HHS Public Access
Author manuscript
Child Dev. Author manuscript; available in PMC 2017 July 01.

Published in final edited form as:
Child Dev. 2016 July ; 87(4): 1277–1290. doi:10.1111/cdev.12538.

Behavioral and Electrophysiological Differences in Executive Control between Monolingual and Bilingual Children

Raluca Barac,
Hospital for Sick Children & York University

Sylvain Moreno, and
Simon Fraser University

Ellen Bialystok
York University

Abstract

This study examined executive control in 62 5-year-old children who were monolingual or bilingual using behavioral and event-related potentials (ERPs) measures. All children performed equivalently on simple response inhibition (gift delay) but bilingual children outperformed monolinguals on interference suppression (ANT) and complex response inhibition (go/no-go task). On the go/no-go task, ERPs showed larger P3 amplitudes and shorter N2 and P3 latencies for bilingual children than for monolinguals. These latency and amplitude data were associated with better behavioral performance and better discrimination between stimuli for bilingual children but not for monolingual children. These results clarify the conditions that lead to advantages for bilingual children in executive control and provide the first evidence linking those performance differences to electrophysiological brain differences in children.

Keywords

executive control; bilingualism; ERPs; go-no/go task; ANT flanker task; neuroplasticity

---

Considerable evidence has accumulated demonstrating that bilingual children outperform monolinguals on a variety of executive control tasks (reviews in Akhtar & Menjivar, 2012; Barac, Bialystok, Castro, & Sanchez, 2014; meta-analysis in Adesope, Lavin, Thompson, & Ungerleider, 2010) but the conditions under which these effects are found and the mechanism responsible are still not fully understood. For example, such bilingual advantages are not always found (e.g., Dunabeitia et al., 2014) and sometimes advantages are found for some tasks but not others within a single study (e.g., Bialystok, Barac, Blaye, & Poulin-Dubois, 2010). In the present study, we administered tasks that varied in their executive control demands to identify the conditions that are associated with this bilingual advantage. Event-related potentials (ERPs) while children performed a go/no-go task were included to investigate the possible neural basis of these effects.

Correspondence: Ellen Bialystok, Department of Psychology, York University, 4700 Keele St., Toronto, ON, Canada M3J 1P3. ellenb@yorku.ca.

To date, our knowledge about experience-dependent brain changes or neuroplasticity in bilingualism is based primarily on adult imaging and electrophysiological data (e.g., Abutalebi et al., 2012; Bialystok et al., 2005; for review see Hervais-Adelman, Moser-Mercer, & Golestani, 2011). No research with children has examined brain function in nonverbal executive control tasks, and so it is not known whether the amount of bilingual experience accrued in childhood is sufficient to modify the neural basis of this behavior in children. A few studies have investigated the neural correlates of verbal processing in children and have demonstrated differences between monolinguals and bilinguals from very early in development. For instance, Conboy and Mills (2006) presented Spanish-English bilingual children who were 19- to 22-months old with known and unknown words spoken in both languages while ERPs were recorded. The results showed different organization patterns for children with high or low vocabularies from 200-400 and 400-600 ms and for the dominant or non-dominant language, with shorter latencies in the dominant language in an early positive component, P100. These findings show that even very brief exposure to two languages during childhood alters the brain responses in language tasks.

Extending this approach to an investigation of neural differences between monolingual and bilingual children in nonverbal executive control requires first establishing the type of tasks for which differences are found. Bilingual children have outperformed monolingual children on tasks measuring attentional control and inhibition (Bialystok & Martin, 2004; Kalashnikova & Mattock, 2012; Yang, Yang, & Lust, 2011), working memory (Blom et al., 2014; Morales, Calvo & Bialystok, 2013), and cognitive flexibility or switching (Barac & Bialystok, 2012; Bialystok & Viswanathan, 2009), but not on tasks in which they were required to delay gratification (Carlson & Meltzoff, 2008), control impulses (Carlson & Meltzoff, 2008), or withhold a habitual or prepotent response (Bonifacci, Giombini, Bellocchi, & Contento, 2011; Martin-Rhee & Bialystok, 2008). Early accounts pointed to inhibition as the critical difference between processing in monolinguals and bilinguals, but subsequent research revealed the inadequacy of this explanation in both children (Bialystok, 2010) and adults (Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009; Hilchey & Klein, 2011), in both cases arguing that inhibition alone could not account for the results. Moreover, inhibition is not a single process, and again research with children (Bunge, Hazeltine, Scanlon, Rosen & Gabrieli, 2002; Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008) and adults (Bunge et al., 2002; Luk, Anderson, Craik, Grady, & Bialystok, 2010) has reported different outcomes in both behavioral and imaging studies relating to different types of inhibitory control, namely response inhibition (withholding or delaying of a prepotent or automatic response) and interference suppression (suppression of interference due to stimulus competition).

One possible explanation for this observation that bilingual advantages appear on only some tasks is that there may be a threshold level of executive demands or complexity, or the need for a particular subset of executive processes for differences between language groups to emerge. This is in line with the idea that there are no “pure” executive control tasks, but rather tasks typically measure more than one executive function (Miyake et al., 2000). Garon, Bryson and Smith (2008) built on this conceptualization of executive control in adults and proposed an integrative framework for studying executive control in children by examining tasks in terms of attentional, working memory, response inhibition, and shifting demands. The authors further distinguished between simple response inhibition which requires withholding/delaying a prepotent automatic response (e.g., gift delay task) and complex response inhibition involving holding a rule in mind, responding according to this rule, and inhibiting a prepotent response (e.g., bear and dragon task: child must do what bear asks and inhibit doing what dragon asks). Thus, it may be that differences in task complexity as reflected by the executive control demands determine whether or not bilingual children will perform differently from monolinguals on that task. This approach to determining the conditions for observing bilingual advantages is based on a more quantitative view of executive control in which varying amounts of effortfulness are required rather than the more usual qualitative view in which different components (e.g., inhibition, shifting) are required. The two approaches are not mutually exclusive in that the need for a wider selection of executive control components leads to more effortfulness.

There is some evidence in support of the idea that bilingual advantages in executive control require some minimal level of executive demands or complexity to emerge. Foy and Mann (2013) compared 5-year-old Spanish-English bilinguals and English monolinguals performing a verbal and a non-verbal go/no-go task. There were no behavioral differences on the verbal task, but on the second block of the non-verbal task there was a bilingual advantage. What was unique to this second block was that targets and distractors were reversed. Thus, in addition to the demand of responding to a target and ignoring a distractor, children also had to switch responses from block to block, thus requiring cognitive flexibility. Foy and Mann (2014) concluded that there was an advantage for bilinguals in a nonverbal task that required switching attention from one target to another in the context of a response inhibition task (i.e., block 2), but not strictly for withholding responses (block 1).

In the present study we applied the distinction between simple and complex response inhibition tasks proposed by Garon and colleagues (2008) and included three executive control tasks that differed in their executive demands: gift delay, go/no-go, and attentional network test (ANT). The gift delay has low working memory and shifting demands and the main requirement for success is to withhold the compelling prepotent response to open the gift. Go/no-go paradigms require participants to produce a response to selected stimuli and refrain from responding when no-go stimuli are presented. Thus, in contrast to the gift delay task, the go/no-go task involves holding a rule in mind, shifting between two different responses, and inhibiting the prepotent response to respond on every trial. The go/no-go stimuli used in the present study were geometric figures that differed in shape (rectangles and triangles) and color (white and purple), but the response rule was based solely on color. Thus, the task involved attentional, working memory and inhibitory demands and is therefore a measure of complex response inhibition. Because these demands are more complex than those in the gift delay, the prediction is that performance on this task will discriminate between the two language groups.

The ANT is a flanker task in which children are asked to focus on selected information given as the middle fish in an array of five fish and ignore the four flanking fish (Rueda et al., 2004). The flankers are more salient than the middle fish, so the prepotent response in this case is to indicate the direction of the flanking fish. The task measures interference suppression as the main demands are related to the suppression of interference due to stimulus competition. The task allows for the evaluation of attention and inhibitory processing in different conditions: with distractors that provide facilitating or conflicting information (congruent and incongruent trials) and without distractors (control trials). Bilingualism has been shown to improve performance on the ANT/flanker task in both children (e.g., Kapa & Colombo, 2013; Mezzacappa, 2004; Yang, Yang, & Lust, 2011; Yoshida, Tran, Benitez, & Kuwabara, 2011) and adults (Costa, Hernandez, & Sebastian-Galles, 2008; Costa et al., 2009). Although typically a bilingual advantage is reported on this task, this pattern is better understood in the light of two further findings. First, the bilingual advantage is present not only on the incongruent trials, but also on the congruent trials, suggesting that it is not just conflict resolution processes that show bilingualism-related plasticity but other executive processes as well. Second, increasing the executive demands of the task by manipulating the ratio of congruent to incongruent trials shows that bilingual advantages are observed only in conditions that require a great deal of monitoring (Costa et al., 2009). The lack of language group differences on the control trials, where the target stimulus is present by itself, supports the argument that when the executive task demands are complex and require involvement of a set of executive processes, bilinguals are better able than monolinguals to handle the combination of cognitive demands, whereas when the executive demands are low, the two groups perform similarly.

The go/no-go task was administered with EEG to investigate the neural basis of the possible executive control differences between monolingual and bilingual children. Two ERP components, N2 and P3, have been found to be reliably related to performance in this task in electrophysiological studies of children's executive control development (Cieselski, Harris, & Cofer, 2004; Lahat, Todd, Mahy, & Zelazo, 2010; Lamm, Zelazo, & Lewis, 2006), making the task appropriate for use with young children. N2 is a negative deflection recorded at approximately 200 to 400 ms after stimulus onset and is typically larger for no-go than go trials, although this is not always the case (e.g., Davis, Bruce, Snyder, & Nelson, 2003). N2 generally shows maximal amplitude at the anterior-central electrode sites in both children (Todd, Lewis, Meusel, & Zelazo, 2008) and adults (Nieuwenhuis,Yeung, Van den Wildenberg, & Ridderinkhof, 2003) and a right-lateralized scalp distribution (Todd et al., 2008). The N2 component is considered to represent response inhibition, conflict monitoring, and perceptual mismatching (Botvinick, Braver, Carter, & Cohen, 2001; Ciesielski, et al., 2004; Duan et al., 2009). The P3 component in adults appears as a positive waveform occurring within 300 to 500 ms post-stimulus onset, with maximal amplitude at the frontal-central electrode sites for the no-go trials and at the parietal sites for the go trials (Pfefferbaum, Ford, Weller, & Kopell, 1985), but this pattern is less consistent with children. For example, Jonkman, Lansbergen, and Stauder (2003) showed that 9- and 10-year-old children made more false alarms than adults and the ERPs results indicated the absence of a fronto-central no-go P3 component but showed a no-go N2 component with adult-like characteristics. In general, P3 is considered to reflect later stages of inhibition such as response evaluation or monitoring the outcome of inhibition (Duan et al., 2009; Schmajuk, Liotti, Busse, & Woldorff, 2006) or response inhibition (Freitas, Azizian, Leung, & Squires, 2007).

In developmental research, both the amplitude and latency of relevant ERP components decrease with age (e.g., Johnstone, Barry, Anderson, & Coyle, 1996), but within a single age group better behavioral performance is associated with larger amplitudes (e.g., Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; Pliszka, Liotti, & Woldorff, 2000). For instance, controls had larger amplitudes and better accuracy than children with ADHD in a go/no-go task (Pliszka et al., 2000) and gifted children showed larger P3 amplitudes and shorter P3 latency than average children in the presence of superior behavioral performance, suggesting that that gifted children have a more mature and efficient control network (Duan et al., 2009; Liu, Xiao, Shi, Zhao, & Liu, 2011). Similarly, in a training study, 5-year-old children who received music training showed increases in P2 amplitude post-training that correlated with increases in verbal intelligence (Moreno et al., 2011). Two recent studies with adults have also shown this pattern of larger N2 and P3 amplitude in bilinguals than in monolinguals for comparable levels of behavioral performance (Fernandez, Tartar, Padron, & Acosta, 2013; Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014).

In the present study, monolingual and bilingual pre-school children performed behavioral tasks differing in their executive control demands (gift delay, ANT flanker, go/no-go) and included electrophysiological data for one of them (go/go-no). Based on previous findings, it was expected that bilinguals would outperform monolinguals on the interference suppression task when distractors are present (ANT; congruent and incongruent trials but not neutral trials), but would perform equivalently to monolinguals on the measures of simple response inhibition (gift delay). For the go/no-go behavioral performance, the prediction was that bilingual children would perform this task better than monolingual children and that the electrophysiological characteristics of the N2 and P3 components would show greater amplitude and shorter latency in bilinguals than in monolinguals. The intention was to identify the types of executive control tasks where performance diverged for monolingual and bilingual children and to determine the electrophysiological basis of those differences. There is increasing interest in neuroplasticity and the power of experience to shape minds (Kuhl & Rivera-Gaxiola, 2008). The stakes are particularly high for executive control because of its involvement academic success (Best, Miller, & Naglieri, 2011; Blair & Razza, 2007) and long term health and well-being (Duncan, Ziol-Guest, & Kalil, 2010).

Method

Participants

Participants were 62 5-year-old children (*M* = 63.9 months, *SD* = 5.6, range 53-76 months). Data on socioeconomic status (SES), as indexed by highest level of maternal education were collected by the means of a Language and Social Background Questionnaire filled out by parents. Inclusion criteria required participants to be right-handed, have normal or corrected-to-normal vision, be free of psychiatric diagnoses and medication, and attend kindergarten programs in which the language of instruction was English. The demographic composition was 32 Caucasian, 11 African-American, 7 Hispanic, 7 Asian, and 5 South Asian. Children were recruited through ads placed in the community in such places as libraries. Data were collected between June and August, 2011, in Toronto, Canada.

Children were assigned to the monolingual (24 girls, 13 boys) or bilingual (10 girls, 15 boys) group on the basis of parents' answers to a questionnaire about children's comprehension and production of language(s) and patterns of language use in and out of the home. The classification as "bilingual" in the present study depended on children's expressive use of both languages, such that "receptive-only bilinguals" were not included in the sample. Thus, 13 additional children who were tested were not included in the analyses because they could not be unambiguously assigned to one of these two language groups. These children lived in families where the parents reported that they spoke a non-English language in the home but that the child did not speak that language. Since the parents did not acknowledge that the child spoke another language, it was not possible to designate the child as bilingual; however, since the child was growing up in a home where another language was used routinely, it was also not possible to designate the child as monolingual. The bilingual children included in the study spoke English plus one of twelve different languages: Spanish ($n = 7$), French ($n = 4$), Mandarin ($n = 3$), Greek ($n = 2$), Korean ($n = 2$), Ukrainian ($n = 1$), Cantonese ($n = 1$), Vietnamese ($n = 1$), Tagalog ($n = 1$), Russian ($n = 1$), German ($n = 1$), and Polish ($n = 1$). About one third (n = 9, 36%) of the children in the bilingual group were simultaneous bilinguals who learned both languages from birth, another third (n = 8, 32%) had English as a first language, and the rest (n = 8, 32%) spoke the non-English language first. The majority of the bilingual children was born in Canada, with only four children born outside Canada. For 64% of the bilingual children, both parents were born outside Canada and for only 16% of the children both parents were born in Canada. The other 20% of the bilingual children had one parent born in a country other than Canada.

Procedure

Children were tested individually in a single session lasting about two hours. All tasks were administered in English. Children completed the Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition, Attention Network Task, gift delay, and the go/no-go task. Order of task administration was counterbalanced across participants.

Language and Social Background Questionnaire (LSBQ)—The questionnaire was completed by parents and included questions about home language use patterns on a scale from 1 to 5, where 1 indicates the exclusive use of English, 5 indicates the exclusive use of a non-English language and 3 indicates balanced use of the two. The scales were combined to produce a mean score for language use by the child at home and a mean score for the language spoken to the child at home. SES was indexed as the level of maternal education on a 5-point scale (1 = no high school diploma, 2 = high school graduate, 3 = some college or college diploma, 4 = bachelor's degree, 5 = graduate degree).

Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition (WPPSI-III)—Children received the Vocabulary and the Block Design subtests of the WPPSI-III to estimate scores for verbal and nonverbal reasoning. The administration and scoring followed the guidelines outlined in the manual (Wechsler, 2002). Scaled scores for each of these subtests were obtained from the raw scores and children's chronological age and used to estimate full-scale IQ.

Gift delay with cover—This is a delay of gratification task (Carlson & Meltzoff, 2008) in which children were offered a gift and needed to wait without peeking inside the gift box while the experimenter was out of the room. The 3-minute period of the experimenter's absence was videotaped and children's reactions were assigned a score between 1 and 5 (1 = removes cover and looks inside box; 2 = looks in window but does not remove cover; 3 = touches box or cover without looking inside; 4 = looks at (but not inside) the box and does not touch box or cover; 5 = never touches or looks at or inside the box). Data were scored independently by two research assistants. Inter-rater reliability was calculated using Cohen's Kappa coefficient and showed substantial agreement between the independent coders, $\kappa = 0.79$, $p < .001$.

Attention Network Task (ANT)—This computerized test indexes three functions of attention: alertness, orientating and conflict resolution (Rueda et al., 2004). The task was programmed in E-Prime software and administered on a Lenovo X61 touch-screen tablet computer with a 12-inch monitor. Stimuli consisted of yellow fish appearing on a blue background. The computer had two mice attached to it, one on each side, and children were instructed to press the indicated button on the left or the right mouse to show the direction that the target (middle) fish was pointing. Children were told that a fish would appear on the screen, either by itself or together with four other fish, and their task was to feed the target fish by pressing the appropriate mouse button. Children received feedback for their performance.

There were two experimental blocks, each with 48 trials, preceded by a practice block of 24 trials. Within each block, there was an equal number of three types of trials: neutral (target fish appeared alone), congruent (target and flanking fish pointed in the same direction) and incongruent trials (flanking fish pointed in the opposite direction from the target fish). Each trial consisted of the following sequence: a fixation cross in the center of the screen for a variable duration between 400 ms and 1600 ms, a warning cue along with a fixation cross for 150 ms, another fixation cross in the center of the screen for 450 ms, the target that appeared either above or below a fixation cross for another 1700 ms, and feedback for 1000 ms. For half of the trials in each block the target array appeared above the fixation cross and for the other half the target array appeared below the fixation cross. The warning cue was represented by an asterisk and there were 4 types of warning cue manipulations: no cue (12 trials), center cue (12 trials; the asterisk appeared in the center of the screen, replacing the fixation cross), double cue (12 trials; two asterisks appeared simultaneously above and below the fixation cross), and spatial cue (12 trials; a single asterisk appeared in the same position as the upcoming target array). Consequently, each trial represented one of the 12 possible combinations of the three target types (neutral, congruent, incongruent) and four warning cues (no cue, central cue, double cue and spatial cue). These warning cue manipulations were performed to allow calculating scores for the three components of the attention network: alertness, orientating and conflict resolution.

Both response times (RTs) and accuracy were recorded and the RTs for different conditions were subsequently used to compute the scores for the three attentional components. Alerting was calculated as the difference in RT between the no cue trials and the double cue trials. Orienting was calculated as the difference in RT between the central cue trial and the spatial cue trials. Finally, the score for the conflict component was calculated by subtracting the RT for the congruent trials from the RT for the incongruent trials.

Go/no-go task and ERP recording—The task was programmed using Presentation software package (Presentation 12.00, Neurobehavioral Systems, Albany, USA) and was administered on a Dell desktop computer with a 19-inch LCD monitor. Children were seated in a comfortable chair, 50 cm from the screen. The seat was adjusted so that the child's eye level was in the middle of the computer screen. The stimuli consisted of 8 geometric shapes – triangle or rectangle, aligned vertically or horizontally, colored white or purple (see Figure 1). On each trial, one of these stimuli was presented in the center of the screen. Children were instructed to press the mouse button when the shape was white and to refrain from pressing when the shape was purple. Different shapes and orientations were included to reduce stimuli repetition effects.

Each trial consisted of the following sequence: a white cross on a black background appeared for 500 ms, a blank screen for a variable duration between 0 and 500 ms before the stimulus, then a stimulus in the center of the screen for 300 ms. A blank-screen interval of 900 ms separated trials, a duration that corresponded to the post-stimulus interval. Thus, from the appearance of the stimulus, children had 1200 ms to make a response. The experiment lasted about 15 minutes and consisted of 200 trials of which 80% (160) were go trials and 20% (40) were no-go trials. This ratio of go to no-go trials is similar to that used in previous ERP studies of response inhibition in children (e.g., Cragg, Fox, Nation, Reid, & Anderson, 2009; Dimoska, Johnstone, Barry, & Clarke, 2003). The 200 trials were presented in random order in a single block. The experimental block was preceded by a practice block of 20 trials to familiarize children with the stimuli and the rules. No feedback was provided during the task. Accuracy rates and ERPs were recorded for go and no-go trials, and RTs were recorded for the go trials.

Electroencephalogram (EEG) was continuously recorded using a Biosemi amplifier system (Amsterdam, BioSemi Active 2) from 64 active Ag-AgCl electrodes mounted on a child-sized elastic cap and located at standard positions (International 10/20 system sites). On-line recordings were referenced to the Common Mode electrode and were re-referenced off-line to the algebraic average of all electrodes. In order to detect horizontal eye movements and blinks, the electro-oculogram was recorded from electrodes placed 1 cm to the left and right of the external canthi and from electrodes beneath the right and left eyes.

The bandpass was 0.01—30 Hz and data were digitized at a 500-Hz sampling rate. Impedances were maintained below 20 Ohms. EEG data were analyzed using the Besa software (Version 5.1.8; MEGIS Software, Gmbh). Recordings were segmented into 1000-ms epochs, starting 200 ms before stimuli. ERP data from go and no-go trials were baseline corrected using the initial 200 ms of each segment. Trials containing ocular and movement artifacts, amplifier saturation or too much noise were excluded from the averaged ERP waveforms ($M = 9.5\%$). Amplitude thresholds were adjusted on a participant-by-participant basis to include a minimum of 85% of the target stimuli in the average. Thresholds ranged from 300 to 400 μV. A 60Hz notch filter was also used on the data. ERPs were then averaged separately for each condition and electrode site. Error trials were not included in the analyses.

Go/no-go task ERP analyses—Analyses were performed on correct trials only. The mean number of trials contributing to the event-related potentials for the monolingual children was 109.3 (*SD* = 21.8) for the go trials and 29.1 (*SD* = 5.5) for the no-go trials. The mean number of trials contributing to the event-related potentials for the bilingual children was 115.8 (*SD* = 25.2) for the go trials and 28.3 (*SD* = 7.1) for the no-go trials. There were no differences between the two language groups on the number of go trials, $t(48) = -0.97$, *n.s.*, or no-go trials, $t(48) = 0.43$, *n.s,* included in the analyses.

The visual stimuli elicited a series of positive and negative deflections that were broadly distributed over the scalp. The waveform components of interest were N2 (time window between 300 and 500 ms post-stimulus) and P3 (time window between 500 and 800 ms post-stimulus). Both ERP components were analyzed for mean amplitude and peak latency. The time windows were chosen based on visual inspection of both grand-average and individual waveforms.

Grand-average ERP waveforms in the two language groups and in the go and no-go conditions were obtained at the following sites: F1, F2, Fz, F3, F4, FC1, FC2, FCz, FC3, FC4, C1, C2, Cz, C3, C4, CP1, CP2, CPz, CP3, CP4, P1, P2, Pz, P3, P4. ERP amplitudes and latencies for each of the two components (i.e., N2 and P3) were analyzed using four-way mixed ANOVA with laterality (5 levels: two on the left, F1, FC1, C1, CP1, P1, and F3, FC3, C3, CP3, P3; midline, Fz, FCz, Cz, CPz, Pz; two on the right, F2, FC2, C2, CP2, P2, and F4, FC4, C4, CP4, P4), anterior-posterior electrode position (5 levels: frontal, F3, F1, Fz, F2, F4; frontal-central, FC3, FC1, FCz, FC2, FC4; central, C3, C1, Cz, C2, C4; central-parietal, CP3, CP1, CPz, CP2, CP4; parietal, P3, P1, Pz, P2, P4), and condition (2 levels, go, no-go trials) as within-subject factors, and language group (2 levels, monolinguals, bilinguals) as a between-subject factor. For the statistical analyses, Greenhouse-Geisser epsilon adjustment was used when appropriate in order to correct for the violation of the assumption of sphericity.

Results

Background Measures

Data regarding home language use, age, SES scores and general cognitive functioning are presented in Table 1. The main variables from the LSBQ were the composite scores indicating the language that the child speaks at home (with 1 being only English) and the language the child hears spoken at home between parents and siblings. Because there was no variability in the home linguistic experience of the monolingual group, the two language groups could not be compared on these scores. Nonetheless, to understand the home linguistic experience of the bilingual children, one-sample *t*-tests were conducted to compare the reported scores to the theoretical mean of 3.0 indicating balanced use of the two languages. Results showed that bilingual children used, $t(24) = -1.2$, *n.s.*, and heard, $t(24) = 0.58$, *n.s.*, both languages relatively equally at home. Although there was variation in these scores for individual children, the actual range of values was small, indicating that all the children in the bilingual group were routinely engaged in both English and the non-English language at home.

On other background measures, monolingual and bilingual children had similar age, $F(1, 60) = 3.01$, *n.s.*, SES, $F < 1$, and general cognitive level (WPPSI-III score), $F < 1$. Comparing scores on the separate scales of the WPPSI-III, one-way ANOVAs showed that monolingual children obtained higher expressive vocabulary scores than bilinguals, $F(1, 59) = 4.13$, $p < .05$, $\eta_p^2 = .07$. This result is consistent with the literature showing that bilingual children have smaller receptive vocabulary in English than is found for monolingual English-speaking children (Bialystok, Luk, Peets, & Yang, 2010), although the combined vocabulary of bilingual children is likely larger than that of monolingual children. There was no difference between language groups for the non-verbal scaled scores of block design, $F(1, 59) = 3.13$, *n.s.*

Behavioral Performance

Table 2 presents the mean and standard deviations for the behavioral measures from the tasks. For gift delay, a one-way ANOVA on scores for gift delay showed no difference between monolingual and bilingual children, $F(1, 60) = 1.47$, *n.s.*

For the ANT task, trials with RTs less than 200 milliseconds were excluded because they likely reflected anticipatory responses (less than 1% of the total number of trials). In addition, data for participants with accuracy lower than 55% for each trial type were not included in the analyses because performance might reflect guessing. As a result, two monolingual children were excluded from analyses of performance on neutral trials and five children (3 monolinguals, 2 bilinguals) were excluded from analyses of the incongruent trials, which produced a final sample of 32 monolingual and 23 bilingual children.

Because the stimulus display was different for neutral trials (single stimulus) than for congruent and incongruent trials (5 stimuli), accuracy on these conditions was analyzed separately. A one-way ANOVA for neutral trials indicated no difference between monolingual and bilingual children, $F < 1$. However, the two-way ANOVA for congruent and incongruent trials by language group showed a main effect of language group, $F(1, 55) = 5.66$, $p = .03$, $\eta_p^2 = .09$, with bilingual children outperforming monolinguals, a main effect of trial type, $F(1, 55) = 24.59$, $p < .0001$, $\eta_p^2 = .19$, with higher accuracy on congruent trials than incongruent trials, and no interaction, $F < 1$. Three additional one-way ANOVA for language group showed no differences between monolingual and bilingual children on any of the three attentional indexes, alerting, orienting and conflict, *Fs* < 1. Similarly, two ANOVAs specifically testing the interaction between language group and type of attentional index (i.e., alerting and conflict for one analysis; orienting and conflict for the other) showed no significant effect, *F*s<1.

Response times for this task were long, with the majority of children (32 monolinguals and 22 bilinguals) obtaining mean RTs longer than 1000 milliseconds. The one-way ANOVA for neutral trials RT showed no differences between monolingual and bilingual children, $F < 1$. The two-way ANOVA for trial type and language group indicated a main effect of trial type, $F(1, 55) = 66.72$, $p < .0001$, $\eta_p^2 = .54$, with faster RTs on the congruent trials than incongruent trials. There was no main effect of language group and no interaction.

For the go/no-go task, go RTs faster than 200 ms were excluded from the analyses as anticipatory responses. Three children (1 monolingual, 2 bilinguals) declined to participate in the ERP testing. Additionally, data for children whose accuracy on either the go or no-go trials was lower than 55% were excluded from analyses, leading to the elimination of data from 5 monolingual and 3 bilingual children. Consequently, the final sample for this task was 31 monolingual and 19 bilingual children. A one-way ANOVA for age with language group as a between-subject factor confirmed that there were no age differences between the monolingual (*M* age = 63.5 months, *SD* = 5.5 months) and bilingual children (*M* age = 65.7 months, *SD* = 5.4 months) in this subsample, $F(1, 48) = 1.87$, *n.s.*

A mixed ANOVA for accuracy on condition and language group showed a main effect of condition, $F(1, 48) = 4.33$, $p < .05$, $\eta_p^2 = .08$, with higher performance on the no-go trials, a main effect of language group, $F(1, 48) = 6.09$, $p = .02$, $\eta_p^2 = .11$, with bilinguals outperforming monolinguals, and no interaction. A one-way ANOVA for RTs on go trials showed a main effect of language group, $F(1, 48) = 6.00$, $p = .02$, $\eta_p^2 = .11$, with bilingual children being faster than monolinguals.

A discriminability index measured by d^1 was calculated to determine perceptual sensitivity to the go and no-go conditions, with higher values indicating better perceptual sensitivity. An one-way ANOVA for group on d^1 scores indicated better discrimination in bilinguals than in monolinguals, $F(1, 48) = 4.52$, $p = .04$, $\eta_p^2 = .09$.

ERP Analyses for Go/No-go Task

There was no group difference in mean amplitude of go and no-go trials for the N2 component, $F(1, 48) = 1.74$, *n.s.*, but for P3, bilingual children showed larger mean amplitude than monolinguals, $F(1, 48) = 3.88$, $p = .05$ (Figure 2a).

Analyses of latency for the N2 component (Figure 2b) indicated an interaction between language group and anterior-posterior electrode position, $F(4, 192) = 2.98$, $p = .02$, showing shorter latency for bilinguals than monolinguals at the frontal and frontal-central electrodes, and no differences at the central, central-parietal and parietal electrodes. Bilinguals also showed shorter latency than monolinguals for the P3 component, $F(1, 48) = 3.71$, $p < .05$. In addition, an interaction between language group, condition, and anterior-posterior electrode site for the P3 component, $F(4, 192) = 2.66$, $p = .04$, indicated shorter latencies for bilinguals than monolinguals on the go trials at central, central-parietal and parietal sites, and an interaction between language group, laterality and anterior-posterior electrode site , $F(16, 768) = 1.86$, $p = .03$, indicated shorter latencies for bilinguals than monolinguals on the left and midline electrodes at the frontal-central, central and central-parietal sites. Descriptive statistics for peak latencies for the N2 and P3 components are summarized in Table 3.

For monolinguals, there was no correlation between d^1 scores and P3 mean amplitude, but for bilinguals, these correlations were significant at the central sites, $r(17) = 0.47$, $p < .05$. Thus, for bilingual children larger amplitudes were associated with better performance and enhanced discrimination of the stimuli. This finding is consistent with studies showing that better performance is related to larger amplitude in children (Pliszka, et al., 2000). Correlations between peak latency of the N2 or P3 component and d^1 score indicate a similar pattern. In bilinguals, shorter latencies on both components were associated with larger d^1 scores, that is, better behavioral performance (e.g., correlation between d^1 and go latency on P3, $r(17) = -0.70$, $p < .001$; d^1 and go latency at C4 site, $r(17) = -0.45$, $p = .05$). Some of these correlations, however, are only marginally significant, perhaps due to lack of power, so these associations need to be interpreted with caution. However, given that the results are consistent for both latency and mean amplitude, and for both N2 and P3 components, they reveal a pattern in which larger amplitudes and shorter latencies reflect better behavioral performance for bilingual children. No such relations were found for monolinguals who were generally less advanced than bilingual children in performing this task.

Discussion

Five-year-old monolingual and bilingual children with similar SES background and cognitive level were tested on executive control tasks using behavioral and electrophysiological indices of performance. Our purpose was to investigate tasks with different executive control demands to determine the conditions under which a bilingual advantage emerges and the possible neural basis of these effects. The larger goal was to understand how one experience, bilingualism, impacts children's development of executive control as a means of assessing the role of neuroplasticity in children's cognitive development. The results support the conclusion that bilingualism provides a powerful form of "brain-training" that improves children's development of executive control, an improvement that is seen by the ability of bilingual children to perform more difficult tasks than their monolingual peers.

The tasks differed in the degree to which over-riding a prepotent response required complex executive control. The simplest task was gift delay, and here there was no difference in performance between children in the two language groups. On both flanker and go/no-go tasks, however, bilingual children outperformed the monolinguals, and in the go/no-go, that difference was evident in both the behavioral and ERP measures. Importantly, the ERP indices showing more advanced performance in terms of P3 amplitude and N2 latency were correlated with better behavioral results for bilinguals. That is, as bilingual children progressed in their ability to perform this task, improvement in their performance was found in both the behavioral and ERP measures; performance of the monolingual children had not yet begun to improve in that way. This pattern of results in which monolingual and bilingual children perform equivalently on a simple task but bilingual children make more gains as the task becomes difficult points to a situation in which bilingual children may have a reserve capacity or developing ability that allows them to manage the more complex tasks.

The results for the specific tasks are consistent with those reported in previous research showing no difference between monolingual and bilingual children performing delay tasks (e.g., Carlson & Meltzoff, 2008) but better performance by bilinguals on flanker tasks (e.g., Yang et al., 2011). However, in contrast with previous research (Bonifacci, et al., 2011), bilingual children also showed an advantage on the go/no-go task. Thus, the specific results are consistent with previous research that had been based on different groups of children in different studies. What, therefore, is the relevant feature in determining whether or not bilingual children will outperform monolinguals on a particular task?

In addition to identifying the importance of quantitative assessment of executive control on performance by monolingual and bilingual children, the study also showed evidence of bilingualism-related neuroplasticity in nonverbal executive control processing in children. This is the first study to our knowledge to link behavioral performance in executive control to electrophysiology in children. The ERP signature of go/no-go performance is well known, and some studies have also provided evidence from children performing these tasks. Specifically, mature performance is indicated by the amplitude and latencies of the N2 and P3 components. For the N2 component, there were no group differences in amplitude but bilingual children showed shorter latencies at more anterior electrode sites (i.e., frontal and frontal-central electrodes); for the P3 component, bilingual children showed larger amplitude than monolinguals regardless of laterality and anterior-posterior electrode position and shorter latencies at central and posterior electrode sites (i.e., central, central-parietal and parietal sites). These patterns are evidence for better performance, an interpretation that was confirmed by the correlation between these measures and d^1 discriminability indices.

The difference in results for the N2 and P3 components in the go/no-go task are not surprising because N2 and P3 show different developmental trajectories (Jonkman et al., 2003) and likely reflect different executive processes (Enriquez-Geppert, Konrad, Pantev, & Huster, 2010). Differences between these components are also found in adults. In the study by Fernandez et al. (2013), bilingual adults showed larger N2 amplitude than monolinguals but the P3 component did not distinguish between the two language groups (Fernandez et al., 2013), and in the study by Moreno et al. (2014), bilinguals showed larger amplitude for both the N2 and P3 components. In both these studies with adults, there were no behavioral differences in performance between the monolinguals and bilinguals.

Shorter latencies for bilingual children on the N2 component, particularly at the frontal electrode sites is interesting in light of a developmental study comparing 6- to 12-year-old children and young adults on their performance on a go/no-go task (Ciesielski et al., 2004). Ciesielski and colleagues found that for the N2 waveform, children displayed a more posterior pattern of brain responses whereas adults showed a more frontal topography. Thus the anteriorization of responses in bilingual children in the present study may be further evidence for their more mature pattern of brain function. Together with the N2 and P3 results and the behavioral measures, this evidence supports the interpretation that the bilingual children in the present study perform this task better than the monolingual children. These results for functional brain development are consistent with a large body of behavioral evidence showing earlier maturation of executive processes in bilingual children.

Previous researchers have attempted to determine the precise component of executive control that is affected by bilingualism and therefore the specific task on which bilinguals may be expected to show better performance than monolinguals. This approach has not produced clear results; studies using different tasks all claiming to test inhibition, for example, lead to different outcomes (e.g., Martin-Rhee & Bialystok, 2008) and individual tasks that are considered to test inhibition, such as the flanker, show that bilinguals outperform monolinguals on both congruent and incongruent trials and not just the incongruent trials that explicitly include distracting cues and require inhibition (e.g., Kapa & Colombo, 2013). Our alternative is to consider a more quantitative assessment of executive control in which some tasks are more effortful because they involve more components (inhibition plus working memory or shifting for example) or a relative degree of control as indicated by simple or complex inhibition (cf., Garon et al., 2008). What is clear is that the approach that attempts to isolate pure tests of specific executive control components has not yielded clear results.

This approach fits well with the present results. All the tasks involved the need to inhibit a prepotent response, but that requirement was embedded in other task demands that added other components or varied the complexity of the inhibition. As these task demands increased, so too did the performance difference between monolingual and bilingual children. Thus, the difference between monolingual and bilingual children is not simply categorical (bilingual children can perform executive control tasks that monolingual children are unable to perform) but rather incremental: bilingual children are making more progress in developing executive control so are further ahead on more difficult tasks. Although functional brain plasticity has been previously documented in bilingual children for verbal processing (e.g., Conboy & Mills, 2006), the present study offers first evidence linking bilingualism to neural correlates of nonverbal executive control in children.

Another interpretation consistent with these results is that offered by Bialystok (2015) in which the relevant executive function difference between monolingual and bilingual children is more broadly defined in terms of attention. Both the go/no-go and flanker tasks include misleading stimuli, making attention to the relevant cue more effortful, whereas the gift delay has no such attentional demands. Specific aspects of attention as defined by the different cue conditions in the flanker task did not distinguish between groups, but the overall need for attention to perform the congruent and incongruent trials did set the bilinguals apart from the monolinguals. Using attention as the relevant factor removes the problem of determining relative complexity of tasks and instead classifies tasks on the basis of whether or not they include misleading cues, thereby making tasks more complex or more effortful. Further research is needed to add precision to our understanding of the exact task features that lead to these changes, but the findings clearly support the role of bilingualism in promoting children's progress in mastering the crucial abilities associated with executive control.

Acknowledgement

This research was funded by grant R01HD052523 from the US National Institutes of Health to Ellen Bialystok and by grant MR10134-08 from the Ontario Center of Excellence to Sylvain Moreno. We are grateful to Lori Astheimer for help with ERPs analyses and to Kornelia Hawrylewicz, Michelle Eisen, Margot Sullivan, Lorinda Mak, Shauna Eisen, Marta Brocki and Zara Chan for help with data collection.

References

Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Sifo P, Keim, Cappa R, Costa A. Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cerebral Cortex. 2012; 22:2076–2086. doi: 10.1093/cercor/bhr287. [PubMed: 22038906]

Adesope OO, Lavin T, Thompson T, Ungerleider C. Systematic review and meta-analysis on the cognitive benefits of bilingualism. Review of Educational Research. 2010; 80:207–245. doi: 10.3102/0034654310368803.

Akhtar, N.; Menjivar, JA. Cognitive and linguistic correlates of early exposure to more than one language. In: Benson, JB., editor. Advances in child development and behavior. Vol. 42. Academic Press; Burlington: 2012. p. 41-78.doi: 10.1016/b978-0-12-394388-0.00002-2

Barac R, Bialystok E, Castro D, Sanchez M. The cognitive development of dual language learners: A critical review. Early Childhood Research Quarterly. 2014; 29:699–714. doi: 10.1016/j.ecresq.2014.02.003. [PubMed: 25284958]

Barac R, Bialystok E. Bilingual effects on development: Role of language, cultural background, and education. Child Development. 2012; 83:413–422. doi: 10.1111/j.1467-8624.2011.01707.x. [PubMed: 22313034]

Best JR, Miller PH, Naglieri JA. Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. Learning and Individual Differences. 2011; 21:327–336. doi: http://dx.doi.org/10.1016%2Fj.lindif.2011.01.007. [PubMed: 21845021]

Bialystok E. Global-local and trail-making tasks by monolingual and bilingual children: Beyond inhibition. Developmental Psychology. 2010; 46:93–105. doi: 10.1037/a0015466. [PubMed: 20053009]

Bialystok E. Bilingualism and the development of executive function: The role of attention. Child Development Perspectives. 2015; 9:117–121. doi: 10.1111/cdep.12116. [PubMed: 26019718]

Bialystok E, Craik FIM, Grady C, Chau W, Ishii R, Gunji A, Pantev C. Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. NeuroImage. 2005; 24:40–49. doi: 10.1016/j.neuroimage.2004.09.044. [PubMed: 15588595]

Bialystok E, Luk G, Peets KF, Yang S. Receptive vocabulary differences in monolingual and bilingual children. Bilingualism: Language and Cognition. 2010; 13:525–531. doi: 10.1017/s1366728909990423.

Bialystok E, Martin MM. Attention and inhibition in bilingual children: Evidence from the dimensional change card sort task. Developmental Science. 2004; 7:325–339. doi: 10.1111/j.1467-7687.2004.00351.x. [PubMed: 15595373]

Bialystok E, Viswanathan M. Components of executive control with advantages for bilingual children in two cultures. Cognition. 2009; 112:494–500. doi: 10.1016/j.cognition.2009.06.014. [PubMed: 19615674]

Bialystok E, Barac R, Blaye A, Poulin-Dubois D. Word mapping and executive functioning in young monolingual and bilingual children. Journal of Cognition and Development. 2010; 11:485–508. doi: 10.1080/15248372.2010.516420. [PubMed: 21197133]

Blom E, Kuntay AC, Messer M, Verhagen J, Leseman P. The benefits of being bilingual: Working memory in bilingual Turkish-Dutch children. Journal of Experimental Child Psychology. 2014; 128C:105–119. doi: 10.1016/j.jecp.2014.06.007. [PubMed: 25160938]

Bonifacci P, Giombini L, Bellocchi S, Contento S. Speed of processing, anticipation, inhibition and working memory in bilinguals. Developmental Science. 2011; 14:256–269. doi: 10.1111/j.1467-7687.2010.00974.x. [PubMed: 22213899]

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. Psychological Review. 2001; 108:624–652. doi: 10 lO37//0033.295X 108.3 624. [PubMed: 11488380]

Bunge SA, Dudukovic NM, Thomason ME, Vaidya CJ, Gabrieli JDE. Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. Neuron. 2002; 33:301–311. [PubMed: 11804576]

Carlson SM. Developmentally sensitive measures of executive function in preschool children. Developmental Neuropsychology. 2005; 28:595–616. doi: 10.1207/s15326942dn2802_3. [PubMed: 16144429]

Carlson SM, Meltzoff AN. Bilingual experience and executive functioning in young children. Developmental Science. 2008; 11:282–298. doi: 10.1111/j.1467-7687.2008.00675.x. [PubMed: 18333982]

Ciesielski KT, Harris RJ, Cofer LF. Posterior brain ERP patterns related to the go/no-go task in children. Psychophysiology. 2004; 41:882–892. doi: 10.1111/j.1469-8986.2004.00250.x. [PubMed: 15563341]

Conboy BT, Mills DL. Two languages, one developing brain: event-related potentials to words in bilingual toddlers. Developmental Science. 2006; 9:F1–F12. doi: 10.1111/j.1467-7687.2005.00453.x. [PubMed: 16445386]

Costa A, Hernández M, Sebastián-Gallés N. Bilingualism aids conflict resolution: Evidence from the ANT task. Cognition. 2008; 106:59–86. doi: 10.1016/j.cognition.2006.12.013. [PubMed: 17275801]

Costa A, Hernández M, Costa-Faidella J, Sebastián-Gallés N. On the bilingual advantage in conflict processing: Now you see it, now you don't. Cognition. 2009; 113:135–149. doi: 10.1016/j.cognition.2009.08.001. [PubMed: 19729156]

Cragg L, Fox A, Nation K, Reid C, Anderson M. Neural correlates of successful and partial inhibitions in children: An ERP study. Developmental Psychobiology. 2009; 51:533–543. doi: 10.1002/dev.20391. [PubMed: 19685486]

Davis EP, Bruce J, Snyder K, Nelson CA. The X-trials: Neural correlates of an inhibitory control task in children and adults. Journal of Cognitive Neuroscience. 2003; 15:432–443. doi: 10.1162/089892903321593144. [PubMed: 12729494]

Dimoska A, Johnstone SJ, Barry RJ, Clarke AR. Inhibitory Motor Control in Children with Attention-Deficit/Hyperactivity Disorder: Event-Related Potentials in the Stop-Signal Paradigm. Biological Psychiatry. 2003; 54:1345–1354. [PubMed: 14675798]

Duan X, Shi J, Wu J, Mou Y, Cui H, Wang G. Electrophysiological correlates for response inhibition in intellectually gifted children: A Go/NoGo study. Neuroscience Letters. 2009; 457:45–48. doi: 10.1016/j.neulet.2009.04.006. [PubMed: 19429159]

Duñabeitia JA, Hernández JA, Antón E, Macizo P, Estévez A, Fuentes LJ, Carreiras M. The inhibitory advantage in bilingual children revisited: myth or reality? Experimental Psychology. 2014; 61:234–251. doi: 10.1027/1618-3169/a000243. [PubMed: 24217139]

Duncan GJ, Ziol-Guest KM, Kalil A. Early childhood poverty and adult attainment, behavior, and health. Child Development. 2010; 81:306–325. doi: 10.1111/j.1467-8624.2009.01396.x. [PubMed: 20331669]

Enriquez-Geppert S, Konrad C, Pantev C, Huster RJ. Conflict and inhibition differentially affect the N200/P300 complex in a combined go/nogo and stop-signal task. Neuroimage. 2010; 51:877–887. doi: 10.1016/j.neuroimage.2010.02.043. [PubMed: 20188191]

Fernandez M, Tartar JL, Padron D, Acosta J. Neurophysiological marker of inhibition distinguishes language groups on a non-linguistic executive function test. Brain and Cognition. 2013; 83:330–336. doi: 10.1016/j.bandc.2013.09.010. [PubMed: 24141240]

Foy JG, Mann VA. Bilingual children show advantages in nonverbal auditory executive function task. International Journal of Bilingualism. 2014; 18:693–716. doi: 10.1177/1367006912472263.

Freitas AL, Azizian A, Leung H, Squires NK. Resisting recently acted-on cues: Compatibility of Go/no-go responses to response history modulates (frontal P3) event-related potentials. Psychophysiology. 2007; 44:2–10. doi: 10.1111/j.1469-8986.2010.00963.x. [PubMed: 17241136]

Garon N, Bryson S, Smith I. A review of executive function in the preschool period using an integrative framework. Psychological Bulletin. 2008; 134:31–60. doi: 10.1037/0033-2909.134.1.31. [PubMed: 18193994]

Hervais-Adelman AG, Moser-Mercer B, Golestani N. Executive control of language in the bilingual brain: integrating the evidence from neuroimaging to neuropsychology. Frontiers in Psychology. 2011; 2:234. doi: 10.3389/fpsyg.2011.00234. [PubMed: 21954391]

Hilchey MD, Klein RM. Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. Psychonomic Bulletin & Review. 2011; 18:625–658. doi: 10.3758/s13423-011-0116-7. [PubMed: 21674283]

Johnstone SJ, Barry RJ, Anderson JW, Coyle SF. Age-related changes in child and adolescent event-related potential component morphology, amplitude and latency to standard and target stimuli in an auditory oddball task. International Journal of Psychophysiology. 1996; 24:223–238. doi: 10.1016/S0167-8760(96)00065-7. [PubMed: 8993997]

Jonkman LM, Lansbergen M, Stauder JEA. Developmental differences in behavioural and ERP responses associated with response preparation and inhibition in a go/nogo task. Psychophysiology. 2003; 40:752–761. doi: 10.1111/1469-8986.00075. [PubMed: 14696728]

Kalashnikova M, Mattock K. Maturation of executive functioning skills in early sequential bilingualism. International Journal of Bilingual Education and Bilingualism. 2012; 17:111–123. doi: 10.1080/13670050.2012.746284.

Kapa LL, Colombo J. Attentional control in early and later bilingual children. Cognitive Development. 2013; 28:233–246. doi: 10.1016/j.cogdev.2013.01.011. [PubMed: 24910499]

Lahat A, Todd RM, Mahy CEV, Lau K, Zelazo PD. Neurophysiological correlates of executive function: a comparison of European-Canadian and Chinese-Canadian 5-year-old children. Frontiers in Neuroscience. 2010; 3:1–10. doi:10.3389/neuro.09.072.2009.

Lamm C, Zelazo PD, Lewis MD. Neural correlates of cognitive control in childhood and adolescence: disentangling the contributions of age and executive function. Neuropsychologia. 2006; 44:2139–2148. doi:10.1016/j.neuropsychologia.2005.10.013. [PubMed: 16310813]

Liotti M, Pliszka SR, Perez R, Kothmann D, Woldorff MG. Abnormal brain activity related to performance monitoring and error detection in children with ADHD. Cortex. 2005; 41:377–88. doi:10.1016/S0010-9452(08)70274-0. [PubMed: 15871602]

Liu T, Xiao T, Shi J, Zhao D. Response preparation and cognitive control of highly intelligent children: a Go-Nogo event-related potential study. Neuroscience. 2011; 180:122–128. doi:10.1016/j.neuroscience.2011.02.022. [PubMed: 21329744]

Luk G, Anderson JAE, Craik FIM, Grady C, Bialystok E. Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. Brain and Cognition. 2010; 74:347–357. doi: 10.1016/j.bandc.2010.09.004. [PubMed: 20965635]

Martin-Rhee MM, Bialystok E. The development of two types of inhibitory control in monolingual and bilingual children. Bilingualism: Language and Cognition. 2008; 11:81–93. doi: 10.1017/s1366728907003227.

Mezzacappa E. Alerting, orienting, and executive attention: developmental properties and sociodemographic correlates in an epidemiological sample of young, urban children. Child Development. 2004; 75:1373–86. doi: 10.1111/j.1467-8624.2004.00746.x. [PubMed: 15369520]

Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerter A, Wager TD. The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. Cognitive Psychology. 2000; 41:49–100. doi: 10.1006/cogp.1999.0734. [PubMed: 10945922]

Morales J, Calvo A, Bialystok E. Working memory development in monolingual and bilingual children. Journal of Experimental Child Psychology. 2013; 114:187–202. doi: 10.1016/j.jecp.2012.09.002. [PubMed: 23059128]

Moreno S, Bialystok E, Barac R, Schellenberg EG, Cepeda NJ, Chau T. Short-term music training enhances verbal intelligence and executive function. Psychological Science. 2011; 22:1425–1433. doi: 10.1177/0956797611416999. [PubMed: 21969312]

Moreno S, Wodniecka Z, Tays W, Alain C, Bialystok E. Inhibitory control in bilinguals and musicians: Event Related Potential (ERP) evidence for experience-specific effects. PLOS ONE. 2014; 9:e94169. doi: 10.1371/journal.pone.0094169. [PubMed: 24743321]

Nieuwenhuis S, Yeung N, Van Den Wildenberg W, Ridderinkhof R. Electrophysiological correlates of anterior cingulated function in a Go/no-go task: Effects of response conflict and trial type frequency. Cognitive, Affective, & Behavioural Neuroscience. 2003; 3:17–26. doi: 10.3758/CABN.3.1.17.

Peal E, Lambert WE. The relation of bilingualism to intelligence. Psychological Monographs. 1962; 76:1–23.

Pfefferbaum A, Ford JM, Weller BJ, Kopell BS. ERPs to response production and inhibition. Electroencephalography and Clinical Neuropsychology. 1985; 60:423–434.

Pliszka SR, Liotti M, Woldorff MG. Inhibitory control in children with attention-deficit/hyperactivity disorder: event-related potentials identify the processing component and timing of an impaired right-frontal response-inhibition mechanism. Biological Psychiatry. 2000; 48:238–46. doi: http://dx.doi.org/10.1016/S0006-3223(00)00890-8. [PubMed: 10924667]

Rueda MR, Fan J, McCandliss BD, Halparin JD, Gruber DB, Lercari LP, Posner MI. Development of attentional networks in childhood. Neuropsychologia. 2004; 42:1029–1040. doi:10.1016/j.neuropsychologia.2003.12.012. [PubMed: 15093142]

Schmajuk M, Liotti M, Busse L, Woldorff MG. Electrophysiological activity underlying inhibitory control processes in normal adults. Neuropsychologia. 2006; 44:384–95. doi: 10.1016/j.neuropsychologia.2005.06.005. [PubMed: 16095637]

Todd RM, Lewis MD, Meusel L-A, Zelazo PD. The time course of social-emotional processing in early childhood: ERP responses to facial affect and familiarity in a Go-Nogo task. Neuropsychologia. 2008; 46:595–613. doi:10.1016/j.neuropsychologia.2007.10.011. [PubMed: 18061633]

Wechsler, D. WPPSI-III administration and scoring manual. Psychological Corporation, San Antonio; TX: 2002.

Yang S, Yang H, Lust B. Early childhood bilingualism leads to advances in executive attention: Dissociating culture and language. Bilingualism: Language and Cognition. 2011; 14:412–422. doi: http://dx.doi.org/10.1017/S1366728910000611.

Yoshida H, Tran DN, Benitez V, Kuwabara M. Inhibition and adjective learning in bilingual and monolingual children. Frontiers in Psychology. 2011; 2:1–14. doi: 10.3389/fpsyg.2011.00210. [PubMed: 21713130]

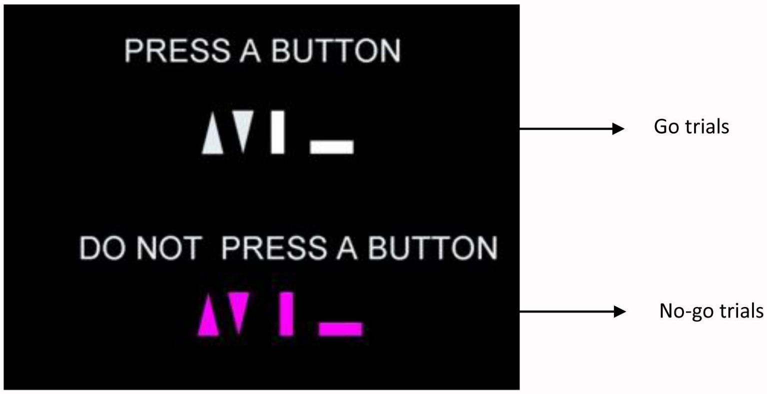

Figure 1.
Schematic presentation of the go/no-go task: Examples of stimuli.

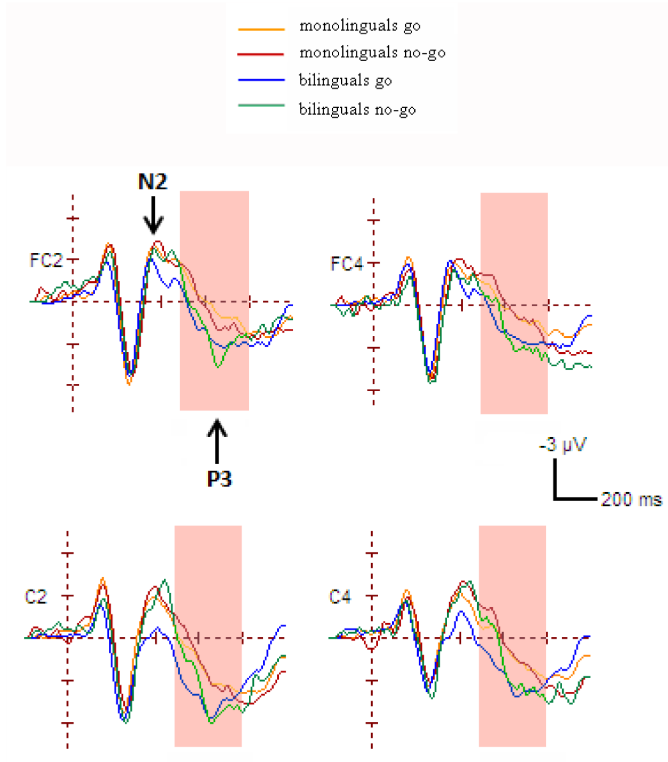

Figure 2a.

ERP results for the go/no-go task. Waveforms for go and no-go trials for monolingual and bilingual children at selected sites. On the P3 component, bilinguals show larger mean amplitude than monolinguals for both go and no-go trials.

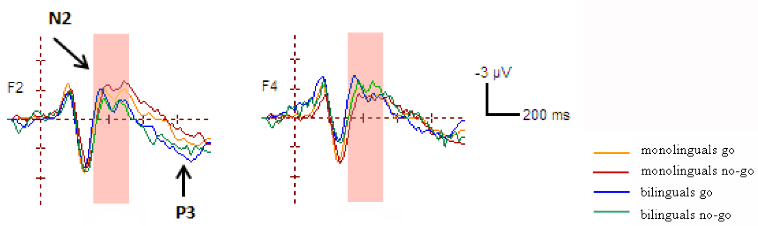

Figure 2b.
ERP results for the go/no-go task. Waveforms for go and no-go trials for monolingual and bilingual children at selected sites. On the N2 component, bilinguals show shorter peak latency than monolinguals for both go and no-go trials.

Table 1

Participant background information by language group

Background Information	Monolinguals M (SD)	Bilinguals M (SD)
Age (in months)	62.9 (5.7)	65.3 (5.2)
Language child speaks at home	1.0 (0)	2.72 (1.21)
Language child hears at home	1.0 (0)	3.16 (1.37)
Socioeconomic status	3.73 (1.07)	3.60 (0.82)
Estimated full-scale IQ	107.53 (12.29)	108.56 (13.76)
Vocabulary (scaled score) *	11.72 (1.98)	10.60 (2.31)
Block Design (scaled score)	10.83 (3.19)	12.32 (3.28)

Note:

Language child speaks at home and Language child hears at home were measured on a scale from 1 to 5, where 1 indicates the exclusive use of English and 5 indicates the exclusive use of a non-English language. Socioeconomic status was indexed as the level of maternal education on a 5-point scale (1 = no high school diploma, 2 = high school graduate, 3 = some college or college diploma, 4 = bachelor's degree, 5 = graduate degree). The scaled scores for the Vocabulary and Block Design subtests can range from 1 to 19.

* indicates statistical significance ($p < .05$)

Table 2

Participant behavioral performance on inhibition tasks by language group

Task	Monolinguals M (SD)	Bilinguals M (SD)
Gift delay: mean score	2.92 (1.38)	2.52 (1.08)
ANT: Accuracy neutral trials	0.80 (0.11)	0.82 (0.13)
Accuracy congruent trials *	0.80 (0.11)	0.86 (0.11)
Accuracy incongruent trials *	0.71 (0.14)	0.79 (0.12)
RT neutral trials (in ms)	993 (127)	1005 (86)
RT congruent trials (in ms)	1041 (126)	1016 (102)
RT incongruent trials (in ms)	1108 (127)	1113 (83)
RT Alerting (in ms)	46 (85)	63 (86)
RT Orienting (in ms)	21 (101)	28 (83)
RT Conflict (in ms)	67 (84)	97 (90)
Go/no-go: Percentage correct go trials *	73.19 (11.04)	81.32 (10.92)
RT mean go trials (in ms) *	677 (84)	624 (55)
Percentage correct no-go trials *	81.87 (13.89)	84.16 (10.82)
Discriminability index (*d'*) *	1.75 (0.53)	2.16 (0.84)

Note:

On the Gift Delay task children could receive a score from 1 to 5 (1 = removes cover and looks inside box; 2 = looks in window but does not remove cover; 3 = touches box or cover without looking inside; 4 = looks at (but not inside) the box and does not touch box or cover; 5 = never touches or looks at or inside the box). ANT task accuracy refers to proportion of correct trials.

* indicates statistical significance ($p < .05$)

Table 3

Mean and standard deviation for peak latencies for the N2 and P3 components by language group and anterior-posterior factor in the go/no-go task

Anterior-posterior site	Monolinguals	Bilinguals	Monolinguals		Bilinguals	
	N2 component		P3 component			
			Go	No-go	Go	No-go
*Frontal electrodes	442 (43)	419 (41)	705 (88)	682 (70)	731 (71)	667 (83)
*Frontal-central electrodes	432 (38)	411 (41)	721 (69)	709 (65)	730 (49)	687 (49)
**Central electrodes	423 (35)	414 (29)	743 (55)	724 (43)	711 (41)	706 (54)
**Central-posterior electrodes	416 (28)	415 (31)	704 (59)	705 (62)	644 (55)	674 (71)
Posterior electrodes	377 (34)	387 (39)	620 (64)	646 (60)	591 (46)	632 (68)

Note:

* variables preceded by show a significant group difference for the N2 component;

** variables preceded by show a significant group difference for the P3 component.