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An fNIRS Examination of Executive Function in Bilingual Young Children

Early bilingual experience and its impact on executive function have been a topical issue in bilingual neuroimaging studies (Moriguchi & Lertladaluck, 2019). The experience of shifting between two languages by inhibiting irrelevant information and attending to relevant information may affect the neural functioning during task switching (Buac & Kaushanskaya, 2014). Some existing studies have suggested that early bilingual experience can positively affect the development of executive function (EF) (Tran, Arredondo, & Yoshida, 2019; Weber, Johnson, Riccio, & Liew, 2016). However, a recent study examining Japanese preschooler's performance during the Dimensional Change Card Sort (DCCS) task using functional near-infrared spectroscopy (fNIRS) found that early bilingual ability was not significantly correlated with the activation of lateral prefrontal regions (Moriguchi & Lertladaluck, 2019). Due to inconsistency in the literature, this study aimed to replicate the previous study (Moriguchi & Lertladaluck, 2019) and crosscheck this finding by examining the activation of prefrontal cortex in Chinese-English bilinguals during the DCCS task using fNIRS.

Bilingualism and Executive Function

Early bilingualism studies found that monolingual children outperformed their bilingual peers in IQ tests (Graham, 1925; Lewis, 1959), verbal intelligence (Darcy, 1953; Jones & Stewart, 1951), arithmetic, reading and academic achievement (Macnamara, 1966; Manuel, 1935). Later, two extensive reviews pointed out the methodological flaws in the previous studies and suggested that there were no differences between monolingual and bilingual children in non-verbal intelligence (Darcy, 1953, 1963), setting the stage for cognitive benefits of bilingualism. The landmark study by Peal and Lambert (1962) controlled many of the methodological issues and provided the first evidence that bilingual children had better cognitive ability. They further speculated that bilingual children's sustained experience in switching between languages might lay the foundation for their non-verbal intelligence. More recent studies have found more precocious metalinguistic development in bilingual children as well as nonverbal cognitive advantages in bilingual children in understanding metalinguistic development (Bialystok, 2001). From then on, the advocators of additive bilingualism tend to believe in the positive impact of early bilingualism on executive functioning (Carlso & Meltzoff, 2008).

Executive function (EF) refers to those functions responsible for planning and organizing behavior and regulating one’s actions, feelings, and thoughts (Weber et al., 2016). EF includes three components, namely inhibition, shifting and working memory, and develops synonymously with the functioning of the prefrontal cortex (PFC) (Hughes & Graham, 2010; Miyake et al., 2000). Recent review studies have supported a domain-general executive processing advantage in bilingual young children (Antoniou, 2019; Barac, Bialystok, Castro, & Sanchez,2014; Higby, Jungna, & Obler, 2013), and theories have been proposed to explain such bilingual advantage. Recognizing the development of inhibitory control as the essential basis of cognitive development, the Inhibitory Control Model (Green, 1998) has suggested that bilingual language processing was based on the Supervisory Attention System (SAS) to inhibit unwanted language and process the target language. This experience in recruiting the frontal lobe to inhibit during bilingual processing had long term effect of enhancing inhibitory processes more broadly, leading to behavioral studies that found bilingual advantage in performing the EF tasks (Bialystok et al., 2009).

In particular, the DCCS is a widely used task for examining children's executive function, which is not partitioned into the subprocesses of inhibition, shifting and working memory as the task involves all of them (Bialystok, 2017; Zelazo et al., 2003). In the DCCS, children are asked to sort a set of two-dimensional (i.e. color and shape) test cards according to two target cards that match the test cards in one dimension but not the other. They have to sort the cards according to the pre-switch rule (e.g., color) and the post-switch rule (e.g., shape). To successfully perform the task, children have to selectively attend to the relevant rule, bear the sorting rule in mind, inhibit attention to the irrelevant rule, and flexibly shift to the post-switch rule by overriding the response established in the pre-switch phase, utilizing different domains of executive function. Previous studies have demonstrated that bilingual children consistently outperformed their monolingual peers in the DCCS (Bialystok & Martin, 2004; Carlso & Meltzoff, 2008; Okanda, Moriguchi, & Itakura, 2010).

Neural Evidence in Young Children's Cognitive Processes

Although very limited, neuroimaging data from monolingual and bilingual children are useful in examining how bilingual experience affects children's brain and cognition. Existing evidence has documented the significant impact of bilingualism on early cognitive development with both structural and functional measures. For example, one structural magnetic resonance imaging (MRI) study has found higher volume in the left inferior parietal gyrus in children who were more bilingual than their less bilingual peers (Della Rosa et al., 2013). Several functional MRI studies have found functionally different activation patterns in the prefrontal and anterior cingulate regions between bilinguals and monolinguals during verbal and non-verbal cognitive tasks (Abutalebi et al., 2012; Gold et al., 2013; Luk et al., 2010). Two EEG studies have demonstrated that bilingual children have a higher sensitivity to stimulus change than their monolingual peers, as indicated by ERP waveforms (Barac et al., 2016; Kuipers & Thierry, 2012). Another fNIRS study has found that bilingual children activated left hemisphere regions more than their monolingual peers during a non-verbal control task, displaying different patterns of brain activation (Arredondo et al., 2017). In general, this neuroimaging evidence, be it higher structural density or functional patterns in bilinguals that resemble those obtained from older children or adults, indicates precocious brain development in bilinguals (Bialystok, 2017).

Furthermore, some studies have also examined the relation between neuroimaging and behavioral results. The EEG study by Barac et al. (2016) demonstrated that better differentiation of the N2/P3 waveform was associated with better discriminability of go and no-go trials of bilingual children. The fNIRS study by Moriguchi and Lertladaluck (2019) have demonstrated that the activation in the right lateral prefrontal regions was correlated with successes during the DCCS task. Still, the correlation between activated regions and the bilingual experience was not significant, calling for more extensive research on how bilingualism affects children's neural processing in the PFC.

The Present Study

Most studies, however, are based on between-group comparisons that require assumptions of equivalence between the groups, as several factors have been found to affect children's EF, such as genetic factors (Blair et al., 2015; Moriguchi & Shinohara, 2018) and socioeconomic factors (Moriguchi & Shinohara, 2019). All these confounding factors, however, are very difficult (if not impossible) to control for (Moriguchi & Lertladaluck, 2019). Therefore, some studies have taken a different approach and examined the relationship between bilingualism and EF performance within the same children (Bialystok & Barac, 2012; Crivello et al., 2016; Moriguchi & Lertladaluck, 2019). By considering bilingualism as a continuum rather than a discrete process, the relation between the intensity of bilingual experience and the nature of EF outcomes can account for the dose-related effects in the literature (Bialystok, 2017).

The present study intends to explore the relationship between children's bilingualism, performance in the DCCS task, and activations in the prefrontal regions using fNIRS. Instead of comparing bilingual against monolingual children, the present study will examine the relationship between bilingualism and children's performance during cognitive shifting task within the same children as a function of their level of bilingualism, avoiding the confounding factors such as genetic and socioeconomic factors. Moreover, children's activation in the prefrontal regions will be examined using fNIRS, as previous studies have documented that preschoolers start to employ the prefrontal cortex during DCCS task (Moriguchi & Hiraki, 2011; Moriguchi & Shinohara, 2019). In particular, the following research questions guided the present study.

1. Is children's bilingualism associated with their performance in the DCCS task?

2. Is prefrontal activation associated with children's bilingualism and performance in the DCCS task?

Methods

Participants

Fifty-six Chinese preschoolers (girls = 24; M_{age} = 66.15 months, *SD* = 7.2, range = 49 – 75 months) were recruited in the study. The University Ethics Committee approved the experiments. All of the children were recruited from a public preschool in Shenzhen, China, which provided an English immersion program that was produced by a 10-year China-Canada collaborative research project. The children in this public preschool were mostly from families of middle socioeconomic status. In each classroom, there was a qualified ESL (English as a second language) teacher who interacts with children in English only and delivers English activities in the afternoon. Therefore, children were exposed to English from 8:00 a.m. to 5:00 p.m. while they were at the preschool. Parents of all these children were informed of the purpose and safety of the study, who provided written consent for their children to participate. Among the 56 children, seven of them failed to complete the experiments and were thus excluded, resulting in a final sample of 49 children.

Measures

Verbal ability measures. Children's English ability was measured by their ESL teacher, who rated on their level of English speaking and reading on a scale of 1 (lowest) to 10 (highest). English teacher’s rated scores were used in this study, because there is no reliable and validated instrument to measure these ESL preschoolers in China, as teaching English as a second language (TESL) in preschools is banned by the educational authorities. The preschool in this study was approved to deliver TESL because it participated in a China-Canada joint research project on early bilingual immersion program. All other preschools in China, however, are not allowed to provide TESL. Despite the regulation, some private preschools continue to offer TESL programs to entertain the high-demanding parents in megacities such as Beijing, Shanghai, and Shenzhen.

Behavioral tasks. Children were invited to perform a modified version of DCCS tasks. A set of white paper cards (3.5 cm x 7.0 cm) that had two dimensions, namely shape and color, were used. The two target cards (i.e., a red boat and a blue rabbit) matched the test cards in one dimension but not the other, and a pair of target trays were used for the test sessions (see Figure 1). Before the test sessions, children underwent training when detailed instructions regarding the rules were given, and children were corrected when rules were misunderstood. Children performed three consecutive test sessions, and each session consisted of a rest phase (30s), a pre-switch phase (20s), and a post-switch phase (20s). During the pre-switch phase, children were given instructions regarding the first rule (e.g., "This is a shape game. All of the boats go here, and all of the rabbits go there."). During the post-switch phase, children were given instructions regarding the second rule (e.g., "This is a color game. All of the red cards go here, and all of the blue cards go there."). Each phase consisted of six trials. The rule order for the three sessions was: (1) color → shape; (2) shape → color; and (3) color → shape. This fixed-order was applied to all the participants, resulting in more color-to-shape switches in this study. Instead of following the design test procedure in a previous study (Moriguchi & Lertladaluck, 2019), we asked the participants to follow different rule orders during the three test sessions to control for learning effects. The dependent measures were the aggregate number of correct responses in all the phases. The task paradigm is shown in Figure 2.

<Insert Figure 1 & 2 here.>

fNIRS recording. Children's brain activity during the DCCS task was measured using fNIRS. This technique provides a more spatially resolved image of brain activity compared to EEG, and is portable and has high sampling rate compared to fMRI (Lloyd-Fox, Blasi, & Elwell, 2010). A multiple-channel fNIRS system (Oxymon Mk III, Artinis, The Netherlands) was used to measure the simultaneous concentration changes of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin (HbT). Two wavelengths in the near-infrared range (i.e., 760nm and 850 nm) were used to measure the changes in optical density and then converted into changes in the concentration of HbO and HbR using the modified Beer-Lambert law.

Seventeen channels were located following the international 10/20 system for EEG, with a 2.5 cm distance between each paired emitters and detectors, corresponding to Brodmann Areas (BAs) 6/8/9/10/40/44 (Figure 3). Ten channels were covering the right frontal cortex, and seven channels were covering the prefrontal cortex. In particular, the channels 1 & 9 were located in BA 6, channels 13, 15, 17 were located in BA 10, channel 10 was located in BA 8, channels 11, 12, 14, 16 were located in BA 9, channel 4 was located in BA 40, and channels 2, 3, 5, 6, 7 and 8 were located in the right IFC (BA 44). A subject-specific differential pathlength factor (DPF) constant was calculated based on the age of each subject (Duncan et al., 1996). And the sampling rate was set at 50Hz for data acquisition.

<Insert Figure 3 here.>

We used Homer2 NIRS processing package functions (Huppert et al., 2009) to perform the data processing in MATLAB (Mathworks, MA USA). Motion artifacts were removed by applying discrete wavelet to every channel data series, whereas very slow drifts and high-frequency noise were reduced using a band-pass filter (third-order Butterworth filter) with cut-off frequencies of 0.01-0.3 Hz (Delpy et al., 1998). The modified Beer-Lambert Law was applied to convert the OD data into concentration changes (Delpy et al., 1998). We found that the concentration of HbO was the most sensitive to changes in regional cerebral blood flow among the three NIRS parameters, which indicated brain activity (Moriguchi & Hiraki, 2019; Sitaram et al., 2007). Then, the raw data was converted into z scores by calculating the mean and standard deviation of the HbO concentration changes in each channel (Moriguchi & Hiraki, 2009).

Results

Behavioral Results

Among the 49 children who completed the experiments, 25 of them passed all the testing items and were grouped into the pass group, indicating the adult-like level of behavioral performance. Twenty children who failed to pass at least two items consecutively during cognitive shifting test were grouped into the perseverate group (see Table 1). Another four children committed some mistakes, but the mistakes were not consecutive, were thus excluded from the final analyses. Independent samples two-sample *t*-tests were conducted to determine any significant differences in their age, English ability and DCCS performance between the pass and perseverate groups. The results showed that the children in the pass and perseverate groups varied significantly in their age (t (43) = -3.29, p = .002), English ability (t (43) = -2.76, p = .008) and aggregate number of correct responses in the DCCS (t (43) = -5.72, p = .000), indicating that children in the pass group were significantly older and better in their bilingualism and EF than those in the perseverate group.

Bivariate correlation analysis showed that children's English ability was significantly correlated with the number of correct responses in DCCS (r = .69, p < .01). Logistic regression analysis was then conducted to further examine the predictive power of children's English ability on their DCCS group membership (pass or perseverate). The regression results ($p = 0.015$, odds ratio = 1.70 with 95% confidence interval 1.107-2.618) indicated that children's English ability significantly predicted their group membership, with one unit of increase in children's English ability lead to 1.70 units of increase in group membership (Table 2). The result indicated that children's bilingualism predicted their pass or perseverate behavior in the DCCS task. In addition, we also examined whether children's DCCS membership predicted their English ability through linear regression. The results indicated that the children's DCCS performance could significantly explain 15% of the variation in their English ability, $\beta = 1.31$, $R^2 = .15$, $F(1, 43) = 7.63$, $p < .001$.

<Insert Table 1 &2 here.>

fNIRS Results

The fNIRS data were processed in Matlab 2013b. For each participant, the average "rest hemoglobin" values for each channel were calculated by averaging 15s of data before the start of each DCCS test session, and the average "task hemoglobin" values were calculated by averaging 40s of data after the onset of each test session. By subtracting the average "rest hemoglobin" values from the average "task hemoglobin" values, we obtain a single value of ΔHbO for each task session. The mean ΔHbO for each participant was calculated by averaging the three test sessions.

First, we analyzed the brain activation for children in the pass group ($n = 25$) and the perseverate group ($n = 20$) separately. Paired t-tests were performed on the mean ΔHbO to examine the differences between the rest and the task for both the pass group and the perseverate group at each channel. Because 17 channels were investigated for this statistical test, the resulting t-tests were corrected for multiple comparisons using the false discovery rate (FDR). In the pass group, significant ΔHbO was observed in the ch 4 (t (24) = 2.62, p = .015) and ch 9 (t (24) = 2.89, p = .008) in the right frontal cortex, as well as in the ch 11 (t (24) = 3.01, p = .005), ch 12 (t (24) = 4.33, p = .000), ch 13 (t (24) = 4.91, p = .000), ch 14 (t (24) = 3.23, p = .004), ch 15 (t (24) = 3.96, p = .001), ch 16 (t (24) = 3.47, p = .002), and ch 17 (t(24) = 5.34, p = .000) in the prefrontal cortex. However, for the perseverate group, there was no significant ΔHbO in the right frontal cortex, but in the ch 12 (t (19) = 3.95, p = .001), ch 13 (t (19) = 3.18, p = .005) and ch 17 (t (19) = 5.13, p = .000) in the prefrontal cortex (also see Figure 4).

Next, we compared the aggregate "task hemoglobin" in all 17 channels for the pass group with the perseverate group using an independent sample t-test in SPSS. The results revealed that children in the pass group exhibited more considerable changes in the prefrontal cortex (ch 11 & 15) than those in the perseverate group (p < .05) (see Table 3).

Finally, we analyzed the correlation between behavioral results, English ability and activations in ch 11 and ch 15 (Table 4). We found that activation in ch 15 was significantly correlated with both behavioral results (r = -.37, p = 0.026) and children's English ability (r = -.34, p = 0.046), after corrected with FDR. This indicated that children's bilingualism affected their EF and brain function, which was evidenced by differences in neural activation during the cognitive shifting task between the pass and the perseverate group of children.

<Insert Figure 4 and Table 3-4 here.>

Discussion

Children's English ability was significantly correlated with their behavioral performance in DCCS, indicating that bilingual experience enhances young children's executive function and corroborates with existing evidence on bilingual advantage in the DCCS task (Moriguchi & Lertladaluck, 2019; Okanda et al., 2010). Previous studies have compared bilingual children with monolingual children and found that bilingual children outperformed monolingual children in the DCCS task, showing advanced executive function (see Barac et al., 2014, for review). The present study further established that among bilingual young children, the degree of their bilingualism, indicated by their verbal ability in a second language, affects their performance in the DCCS task that requires young children to inhibit irrelevant rules, shift between rules, and hold the current rule in mind.

Children's brain activations during the DCCS task were also observed, with different activation patterns for pass group and perseverate group: Children in the pass group significantly activated the prefrontal cortex than those in the perseverate group, corroborating with existing evidence that the maturation of the prefrontal cortex develops in parallel with preschoolers' executive function (Moriguchi & Hiraki, 2011; Moriguchi, Sakata, Ishibashi, & Ishikawa, 2015), as children in the pass group were significantly older and better in their EF than those in the perseverate group. It also corroborates the findings in the ERP study that children who perseverate failed to recruit lateral PFC and failed to reflect upon the rule representations during the DCCS (Espinet et al., 2012).

Furthermore, activation in the prefrontal region was significantly correlated with Chinese preschooler’s English ability, providing neural evidence that this brain region was responsible for the behavioral improvement with bilingual experience. Moriguchi et al.'s (2019) study did not establish such relationships because they examined different brain regions. However, the results were partially supported by another fNIRS study (Arredondo, Hu, Satterfield, & Kovelman, 2017), which found that bilingual school-aged children show stronger activations in the left prefrontal cortex during a non-verbal attentional control task. The two studies used different behavioral tasks, but they utilized similar brain regions that assist children's executive processing (Morton, Bosma, & Ansari, 2009). Combing the fNIRS evidence from the present study and the MRI evidence in Morton et al.'s (2009) study, we can conclude that children's bilingual experience has shaped their brain development that yields changes in their cognitive development.

Conclusion

This study has examined the relationship between Chinese preschoolers’ bilingualism and their performance in the Dimensional Card Change Sort (DCCS) task to ascertain whether prefrontal activation was associated with their bilingualism and executive function. The results indicated that Chinese preschoolers’ English ability was significantly correlated with their behavioral performance in DCCS and predicted children's group membership (pass or perseverate). In addition, children in the pass group significantly activated the prefrontal cortex than those in the perseverate group, indicating that activation in the prefrontal region was significantly correlated with children's English ability. As the first fNIRS study on Chinese-English bilingual preschoolers, who are very few in China because of the ban of TESL in preschools, this study has provided neuroimaging evidence to support the positive effect of early bilingualism on the development of executive function and prefrontal activation. This finding lends empirical support to the positive effect of bilingual cognitive advantage, thus tends to uphold the additive bilingualism rather than subtractive bilingualism.

The present study, however, has some limitations. First, we only examined 17 channels due to the limited channels provided by the NIRS device. Children in the pass and perseverate group might utilize some different brain regions that were not examined in the present study. Multiple regions were found to be reliably activated across a series of executive function studies: the anterior areas (including the PFC and the anterior cingulate cortex, ACC) and the posterior (parietal) areas (Abutalebi & Green, 2008; Collette et al., 2005). Second, we had to use teachers' rated scores to evaluate children's English proficiency because of the lack of reliable and validated instrument for Chinese preschoolers. Third, this cross-sectional study might not be able to provide substantial evidence to confirm the cause-effect relationship; thus, future studies shall employ longitudinal design to follow up with the developmental changes in children's EF. Fourth, we only examined the effect of English ability among bilingual children; the effect of English ability among monolingual children was not explored. Several studies have considered early language ability that precedes and facilitates the acquisition of EF abilities during early childhood (Gooch, Thompson, Nash, Snowling, & Hulme, 2016; Kuhn et al., 2014); thus, future studies shall also include monolingual children to examine the role of language as precursors of EF development. Last but not least, we did not exam the verbal age of Chinese language in this study, because Moriguchi and Lertladaluck (2019) found a significant correlation between English verbal age and successful switching even after controlling for Japanese verbal age. In future studies, however, children's verbal age of Chinese language should be examined to explore any other possible relationships.

Nevertheless, this study has challenged the non-significant finding reported by Moriguchi and Lertladaluck (2019) whereas supported the conclusion on bilingual advantage in EF by comparing bilingual children with monolingual children (Bialystok, 2014). It offers the first neural evidence that young children's early bilingualism interacts with early cognitive development to confer changes in the functionality of the prefrontal cortex for children's executive functioning.

Reference

Abutalebi, J., & Green, D. W. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognition Processes, 23*(4), 557-582. doi:10.1080/01690960801920602

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., . . . Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22*(9), 2076-2086.

Adi-Japha, E., Berberich-Artzi, J., & Libnawi, A. (2010). Cognitive flexibility in drawings of bilingual children. *Child Development, 81*(5), 1356-1366. doi:10.1111/j.1467-8624.2010.01477.x.

Antoniou, M. (2019). The advantages of bilingualism debate. *Annual Reviews of Linguistics, 5*, 395-415. doi:10.1146/annurev-linguistics-011718-011820

Arredondo, M. M., Hu, X.-S., Satterfield, T., & Kovelman, I. (2017). Bilingualism alters children's frontal lobe functioning for attentional control. *Developmental Science, 20*, e12377.

Barac, R., Bialystok, E., Castro, D. C., & Sanchez, M. (2014). The cognitive development of young dual language learners: A critical review. *Early Childhood Research Quarterly, 29*(4), 699-714. doi:10.1016/j.ecresq.2014.02.003

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. *Child Development, 87*, 1277-1290.

Bialystok, E. (2001). *Bilingualism in development: Language, literacy and cognition.* Cambridge University Press.

Bialystok, E. (2010). Global-local and trial-making tasks by monolingual and bilingual children: Beyond inhibition. *Developmental Psychology, 46*(1), 93-105.

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin, 142*(3), 233-262. doi:10.1037/bul10000099

Bialystok, E., & Barac, R. (2012). Emerging bilingualism: Dissociating advantages for metalinguistic awareness and executive control. *Cognition, 122*, 67-73. doi:10.1016/j.cognition.2011.08.003

Bialystok, E., & Martin, M. M. (2004). Attention and inhibition in bilingual children: Evidence from the dimensional change card sort task. *Developmental Science, 7*, 325-339. doi:10.1111/j.1467-7687.2004.00351.x

Bialystok, E., Craik, F. I., Green, D. W., & Gollan, T. H. (2009). Bilingual minds. *Psychological Science in the Public Interest, 89-129*, 10. doi:10.1177/1529100610387084

Blair, C., Sulik, M., Willoughby, M., Mills-Koonce, R., Petrill, S., Bartlett, C., & Greenberg, M. (2015). Catechol-O-methyltransferase Val158met polymorphism interacts with early experience to predict executive functions in early childhood. *Developmental Psychobiology, 57*(7), 833-841.

Buac, M., & Kaushanskaya, M. (2014). The relationship between linguistic and non-linguistic cognitive control skills in bilingual children from low socioeconomic backgrounds. *Frontiers in Psychology, 5*, 1-12.

Carlso, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science, 11*(2), 282-298. doi:10.1111/j.1467-7687.2008.00675.x.

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping, 25*(4), 409-423.

Crivello, C., Kuzyk, O., Rodrigues, M., Friend, M., Zesiger, P., & Poulin-Dubois, D. (2016). The effects of bilingual growth on toddlers’ executive function. *Journal of Experimental Child Psychology, 141*, 121-132. doi:10.1016/j.jecp.2015.08.004

Darcy, N. T. (1953). A review of the literature on the effects of bilingualism upon the measurement of intelligence. *Journal of Genetic Psychology, 82*, 21-57.

Darcy, N. T. (1963). Bilingualism and the measure of intelligence: Review of a decade of research. *Journal of Genetic Psychology, 82*, 259-282. doi:10.1080/00221325.1963.10532521.

Della Rosa, P. A., Videsott, G., Borsa, V. M., Canini, M., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2013). A neural interactive locationfor multilingual talent. *Cortex, 49*, 605-608. doi:10.1016/j.cortex.2012.12.001

Delpy, D. T., Cope, M., van der Zee, P., Arridge, S. R., Wray, S., & Wyatt, J. S. (1998). Estimation of optical pathlength through tissue from direct time of flight measurement. *Physics in Medicine & Biology, 33*(12), 1433-1445.

Duncan, A., Meek, J. H., Clemence, M., Elwell, C. E., Fallon, P., Tyszczuk, L., . . . Delpy, D. T. (1996). Measurement of cranial optical path length as a function of age using phase resolved near-infrared spectroscopy. *Pediatric Research, 39*(5), 889-894.

Espinet, S. D., Anderson, J. E., & Zelazo, P. D. (2012). N2 amplitude as a neural marker of executive function in young children: An ERP study of children who switch versus perseverate on the Dimensional Change Card Sort. *Developmental Cognitive Neuroscience, 2S*, S49-S58.

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *The Journal of Neuroscience, 33*(2), 387.

Graham, V. T. (1925). The intelligence of Italian and Jewish children. *Journal of Abnormal and Social Psychology, 2*, 3710-3716. doi:10.1037/h0073438

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition, 1*, 67-81.

Hayakawa, S., & Marian, V. (2019). Consequences of multilingualism for neural architecture. *Behavioral and Brain Functions, 15*(6), 1-24. doi:10.1186/s12993-019-0157-z

Higby, E., Jungna, K., & Obler, L. K. (2013). Multilingualism and the brain. *Annual Review of Applied Linguistics, 33*, 68-101. doi:10.1017/S0267190513000081

Hughes, C., & Graham, A. (2010). Executive functions and development. In J. Reed, & J. Warner-Rogers, *Child Neuropsychology: Concepts, Theory, and Practice* (pp. 264-284). Cambridge University Press.

Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics, 48*(10), D280-D298.

Jones, W. R., & Stewart, W. A. (1951). Bilingualism and verbal intelligence. *British Journal of Psychology, 4*, 3-8. doi:10.1111/j.2044-8317.1951.tb00300.x

Kroll, J. F. (2015). On the consequences of bilingualism: We need language and the brain to understand cognition. *Bilingualism: Language and Cognition, 18*, 32-34.

Kuipers, J. R., & Thierry, G. (2012). Event-related potential correlates of language change detection in bilingual toddlers. *Developmental Cognitive Neuroscience, 2*, 97-102.

Lewis, D. G. (1959). Bilingualism and non-verbal intelligence: A further study of test results. *British Journal of Educational Psychology, 29*, 17-22. doi:10.1111/j.2044-8279.1959.tb01470.x

Li, P., Legualt, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: Anatomincal changes in the human brain. *Cortex, 58*, 301-324.

Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010). Illuminating the developing brain: The past, present and future of functional near-infrared spectroscopy. *Neuroscience and Behavioral Reviews, 34*, 269-284.

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. *Brain and Cognition, 74*(3), 347-357.

Macnamara, J. (1966). *Bilingualism and primary education.* Edinburgh University Press.

Manuel, H. T. (1935). A comparison of Spanish-speaking and English-speaking children in reading and arithmetic. *Journal of Applied Psychology, 19*, 189-202.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100. doi:10.1006/cogp.1999.0734

Morales, J., Calvo, A., & Vialystok, E. (2013). Working memory development in monolingual and bilingual children. *Journal of Experimental Child Psychology, 114*(2), 187-202. doi:10.1016/j.jecp.2012.09.002.

Moriguchi, Y., & Hiraki, K. (2009). Neural origin of cognitive shifting in young children. *Proceedings of the National Academy of Sciences, 106*(14), 6017-6021.

Moriguchi, Y., & Hiraki, K. (2011). Longitudinal development of prefrontal function during early childhood. *Developmental Cognitive Neuroscience, 1*(2), 153-162.

Moriguchi, Y., & Hiraki, K. (2011). Neural origin of cognitive shifting in young children. *Proceedings of the National Academy of Sciences, 106*(14), 6017-6021.

Moriguchi, Y., & Lertladaluck, K. (2019). Bilingual effects on cognitive shifting and prefrontal activations in young children. *International Journal of Bilingualism*, 1-11. doi:10.1177/1367006919880274

Moriguchi, Y., & Shinohara, I. (2018). Effect of the COMT Val158Met genotype on lateral prefrontal activations in young children. *Developmental Science, 21*(5), e12649.

Moriguchi, Y., & Shinohara, I. (2019). Socioeconomic disparity in prefrontal development during early childhood. *Scientific Reports, 9*(1), 2585.

Moriguchi, Y., Sakata, Y., Ishibashi, M., & Ishikawa, Y. (2015). Teaching others rule-use improves executive function and prefrontal activations in young children. *Frontiers in psychology, 6*, 894.

Morton, J. B., Bosma, R., & Ansari, D. (2009). Age-related changes in brain activation associated with dimensional shifts of. *NeuroImage, 46*, 249-256.

Okanda, M., Moriguchi, Y., & Itakura, S. (2010). Language and cognitive shifting: Evidence from young monolingual and bilingual children. *107*, 68-78. doi:10.2466/03.10.28.PRO.107.4.68-78

Peal, E., & Lambert, W. E. (1962). The relation of bilingualism to intelligence. *Psychological Monographs, 76*, 1-23.

Sitaram, R., Zhang, H., Guan, C., Thulasidas, M., Hoshi, Y., Ishikawa, A., … Birbaumer, N. (2007). Temporal classification of multichannel near-infrared spectroscopy signals of motor imagery for developing a brain-computer interface. *NeuroImage*, *34*(4), 1416–1427.

Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive Development, 11*, 37-63.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood: I. The development of executive function. *Monographs of the society for research in child development, 68*(3), 11-27.