52	0.37

(*table continues*)

Channels	Pig	Pig No-Go	Pig Go
HRFHbO54_Pig	0.42	.99**	0.13
HRFHbR54_Pig	0.17	-0.72	0.4
HRFHbT54_Pig	0.57	.95*	0.3
HRFHbO56_Pig	-0.19	0.18	-0.25
HRFHbR56_Pig	0.08	0.01	0.08
HRFHbT56_Pig	-0.04	0.08	-0.07
HRFHbO64_Pig	-0.13	-0.33	-0.04
HRFHbR64_Pig	-0.21	-0.07	-0.2
HRFHbT64_Pig	-0.14	-0.31	-0.05
HRFHbO65_Pig	-0.04	-0.58	0.13
HRFHbR65_Pig	-0.11	0.23	-0.19
HRFHbT65_Pig	-0.14	-0.75	0.09
HRFHbO66_Pig	-0.01	-0.51	0.15
HRFHbR66_Pig	0.13	-0.22	0.2
HRFHbT66_Pig	0.06	-0.38	0.18
HRFHbO75_Pig	-0.24	-0.08	-0.23
HRFHbR75_Pig	-0.26	0.82	-0.53
HRFHbT75_Pig	-0.3	0.21	-0.38
HRFHbO77_Pig	-0.63	-0.34	-0.55
HRFHbR77_Pig	0.15	0.66	-0.05
HRFHbT77_Pig	-0.37	0.15	-0.44
HRFHbO86_Pig	-0.08	-0.85	0.18
HRFHbR86_Pig	-0.43	0.15	-0.5
HRFHbT86_Pig	-0.19	-0.77	0.04
HRFHbO87_Pig	0.04	-0.25	0.13
HRFHbR87_Pig	0.12	-0.26	0.21
HRFHbT87_Pig	0.07	-0.26	0.16

* = *p < .05.*
** = *p < .01.*

Appendix C

Silly Sounds

Table C1

Monolingual Silly Sounds Correlations

Channels	Silly Sounds
HRFHbO11_SSG	-.98*
HRFHbR11_SSG	-0.37
HRFHbT11_SSG	-0.91
HRFHbO12_SSG	-0.91
HRFHbR12_SSG	-0.47
HRFHbT12_SSG	-0.85
HRFHbO21_SSG	-0.86
HRFHbR21_SSG	0.16
HRFHbT21_SSG	-.97*
HRFHbO23_SSG	-0.53
HRFHbR23_SSG	0.2
HRFHbT23_SSG	-0.29
HRFHbO32_SSG	-0.39
HRFHbR32_SSG	-0.05
HRFHbT32_SSG	-0.55
HRFHbO33_SSG	0.95
HRFHbR33_SSG	-0.17
HRFHbT33_SSG	0.54
HRFHbO34_SSG	0.08
HRFHbR34_SSG	-0.81
HRFHbT34_SSG	-0.11
HRFHbO42_SSG	-.98*
HRFHbR42_SSG	-0.18
HRFHbT42_SSG	-.95*
HRFHbO44_SSG	-0.55
HRFHbR44_SSG	-0.39
HRFHbT44_SSG	-0.54
HRFHbO45_SSG	-0.9
HRFHbR45_SSG	0.87
HRFHbT45_SSG	-0.74
HRFHbO53_SSG	0.06
HRFHbR53_SSG	-0.64
HRFHbT53_SSG	-0.11

(*table continues*)

Channels	Silly Sounds
HRFHbO54_SSG	0.02
HRFHbR54_SSG	-0.16
HRFHbT54_SSG	-0.15
HRFHbO56_SSG	-0.71
HRFHbR56_SSG	-0.74
HRFHbT56_SSG	-0.91
HRFHbO64_SSG	-0.72
HRFHbR64_SSG	-0.18
HRFHbT64_SSG	-0.61
HRFHbO65_SSG	-0.93
HRFHbR65_SSG	0.6
HRFHbT65_SSG	-0.5
HRFHbO66_SSG	-0.7
HRFHbR66_SSG	-0.39
HRFHbT66_SSG	-0.87
HRFHbO75_SSG	-0.85
HRFHbR75_SSG	-0.38
HRFHbT75_SSG	-0.91
HRFHbO77_SSG	-0.76
HRFHbR77_SSG	-0.09
HRFHbT77_SSG	-0.85
HRFHbO86_SSG	-0.75
HRFHbR86_SSG	-0.32
HRFHbT86_SSG	-0.79
HRFHbO87_SSG	-1.00**
HRFHbR87_SSG	-0.31
HRFHbT87_SSG	-.96*

* = $p < .05$.

** = $p < .01$.

Table C2

Bilingual Silly Sounds Correlations

Channels	Silly Sounds
HRFHbO11_SSG	0.86
HRFHbR11_SSG	0.88
HRFHbT11_SSG	.92*
HRFHbO12_SSG	-0.78
HRFHbR12_SSG	-0.11
HRFHbT12_SSG	-0.78
HRFHbO21_SSG	-0.71
HRFHbR21_SSG	-0.75
HRFHbT21_SSG	-0.72
HRFHbO23_SSG	-0.53
HRFHbR23_SSG	0.61
HRFHbT23_SSG	-0.24
HRFHbO32_SSG	0.8
HRFHbR32_SSG	-0.4
HRFHbT32_SSG	0.85
HRFHbO33_SSG	-0.86
HRFHbR33_SSG	0.43
HRFHbT33_SSG	-0.75
HRFHbO34_SSG	-0.68
HRFHbR34_SSG	.88*
HRFHbT34_SSG	-0.08
HRFHbO42_SSG	-0.75
HRFHbR42_SSG	-0.29
HRFHbT42_SSG	-0.82
HRFHbO44_SSG	-0.66
HRFHbR44_SSG	0.3
HRFHbT44_SSG	-0.85
HRFHbO45_SSG	-0.37
HRFHbR45_SSG	0.26
HRFHbT45_SSG	0.16
HRFHbO53_SSG	-0.61
HRFHbR53_SSG	0.24
HRFHbT53_SSG	-0.44

(*table continues*)

Channels	Silly Sounds
HRFHbO54_SSG	-0.87
HRFHbR54_SSG	0.07
HRFHbT54_SSG	-0.62
HRFHbO56_SSG	-0.66
HRFHbR56_SSG	-0.02
HRFHbT56_SSG	-0.49
HRFHbO64_SSG	0.05
HRFHbR64_SSG	0.31
HRFHbT64_SSG	0.39
HRFHbO65_SSG	-0.59
HRFHbR65_SSG	0.16
HRFHbT65_SSG	-0.5
HRFHbO66_SSG	-0.74
HRFHbR66_SSG	-0.44
HRFHbT66_SSG	-0.81
HRFHbO75_SSG	0.19
HRFHbR75_SSG	0.42
HRFHbT75_SSG	0.39
HRFHbO77_SSG	-0.4
HRFHbR77_SSG	0.49
HRFHbT77_SSG	0.02
HRFHbO86_SSG	-0.53
HRFHbR86_SSG	0.08
HRFHbT86_SSG	-0.67
HRFHbO87_SSG	-0.48
HRFHbR87_SSG	-0.42
HRFHbT87_SSG	-0.72

* = $p < .05$.

Appendix D

Something's the Same

Table D1

Monolingual Something's the Same Correlations

Channels	Something's the Same
HRFHbO11_STS	-0.56
HRFHbR11_STS	-0.95
HRFHbT11_STS	-0.62
HRFHbO12_STS	-0.79
HRFHbR12_STS	-0.78
HRFHbT12_STS	-0.8
HRFHbO21_STS	-0.36
HRFHbR21_STS	-0.08
HRFHbT21_STS	-0.3
HRFHbO23_STS	-0.41
HRFHbR23_STS	-0.23
HRFHbT23_STS	-0.39
HRFHbO32_STS	-0.73
HRFHbR32_STS	-0.75
HRFHbT32_STS	-0.83
HRFHbO33_STS	-0.61
HRFHbR33_STS	-0.79
HRFHbT33_STS	-0.67
HRFHbO34_STS	-0.36
HRFHbR34_STS	0.31
HRFHbT34_STS	-0.19
HRFHbO42_STS	-0.78
HRFHbR42_STS	0.11
HRFHbT42_STS	-0.87
HRFHbO44_STS	-0.4
HRFHbR44_STS	0.18
HRFHbT44_STS	-0.38
HRFHbO45_STS	-0.86
HRFHbR45_STS	-0.18
HRFHbT45_STS	-0.71
HRFHbO53_STS	-0.52
HRFHbR53_STS	-0.59
HRFHbT53_STS	-0.55

(*table continues*)

Channels	Something's the Same
HRFHbO54_STS	-0.59
HRFHbR54_STS	0.32
HRFHbT54_STS	-0.5
HRFHbO56_STS	-0.27
HRFHbR56_STS	-0.25
HRFHbT56_STS	-0.26
HRFHbO64_STS	-0.52
HRFHbR64_STS	-0.32
HRFHbT64_STS	-0.47
HRFHbO65_STS	-0.04
HRFHbR65_STS	0.49
HRFHbT65_STS	0.11
HRFHbO66_STS	-0.25
HRFHbR66_STS	0.09
HRFHbT66_STS	-0.18
HRFHbO75_STS	0.31
HRFHbR75_STS	0.61
HRFHbT75_STS	0.52
HRFHbO77_STS	0.09
HRFHbR77_STS	0.44
HRFHbT77_STS	0.26
HRFHbO86_STS	-0.05
HRFHbR86_STS	.99*
HRFHbT86_STS	0.07
HRFHbO87_STS	0.02
HRFHbR87_STS	0.27
HRFHbT87_STS	0.08

* = $p < .05$.

Table D2

Bilingual Something's the Same Correlations

Channels	Something's the Same
HRFHbO11_STS	0.28
HRFHbR11_STS	0.03
HRFHbT11_STS	0.15
HRFHbO12_STS	0.19
HRFHbR12_STS	-0.32
HRFHbT12_STS	-0.03
HRFHbO21_STS	-0.35
HRFHbR21_STS	-.96**
HRFHbT21_STS	-0.47
HRFHbO23_STS	-0.61
HRFHbR23_STS	-0.08
HRFHbT23_STS	-0.54
HRFHbO32_STS	-0.37
HRFHbR32_STS	-0.67
HRFHbT32_STS	-0.61
HRFHbO33_STS	-0.41
HRFHbR33_STS	-.90*
HRFHbT33_STS	-0.56
HRFHbO34_STS	-0.12
HRFHbR34_STS	-0.36
HRFHbT34_STS	-0.83
HRFHbO42_STS	-0.64
HRFHbR42_STS	-0.34
HRFHbT42_STS	-0.73
HRFHbO44_STS	-0.69
HRFHbR44_STS	-0.08
HRFHbT44_STS	-0.39
HRFHbO45_STS	-0.33
HRFHbR45_STS	-0.3
HRFHbT45_STS	-0.46
HRFHbO53_STS	0.16
HRFHbR53_STS	0.15
HRFHbT53_STS	0.16
HRFHbO54_STS	-0.24

Channels	Something's the Same
HRFHbR54_STS	-0.38
HRFHbT54_STS	-0.32
HRFHbO56_STS	-0.19
HRFHbR56_STS	-0.52
HRFHbT56_STS	-0.35
HRFHbO64_STS	0.36
HRFHbR64_STS	0.05
HRFHbT64_STS	0.26
HRFHbO65_STS	0.14
HRFHbR65_STS	-0.1
HRFHbT65_STS	0.11
HRFHbO66_STS	0.05
HRFHbR66_STS	-0.47
HRFHbT66_STS	-0.41
HRFHbO75_STS	0.24
HRFHbR75_STS	0.18
HRFHbT75_STS	0.22
HRFHbO77_STS	0.51
HRFHbR77_STS	0.41
HRFHbT77_STS	0.51
HRFHbO86_STS	0.12
HRFHbR86_STS	-0.4
HRFHbT86_STS	-0.58
HRFHbO87_STS	0.17
HRFHbR87_STS	-0.08
HRFHbT87_STS	0.12

* = *p < .05.*

** = *p < .01.*

Appendix E

Pick the Picture

Table E1

Monolingual Pick the Picture Correlations

Channels	Pick the Picture
HRFHbO11_PTP	-0.39
HRFHbR11_PTP	-0.9
HRFHbT11_PTP	-0.55
HRFHbO12_PTP	-0.94
HRFHbR12_PTP	-0.9
HRFHbT12_PTP	-0.92
HRFHbO21_PTP	0.26
HRFHbR21_PTP	0.64
HRFHbT21_PTP	0.4
HRFHbO23_PTP	.98*
HRFHbR23_PTP	0.94
HRFHbT23_PTP	.96*
HRFHbO32_PTP	0.09
HRFHbR32_PTP	0.78
HRFHbT32_PTP	0.4
HRFHbO33_PTP	0.15
HRFHbR33_PTP	0.56
HRFHbT33_PTP	0.29
HRFHbO34_PTP	-0.43
HRFHbR34_PTP	-0.87
HRFHbT34_PTP	-0.7
HRFHbO42_PTP	-0.81
HRFHbR42_PTP	-0.42
HRFHbT42_PTP	-0.74
HRFHbO44_PTP	-0.3
HRFHbR44_PTP	.98*
HRFHbT44_PTP	0.3
HRFHbO45_PTP	-0.45
HRFHbR45_PTP	-0.3
HRFHbT45_PTP	-0.38
HRFHbO53_PTP	0.4
HRFHbR53_PTP	0.9
HRFHbT53_PTP	0.6

(*table continues*)

Channels	Pick the Picture
HRFHbO54_PTP	0.03
HRFHbR54_PTP	0.71
HRFHbT54_PTP	0.27
HRFHbO56_PTP	-0.41
HRFHbR56_PTP	0.19
HRFHbT56_PTP	-0.24
HRFHbO64_PTP	-0.15
HRFHbR64_PTP	0.94
HRFHbT64_PTP	0.29
HRFHbO65_PTP	0.48
HRFHbR65_PTP	0.85
HRFHbT65_PTP	0.87
HRFHbO66_PTP	-0.45
HRFHbR66_PTP	0.85
HRFHbT66_PTP	-0.23
HRFHbO75_PTP	-0.55
HRFHbR75_PTP	-0.38
HRFHbT75_PTP	-0.47
HRFHbO77_PTP	0.04
HRFHbR77_PTP	0.48
HRFHbT77_PTP	0.13
HRFHbO86_PTP	-0.18
HRFHbR86_PTP	0.14
HRFHbT86_PTP	-0.12
HRFHbO87_PTP	-0.09
HRFHbR87_PTP	0.27
HRFHbT87_PTP	-0.01

* = *p < .05.*

Table E2

Bilingual Pick the Picture Correlations

Channels	Pick the Picture
HRFHbO11_PTP	-0.07
HRFHbR11_PTP	0.32
HRFHbT11_PTP	0.12
HRFHbO12_PTP	-0.1
HRFHbR12_PTP	-0.03
HRFHbT12_PTP	-0.07
HRFHbO21_PTP	-0.41
HRFHbR21_PTP	0.19
HRFHbT21_PTP	-0.42
HRFHbO23_PTP	-0.6
HRFHbR23_PTP	0.53
HRFHbT23_PTP	-0.42
HRFHbO32_PTP	-.90*
HRFHbR32_PTP	0.48
HRFHbT32_PTP	-0.45
HRFHbO33_PTP	-0.46
HRFHbR33_PTP	-0.31
HRFHbT33_PTP	-0.7
HRFHbO34_PTP	0.84
HRFHbR34_PTP	-0.84
HRFHbT34_PTP	0.69
HRFHbO42_PTP	-0.27
HRFHbR42_PTP	-0.63
HRFHbT42_PTP	-0.43
HRFHbO44_PTP	-0.46
HRFHbR44_PTP	-0.18
HRFHbT44_PTP	-0.47
HRFHbO45_PTP	-0.43
HRFHbR45_PTP	0.18
HRFHbT45_PTP	-0.16
HRFHbO53_PTP	-0.49
HRFHbR53_PTP	-0.51
HRFHbT53_PTP	-0.54

(*table continues*)

Channels	Pick the Picture
HRFHbO54_PTP	0
HRFHbR54_PTP	-0.2
HRFHbT54_PTP	-0.1
HRFHbO56_PTP	0.53
HRFHbR56_PTP	-0.15
HRFHbT56_PTP	0.4
HRFHbO64_PTP	0.53
HRFHbR64_PTP	-0.14
HRFHbT64_PTP	0.27
HRFHbO65_PTP	0.04
HRFHbR65_PTP	0.02
HRFHbT65_PTP	0.3
HRFHbO66_PTP	-0.32
HRFHbR66_PTP	-0.38
HRFHbT66_PTP	-0.45
HRFHbO75_PTP	0.06
HRFHbR75_PTP	0.22
HRFHbT75_PTP	0.14
HRFHbO77_PTP	-.89*
HRFHbR77_PTP	0.36
HRFHbT77_PTP	-0.71
HRFHbO86_PTP	0.08
HRFHbR86_PTP	0.61
HRFHbT86_PTP	0.81
HRFHbO87_PTP	.89*
HRFHbR87_PTP	-0.04
HRFHbT87_PTP	0.65

Note. * = $p < .05$

Appendix F

One-Tail Independent Samples *t* Tests

Table F1

One-Tail t *Tests for All Tasks*

Channels	*t*	*df*	Two-Sided *p*
HbO11_Arrow	-0.56	8	0.59
HbR11_Arrow	0.15	8	0.88
HbT11_Arrow	-0.38	8	0.71
HbO12_Arrow	-0.56	8	0.59
HbR12_Arrow	-0.09	8	0.93
HbT12_Arrow	-0.58	8	0.58
HbO21_Arrow	0.18	8	0.86
HbR21_Arrow	0.68	8	0.52
HbT21_Arrow	0.36	8	0.73
HbO23_Arrow	-0.93	8	0.38
HbR23_Arrow	0.11	8	0.91
HbT23_Arrow	-0.77	5.2	0.48
HbO32_Arrow	-1.9	8	0.09^
HbR32_Arrow	0.86	4.34	0.43
HbT32_Arrow	-0.71	8	0.5
HbO33_Arrow	0.88	8	0.4
HbR33_Arrow	1.3	5.87	0.24
HbT33_Arrow	1.14	8	0.29
HbO34_Arrow	-3.59	8	0.01**
HbR34_Arrow	1.96	8	0.09^
HbT34_Arrow	-3.1	4.32	0.03*
HbO42_Arrow	-0.88	8	0.41
HbR42_Arrow	-1.26	8	0.24
HbT42_Arrow	-1.26	8	0.24
HbO44_Arrow	-0.03	8	0.97
HbR44_Arrow	0.26	8	0.8
HbT44_Arrow	0.26	8	0.81
HbO45_Arrow	-0.25	8	0.81
HbR45_Arrow	0.2	8	0.85
HbT45_Arrow	-0.16	8	0.88
HbO53_Arrow	-0.6	5.22	0.57
HbR53_Arrow	0.5	8	0.63
HbT53_Arrow	-0.31	5.09	0.77
HbO54_Arrow	-1.57	8	0.15
HbR54_Arrow	0.61	8	0.56
HbT54_Arrow	-1.04	8	0.33
HbO56_Arrow	-1.85	8	0.1^

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbR56_Arrow	-0.03	4.67	0.98
HbT56_Arrow	-1.63	8	0.14
HbO64_Arrow	1.15	8	0.28
HbR64_Arrow	0.44	8	0.67
HbT64_Arrow	1.57	8	0.16
HbO65_Arrow	0.86	8	0.42
HbR65_Arrow	1.41	8	0.2
HbT65_Arrow	1.56	8	0.16
HbO66_Arrow	0.05	8	0.96
HbR66_Arrow	-0.3	8	0.78
HbT66_Arrow	-0.1	8	0.93
HbO75_Arrow	-0.92	8	0.38
HbR75_Arrow	0.91	8	0.39
HbT75_Arrow	0.09	8	0.93
HbO77_Arrow	0.79	8	0.45
HbR77_Arrow	1.2	8	0.27
HbT77_Arrow	1.15	8	0.28
HbO86_Arrow	-0.83	5.3	0.44
HbR86_Arrow	0.16	8	0.88
HbT86_Arrow	-0.61	8	0.56
HbO87_Arrow	-0.72	8	0.49
HbR87_Arrow	-0.73	8	0.48
HbT87_Arrow	-0.79	8	0.45
HbO11_Pig	1.69	8	0.13
HbR11_Pig	-1.43	8	0.19
HbT11_Pig	1.38	8	0.2
HbO12_Pig	0.27	8	0.79
HbR12_Pig	-3.18	8	0.01**
HbT12_Pig	-1.76	8	0.12
HbO21_Pig	2.06	8	0.07^
HbR21_Pig	-0.42	8	0.68
HbT21_Pig	1.14	8	0.29
HbO23_Pig	2.23	4.57	0.08^
HbR23_Pig	-0.66	8	0.53
HbT23_Pig	1.32	8	0.22
HbO32_Pig	0.98	8	0.36
HbR32_Pig	-0.79	8	0.45
HbT32_Pig	0.77	8	0.46
HbO33_Pig	1.34	8	0.22
HbR33_Pig	-0.91	8	0.39

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbT33_Pig	0.57	8	0.59
HbO34_Pig	1.84	8	0.1
HbR34_Pig	-2.46	8	0.04*
HbT34_Pig	0.18	8	0.86
HbO42_Pig	-1.18	8	0.27
HbR42_Pig	-1.67	8	0.13
HbT42_Pig	-1.57	8	0.16
HbO44_Pig	0.68	8	0.51
HbR44_Pig	-3.05	8	0.02
HbT44_Pig	-0.4	8	0.7
HbO45_Pig	1.01	8	0.34
HbR45_Pig	-2.7	8	0.03*
HbT45_Pig	-0.64	4.54	0.56
HbO53_Pig	1.38	8	0.2
HbR53_Pig	-2.04	8	0.08^
HbT53_Pig	0.55	8	0.59
HbO54_Pig	2.66	8	0.03*
HbR54_Pig	0.35	8	0.73
HbT54_Pig	2.26	8	0.05*
HbO56_Pig	0.39	8	0.71
HbR56_Pig	-1.16	8	0.28
HbT56_Pig	-0.32	8	0.76
HbO64_Pig	2.12	8	0.07^
HbR64_Pig	-0.75	8	0.47
HbT64_Pig	1.67	8	0.13
HbO65_Pig	0.22	8	0.83
HbR65_Pig	-1.1	8	0.3
HbT65_Pig	-0.42	8	0.69
HbO66_Pig	0.29	8	0.78
HbR66_Pig	-0.88	8	0.4
HbT66_Pig	-0.22	8	0.83
HbO75_Pig	1.13	8	0.29
HbR75_Pig	-0.5	8	0.63
HbT75_Pig	0.75	8	0.47
HbO77_Pig	2.7	8	0.03
HbR77_Pig	0.52	8	0.62
HbT77_Pig	2.33	8	0.05
HbO86_Pig	1.23	8	0.25
HbR86_Pig	-0.47	8	0.65
HbT86_Pig	0.83	8	0.43

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbO87_Pig	0.34	8	0.74
HbR87_Pig	-0.57	8	0.59
HbT87_Pig	0.08	8	0.94
HbO11_SSG	0.85	7	0.43
HbR11_SSG	0.48	7	0.65
HbT11_SSG	0.74	7	0.48
HbO12_SSG	1.4	7	0.2
HbR12_SSG	-0.64	7	0.54
HbT12_SSG	1	7	0.35
HbO21_SSG	-0.4	7	0.7
HbR21_SSG	0.19	7	0.86
HbT21_SSG	-0.32	5.17	0.76
HbO23_SSG	0.25	7	0.81
HbR23_SSG	-0.5	7	0.63
HbT23_SSG	-0.04	7	0.97
HbO32_SSG	2.17	7	0.07^
HbR32_SSG	-0.44	7	0.68
HbT32_SSG	2.72	7	0.03*
HbO33_SSG	-0.17	7	0.87
HbR33_SSG	0.63	4.48	0.56
HbT33_SSG	0.13	7	0.9
HbO34_SSG	0.33	7	0.75
HbR34_SSG	0.09	5.17	0.93
HbT34_SSG	0.49	3.73	0.65
HbO42_SSG	0	7	1
HbR42_SSG	-2.19	7	0.06
HbT42_SSG	-0.74	7	0.48
HbO44_SSG	0.34	7	0.74
HbR44_SSG	-0.68	7	0.52
HbT44_SSG	0.1	7	0.93
HbO45_SSG	0.53	3.72	0.63
HbR45_SSG	-0.66	7	0.53
HbT45_SSG	-0.31	7	0.77
HbO53_SSG	-0.81	7	0.44
HbR53_SSG	-1.65	6.36	0.15
HbT53_SSG	-1.24	7	0.25
HbO54_SSG	0.74	7	0.48
HbR54_SSG	0.83	7	0.43
HbT54_SSG	1.24	5.47	0.27
HbO56_SSG	-1.05	7	0.33

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbR56_SSG	-1.06	7	0.32
HbT56_SSG	-1.36	7	0.22
HbO64_SSG	0.64	7	0.54
HbR64_SSG	-0.29	7	0.78
HbT64_SSG	0.28	7	0.79
HbO65_SSG	0.91	7	0.39
HbR65_SSG	-0.62	7	0.55
HbT65_SSG	0.4	7	0.7
HbO66_SSG	-0.05	7	0.96
HbR66_SSG	-1.06	7	0.33
HbT66_SSG	-0.46	7	0.66
HbO75_SSG	0.17	7	0.87
HbR75_SSG	-1.56	7	0.16
HbT75_SSG	-0.57	7	0.59
HbO77_SSG	-0.32	7	0.76
HbR77_SSG	-0.09	7	0.93
HbT77_SSG	-0.66	7	0.53
HbO86_SSG	0.24	7	0.82
HbR86_SSG	0.59	7	0.58
HbT86_SSG	0.66	7	0.53
HbO87_SSG	0.03	7	0.98
HbR87_SSG	-0.44	7	0.67
HbT87_SSG	-0.12	7	0.91
HbO11_STS	0.22	3.15	0.84
HbR11_STS	-1.22	7	0.26
HbT11_STS	-0.13	7	0.9
HbO12_STS	0.92	7	0.39
HbR12_STS	-1.71	7	0.13
HbT12_STS	0.13	7	0.9
HbO21_STS	0.27	7	0.79
HbR21_STS	-0.28	7	0.79
HbT21_STS	0.16	7	0.87
HbO23_STS	0.98	7	0.36
HbR23_STS	-0.12	7	0.91
HbT23_STS	0.8	7	0.45
HbO32_STS	-0.06	7	0.96
HbR32_STS	-0.48	7	0.65
HbT32_STS	-0.26	7	0.8
HbO33_STS	1.97	7	0.09^
HbR33_STS	2.64	4.38	0.05*

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbT33_STS	2.27	7	0.06^
HbO34_STS	-0.83	7	0.43
HbR34_STS	-2.05	7	0.08^
HbT34_STS	-1.65	7	0.14
HbO42_STS	-0.81	7	0.45
HbR42_STS	0.49	7	0.64
HbT42_STS	-0.75	7	0.48
HbO44_STS	0.43	7	0.68
HbR44_STS	0.38	7	0.72
HbT44_STS	0.52	7	0.62
HbO45_STS	-0.54	7	0.61
HbR45_STS	-1.3	7	0.24
HbT45_STS	-1.01	7	0.35
HbO53_STS	-0.15	7	0.89
HbR53_STS	-0.85	7	0.43
HbT53_STS	-0.38	7	0.72
HbO54_STS	1.6	7	0.15
HbR54_STS	0.82	7	0.44
HbT54_STS	1.39	7	0.21
HbO56_STS	-0.6	7	0.57
HbR56_STS	-1.63	7	0.15
HbT56_STS	-0.88	7	0.41
HbO64_STS	0.43	7	0.68
HbR64_STS	-0.37	7	0.73
HbT64_STS	0.23	7	0.82
HbO65_STS	1.71	7	0.13
HbR65_STS	-0.19	7	0.85
HbT65_STS	1.3	7	0.23
HbO66_STS	0.74	7	0.48
HbR66_STS	0.31	7	0.77
HbT66_STS	0.7	7	0.51
HbO75_STS	1.72	7	0.13
HbR75_STS	0.55	7	0.6
HbT75_STS	1.36	7	0.22
HbO77_STS	2.4	7	0.05*
HbR77_STS	1	7	0.35
HbT77_STS	2.24	7	0.06^
HbO86_STS	0.42	3.15	0.7
HbR86_STS	-0.39	7	0.71
HbT86_STS	0.29	3.13	0.79

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbO87_STS	1.72	7	0.13
HbR87_STS	0.91	7	0.39
HbT87_STS	1.7	7	0.13
HbO11_PTP	-1.18	7	0.28
HbR11_PTP	-0.84	7	0.43
HbT11_PTP	-1.18	7	0.27
HbO12_PTP	-0.07	7	0.95
HbR12_PTP	-0.43	7	0.68
HbT12_PTP	-0.23	7	0.83
HbO21_PTP	1.27	7	0.25
HbR21_PTP	1.59	7	0.16
HbT21_PTP	1.63	7	0.15
HbO23_PTP	1.17	7	0.28
HbR23_PTP	0.98	7	0.36
HbT23_PTP	1.19	3.32	0.31
HbO32_PTP	0.7	7	0.51
HbR32_PTP	0.13	7	0.9
HbT32_PTP	0.84	7	0.43
HbO33_PTP	1.05	3.95	0.35
HbR33_PTP	2.09	7	0.08
HbT33_PTP	1.41	3.37	0.24
HbO34_PTP	-1.57	7	0.16
HbR34_PTP	1.36	7	0.22
HbT34_PTP	-0.4	3.22	0.71
HbO42_PTP	-2.35	3.82	0.08^
HbR42_PTP	-3.37	7	0.01**
HbT42_PTP	-2.7	4.22	0.05*
HbO44_PTP	-0.17	7	0.87
HbR44_PTP	0.17	7	0.87
HbT44_PTP	-0.03	7	0.98
HbO45_PTP	-1.33	7	0.23
HbR45_PTP	-1.11	7	0.3
HbT45_PTP	-1.25	7	0.25
HbO53_PTP	-0.15	7	0.89
HbR53_PTP	1.33	7	0.23
HbT53_PTP	0.35	7	0.73
HbO54_PTP	0.65	3.86	0.55
HbR54_PTP	2.47	7	0.04*
HbT54_PTP	1.47	7	0.18
HbO56_PTP	-0.55	7	0.6

(*table continues*)

Channels	*t*	*df*	Two-Sided *p*
HbR56_PTP	1.57	7	0.16
HbT56_PTP	0.14	7	0.89
HbO64_PTP	-1.05	7	0.33
HbR64_PTP	1.3	7	0.23
HbT64_PTP	-0.17	7	0.87
HbO65_PTP	-0.35	7	0.74
HbR65_PTP	1.86	7	0.11
HbT65_PTP	1.31	3.1	0.28
HbO66_PTP	0.27	7	0.8
HbR66_PTP	3.63	7	0.01**
HbT66_PTP	1.23	7	0.26
HbO75_PTP	-0.33	7	0.75
HbR75_PTP	0.55	7	0.6
HbT75_PTP	0.04	7	0.97
HbO77_PTP	0.57	7	0.59
HbR77_PTP	0.29	7	0.78
HbT77_PTP	0.6	7	0.57
HbO86_PTP	2.02	7	0.08^
HbR86_PTP	2.58	7	0.04*
HbT86_PTP	3.78	7	0.01**
HbO87_PTP	1.1	3.26	0.35
HbR87_PTP	1.9	7	0.1^
HbT87_PTP	1.51	7	0.18

^ = $p < .1$.
* = $p < .05$.
** = $p < .01$.