NEUROPLASTICITY IN YOUNG BILINGUAL CHILDREN: EVIDENCE FROM ERPS IN AN EXECUTIVE CONTROL TASK

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Abstract

Accumulating behavioural evidence shows that bilingualism is associated with improved executive functioning for children, adults, and older adults on tasks that require participants to resolve conflict between stimuli, ignore irrelevant information, or switch efficiently between tasks. A small number of neuroimaging studies has also revealed structural and functional differences between monolingual and bilingual adults at the brain level. However, no studies to date have examined the neural correlates of non-verbal executive control in bilingual children. Investigating the neural basis of the bilingual advantage is the key to understanding how sustained experience with two languages results in neurocognitive differences and how brain plasticity is related to behavioural performance.

The present study used event-related potentials (ERPs) to examine bilingualism-induced brain plasticity in 62 5-year-old children performing non-verbal executive control tasks. Behavioural performance was consistent with previous research and showed a bilingual advantage in cognitive tasks with high control demands. The ERP analyses focused on two waveform components associated with response inhibition in go/no-go tasks: N2 and P3. Electrophysiological data showed that bilingual children performing a non-verbal go/no-go task showed larger amplitudes than monolinguals on the P3 component and shorter latencies on the N2 and P3 components. These findings provide first evidence that bilingualism results in functional brain changes when processing non-verbal control tasks in young children. The present results suggest that when monolingual and bilingual children are engaged in a task with complex demands that require high levels of cognitive resources for monitoring, response selection and response inhibition, bilingual children show a more efficient use of their neural systems.

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"In contrast to the predominant general view that applied two decades ago, it is currently accepted that cortical maps are dynamic constructs that are remodeled in detail by behaviorally important experiences throughout life" (Buonomano & Merzenich, 1998, p. 150). Since that time almost 15 years ago, an increasing body of evidence has accumulated to empirically support this idea of neuroplasticity, the brain's capacity for reorganization in response to experiences such as learning, skill acquisition, brain damage, and sensory deprivation, in both children and adults (Bavelier & Neville, 2002; Butz, Worgotter, & van Ooyen, 2009). In a recent review, Butz and colleagues distinguished between functional plasticity, defined as changes in the strengths of the synapses which are not accompanied by changes in the anatomical connectivity between neurons, and structural plasticity, which entails anatomical changes such as alterations in the number of synapses, neuronal cells, and density of axons (Butz et al., 2009).

Historically, plasticity has been understood in the context of changes in cortical organization in response to lesions, a process called reactive plasticity. More recently life experiences such as playing the piano (Bengtsson et al., 2005), juggling (Draganski, Gaser, Busch, Schuierer, & May, 2004; Scholz, Klein, Behrens, & Johansen-Berg, 2009), dance expertise (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005), taxi driving in London (Maguire et al., 2000), musical training (Schlaug, Norton, Overy, & Winner, 2005), and bilingualism (Mechelli et al., 2004) have been reported to induce spontaneous or experience-dependent brain plasticity.

Professional musicians, for instance, differed from non-musicians in the event-related potentials (ERPs) in response to temporal changes in sequences of tones (Russeler, Altenmuller, Nager, Kohlmetz, & Munte, 2001). Participants were presented with sequences of regularly spaced tones. Within these sequences, some tones were mistimed by 20 milliseconds (ms) or 50 ms. Even when the tones were mistimed by as little as 20 ms, professional musicians displayed a frontal negative wave, the mismatch negativity, which is considered to be an index of change detection in the timing of stimuli. When the tones were mistimed by 50 ms, all participants showed the mismatch negativity, but the effect was stronger in professional musicians. Structurally, several anatomical differences have been reported between musicians and non-musicians, including larger mean relative cerebellar volume in musicians (Schlaug, 2001). Based on these and related findings showing the effects of professional musical training on the structure and function of the brain, Munte and colleagues proposed the musician's brain as a model of neuroplasticity (Munte, Altenmuller, & Jancke, 2002).

Another equally remarkable and more frequent life experience is the acquisition and use of two languages, bilingualism. Rodriguez-Fornells, De Diego Balaguer, and Munte (2006) proposed that "the creation and crystallization of a full new lexicon can be considered a highly interesting natural experiment" (p. 134). A strong body of empirical evidence supports the idea that the exercise of managing two linguistic systems results in cognitive benefits that extend beyond language processing to a series of related cognitive skills known as executive functions (or executive control) (e.g., Bialystok & Craik, 2010). Miyake and colleagues characterized executive functions as general-purpose control mechanisms that coordinate the way in which cognitive processes operate (Miyake et al., 2000). Although there is substantial behavioral evidence demonstrating the plasticity of executive functions as a result of bilingualism, at present we know little about the neurocorrelates of these executive control tasks for monolingual and bilingual children. Thus many questions remain unanswered: Is bilingualism an experience that has the potential to alter brain function and organization? Is bilingualism-related neuroplasticity evident early on in development, during childhood, after only limited bilingual experience? How does functional neuroplasticity relate to bilingual advantages reported in behavioral tasks? Can ERPs reveal the secret of the behavioral performance differences between monolingual and bilingual children?

Although other life experiences such as playing the piano, juggling, and taxi driving in London have been associated with structural and functional neuroplasticity, it is not clear in these cases if the modification was the result of the experience or if individuals with particular talent or interest embarked on those activities. Like these experiences, bilingualism is an intense activity sustained over time, but unlike these experiences, children born into homes where two languages are spoken are not pre-selected. Therefore, bilingual children potentially provide strong evidence for plasticity in brain development.

The present study examines how the experience of speaking two languages shapes the way in which children's brains perform non-verbal tasks that require executive functions. The introduction is organized in four parts. The first part reviews *behavioral evidence* demonstrating bilingual advantages in different components of executive functions in children. The next part summarizes research that documents changes at the *brain level* related to training and life experiences, in particular bilingualism. The third part discusses several *theoretical models* of bilingualism and possible mechanisms underlying these effects. Finally, the fourth part reviews the *ERP methodology* and developmental data on ERPs and response inhibition.

Executive Functions and Bilingualism: Behavioral Findings

The present dissertation investigates the effects of speaking two languages on the *plasticity of executive functions* in children, at the brain and at the behavioral level. In what follows, a review of existing research demonstrating bilingual influences on executive functions is preceded by a brief summary of the way in which executive functions are conceptualized in the literature. This sets a foundation for the idea investigated in the current dissertation that variations in language experience result in differences in abilities and underlying neural resources.

Executive functioning components. Regardless of the way in which executive functions are conceptualized, most researchers concur that their main role is to support goal-directed, flexible and adaptive behaviors by controlling sources of distraction and habit such as automatic or prepotent thoughts and responses (Diamond, 2006; Garon, Bryson, & Smith, 2008; Miyake et al., 2000; Munakata, 2001; Zelazo & Frye, 1998). In this way, executive functions are higher-order cognitive processes that control and coordinate information processing and actions (Carter et al., 2000; Jurado & Rosselli, 2007). Miller and Cohen (2001) proposed that executive functions work to achieve an internal goal by keeping active only the information that is relevant to the current task.

Recently, there has been an interest in identifying the neural correlates of executive functions. Early lesion studies and modern neuroimaging techniques all point to the fact that executive processes are supported by the frontal lobes (Fuster, 2002; Miller & Cohen, 2001), particularly the posterior medial frontal cortex and lateral frontal cortex (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). However, there are inconsistencies in specifying the exact localization and extent within the frontal lobes, mainly due to differences among studies in the nature and demands of the experimental tasks and the techniques used to collect and analyze data.

Despite differences in the theoretical approach to the organization of executive functions, three main abilities are typically proposed to constitute its core (Diamond, 2006; Miyake et al., 2000): inhibition (ability to resist a habitual response or information that is not relevant), working memory or updating (ability to hold information in mind and mentally manipulate it), and cognitive flexibility or shifting (ability to adjust to changes in demands or priorities and switch between goals). Using a confirmatory factor analysis, the authors showed that inhibition, working memory and shifting represent three distinct executive processes which nevertheless share a common underlying mechanism.

Miyake et al. (2000) speculated that inhibition might be the executive process that serves as a common underlying mechanism, supporting working memory and updating processes, for instance by inhibiting distracting information in working memory tasks. Consequently, although experimental tasks typically target a specific executive component, performance on a task is rarely a pure measure of that single component, but rather a combination of different executive abilities that are recruited to different degrees. Thus, task impurity is a persistent issue when studying executive functions.

Importance of studying executive functions. Despite these differences in conceptualization and measurement, executive control came to occupy a central role in explanations proposed in diverse psychological domains. Part of the reason is that there are reliable correlations between executive functions and other cognitive abilities. For instance, there are moderate correlations between different components of executive functions and general intelligence (e.g., Carpenter, Just, & Shell, 1990; Kail, 2000; Kyllonen, 2002), and executive functions explain academic success over and above what is predicted by the intelligence measures (Best, Miller & Jones, 2005). Moreover, development of executive function abilities has been proposed to support social competence (e.g., Hughes, Dunn & White, 1998), moral behavior (e.g., Kochanska, Murray & Harlan, 2000), school readiness (e.g., Riggs, Blair & Greenberg, 2003), and theory of mind (e.g., Carlson, Mandell & Williams, 2004; Carlson & Moses, 2001). In fact, Diamond (1991) remarked that "Cognitive development can be conceived of, not only as the progressive acquisition of knowledge, but also as the enhanced inhibition of reactions that get in the way of demonstrating knowledge that is already present" (p. 67). Similarly, Harnishfeger and Bjorklund (1993) argued that the process of inhibition has the potential to explain cognitive development in general. In atypical development, deficiencies in executive control have been proposed to underlie psychopathologies such as attention deficit hyperactivity disorder (Barkley, 1997), autism (Ciesielski & Harris, 1997), obsessive-compulsive disorder (Enright & Beech, 1993), schizophrenia (Nestor &

O'Donnell, 1998) and Tourette syndrome (Crawford, Channon, & Robertson, 2005). For these reasons it is important to examine what factors potentially impact the development of different executive functions. One of these factors is bilingualism, and the following subsection summarizes research showing how bilingualism changes the development of executive functions.

Bilingualism and executive functions.

Early studies on bilingualism in children. The study of cognitive consequences of bilingualism has a relatively long history that dates back to the beginning of the 20th century, but the effects of bilingualism on executive functions has only recently become a topic of research. From the beginning, bilingual research with children was concerned with the domains of intelligence and linguistic and metalinguistic performance, just as it is now. This trend reflects an intuitive understanding that bilingualism, essentially a linguistic experience, must affect linguistic performance and also an unfounded fear that managing two languages is a demanding task that may exceed children's cognitive resources and thus could potentially lead to intellectual impairment. With a few exceptions that remained largely ignored (Arsenian, 1937; Hill, 1936; Pintner & Arsenian, 1937; Stark, 1940), the majority of early studies on bilingualism in children reported superior performance in monolingual children (review in Barac & Bialystok, 2011). This monolingual advantage was found on a range of tasks such as IQ tests (Graham, 1925; Jones & Stewart, 1951; Lewis, 1959; Mead, 1927; Rigg, 1928; Saer, 1923; Wang, 1926), verbal intelligence (Darcy, 1953) arithmetic and reading achievement (Macnamara, 1966; Manuel, 1935).

One of these early studies (Saer, 1923) compared the performance on the Stanford-Binet Scale of Intelligence in over one thousand English monolingual and Welsh-English bilingual school-aged children from rural and urban backgrounds in Wales. The findings showed lower intelligence scores in bilingual children from rural areas at all ages tested (i.e., 7 to 11 years), with the gap in performance between the two language groups becoming larger with age. The author interpreted this finding as a sign of "mental confusion" encountered by the bilingual child. Later analyses of this study pointed out several methodological flaws that essentially applied to most early research on bilingualism: (a) the groups of comparison were not properly matched on variables such as age, gender and socio-economic status, (b) the testing was typically conducted solely in one language, and bilingual children varied in the degree to which they comprehended and produced the language of testing, and (c) bilingualism was not properly defined and quantified, and sometimes bilingualism was simply assumed in children based on parents' names and country of birth (Darcy, 1953; Peal & Lambert, 1962).

Interestingly, two extensive reviews (Darcy, 1953; 1963) clearly blamed early negative outcomes to methodological flaws and pointed out an important dissociation in the results: typically bilingualism was found to produce costs in verbal intelligence tests but there were no differences between monolingual and bilingual children in non-verbal intelligence. This observation sets the stage for finding cognitive benefits of bilingualism or at least for distancing from the early notion of inevitable and pervasive bilingual cognitive disadvantages.

A landmark study that contributed significantly to the change in attitude from believing that bilingualism was a negative experience for children to one in which it is now seen as a positive boost to cognitive functioning was conducted by Peal and Lambert in 1962. They gave a battery of intelligence tests to 10-year-old French-speaking children in Montreal, some of whom were also fluent English speakers. The authors carefully measured language experience and proficiency, quantified the degree of bilingualism and matched the groups on gender, age and socioeconomic class. This resulted in a sample of 75 French monolinguals with about half a year of English experience and 89 French-English bilinguals with an average of 6 years of English language experience.

Peal and Lambert (1962) hypothesized that there would be no differences between the groups on measures of nonverbal intelligence but there would be a monolingual advantage in verbal intelligence. Contrary to these predictions, bilingual children outperformed monolinguals on two measures of nonverbal intelligence (Raven Progressive Matrices and the Lavoie-Laurendeau Nonverbal IQ), as well as on measures of verbal intelligence (Lavoie-Laurendeau Verbal IQ). More detailed analyses of children's performance on each subtest revealed that bilingual children generally had higher scores than monolinguals on subtests that required symbolic manipulations and reorganization but not on measures with high spatial-perceptual demands. In contrast, monolinguals did not surpass bilinguals on any of the subtests. On the basis of these findings, Peal and Lambert suggested that bilingual children may actually show enhanced cognitive ability, especially on tests of concept formation and symbolic flexibility. The authors further speculated that bilingual children's early and sustained experience with two linguistic symbols standing for every one thing in the world coupled with the exercise of switching between the two languages might be at the root of their advantage in nonverbal intelligence. This was the first evidence that not only was bilingualism not damaging to children's cognitive growth but also it might be a positive experience that led to cognitive enhancement.

Although Peal and Lambert identified and controlled many of the methodological issues from past research, the study was not flawless. The authors used strict selection criteria to assign children in the monolingual and bilingual groups and to ensure that the bilingual children formed a homogeneous group with equal proficiency in French and English (i.e., "balanced bilinguals"). However, it is possible that applying these strict criteria might have led to the selection of a special subset of the bilingual population in that the authors excluded more than half of the original sample: 200 children out of 364 were classified as having ambiguous language experience. Thus it is possible that the bilingual children in the study were a particularly high achieving group who may not be completely representative of the bilingual population in general whose proficiency in two languages is more average.

Bilingualism effects on metalinguistic performance in children. Following 1962, bilingualism research focused on linguistic and metalinguistic performance for a few more decades, generally showing lower linguistic proficiency and more precocious metalinguistic development in bilingual children (review in Bialystok, 2001). Metalinguistic awareness is the explicit knowledge of linguistic structure and the ability to access it intentionally, abilities that are crucial to children's development of complex uses of language and the acquisition of literacy. In other words, metalinguistic awareness allows children to separate the meaning of words from their form and make independent judgments about the semantic, syntactic, phonological or morphological aspects of language. An advance in bilingualism research which contributed significantly to the active interest in the nonverbal cognitive effects of bilingualism from the last two decades was the development of a framework for understanding metalinguistic development. Bialystok (1986, 1993) proposed a distinction between representation of *linguistic knowledge* and *control of attentional resources*, and further argued that the bilingual advantage on metalinguistic tasks was in fact due to their enhanced control skills. This is why bilingual children surpassed monolingual peers when judging the grammaticality of sentences that contained semantic errors, thus having the added demand of ignoring the abnormal meaning, but did not differ from monolinguals when the sentences were semantically intact. The question then becomes why bilinguals, who typically show representational skills that are lower than or equivalent to those of monolinguals, have superior control abilities. The answer to this question is discussed in detail in the third section of the introduction; in short it has been proposed that the continuous exercise of setting and managing two linguistic systems requires control skills and through training, these skills become stronger.

Bilingualism effects on inhibitory processes. Research with metalinguistic tasks led to the hypothesis that the effect of bilingualism was to enhance the performance of the executive function system, not just for linguistic processing, but for nonverbal processing as well. This proposal represents a new conceptualization of the effects of speaking two languages and over the past two decades has been empirically supported by a growing number of studies with both children and adults.

The majority of studies of bilingual effects on nonlinguistic executive performance has focused on tasks measuring conflict resolution and interference suppression in search for a task-general inhibitory control advantage in bilinguals. This is in line with the idea that an inhibitory control mechanism is recruited to suppress the interference from the language that is not in use, but which is activated in parallel with the relevant language (Green, 1998). For example, in one of the early studies, Bialystok (1992) reported that bilingual children performed better than their monolingual counterparts on the Embedded Figures Test. In this test, participants must find a simple visual pattern concealed in a larger complex figure. More specifically, children are presented with a complex shape, which is a recognizable picture that contains a simple triangle or a house-shaped configuration and their task is to identify the hidden or embedded shape. Bialystok suggested that the better performance of bilingual children might reflect their superior ability to focus on wanted information and ignore misleading information. That is, the advantage might be one of enhanced selective attention, involving the ability to inhibit irrelevant or unwanted information and the complementary ability to concentrate on relevant aspects.

More generally, in the research examining non-verbal executive function performance, the investigator typically compares performance by monolinguals and bilinguals on tasks that are superficially similar but include one condition that additionally requires some aspect of executive control. An example of this approach can be seen in research using the dimensional change card sort task (DCCS) developed by Zelazo, Frye and Rapus (1996). This is a game in which images that vary on two dimensions, usually shape and color, are sorted according to one of them. For example, cards containing either red circles or blue squares are sorted into containers marked by an image of either a red square or a blue circle; all the features are represented on the containers but their combination does not match the images on the cards to be sorted. Children are asked to first sort the cards by one dimension – blues in this box and reds in this box – and then to switch to the other – circles in this box and squares in this box. Thus, this problem places two types of rules in conflict because each card needs to be placed in the opposite box for the new rule. The ability to do this involves several aspects of the executive function – inhibit attending to the irrelevant rule, shift between rules when the game changes, and hold the current rule in mind. The dramatic finding is that young children can easily state the new rule when it changes but continue to sort by the first rule; they have great difficulty overriding the habit set up in the first phase. When this experiment was repeated with bilingual and monolingual children aged between 4 and 5 years, the bilingual children were significantly better at switching to the new rule (Bialystok, 1999; Bialystok & Martin, 2004). This result was obtained despite there being no difference in pre-switch performance. The researchers thus concluded that the constant need to inhibit the non-used language generalized to more effective inhibition of nonverbal information.

Other studies have used computerized tasks such as the conflict resolution part of the child Attentional Network Test (child ANT) and the Simon task in order to examine inhibitory processes in monolingual and bilingual children. The child ANT is a child-friendly version of the classic flanker task designed by Rueda and colleagues to measure attentional processes in children (Rueda et al., 2004). In the classic flanker paradigm the target is an arrow pointing to the left or to the right and is surrounded by flankers, stimuli that point in the same or opposite direction as the target (Eriksen & Eriksen, 1974). The typical finding is that participants are slowed down in incongruent trials, when the flankers and the target indicate different responses compared to congruent trials in which both the flankers and the target require the same response. Rueda and colleagues adapted this task and replaced the arrows by colored fish that pointed either to the left or to the right (Rueda et al., 2004). Comparisons of monolingual and bilingual children's performance on this task showed smaller costs (Mezzacappa, 2004) or more accurate and faster performance (Yang, Yang, & Lust, 2011) for bilinguals on the incongruent trials. Yang and colleagues compared four groups of 4-year-old children (Korean-English bilinguals, English monolinguals, Korean monolinguals in the U.S.A and Korean monolinguals in Korea) and found that bilinguals had a more efficient overall performance on the task, as indicated by the small inverse efficiency scores, which offer a measure of processing efficiency independent of possible speed-accuracy trade-offs (Yang et al., 2011).

The Simon task is another standard task measuring inhibition (Simon, 1969). In the Simon task, the stimuli are colored squares that appear one at a time, on the left or right side of the screen, and are associated with a right or left key press. The decision to press the right or left key is dictated by one feature of the stimulus, namely the color. For example, red squares require a left key press and green squares require a right key press. However, another salient, although irrelevant, feature of the stimulus that contributes to the response selection is the position of the stimulus on the screen. In congruent trials, the position and color information are convergent and indicate the same response, but in incongruent trials, the correct response based on the color information conflicts with the position information and consistently leads to costs in performance. This cost in performance measured by longer response times to the incongruent trials is the Simon effect (Simon, 1969) and reflects the conflict between the two features of the stimulus during response selection. Comparisons of monolingual and bilingual children's performance on the Simon task showed shorter response times for bilinguals for both congruent and incongruent trials (e.g., Martin-Rhee & Bialystok, 2008, study 1). Thus, all these studies demonstrate that the experience of speaking two languages on a daily basis has consequences for the way in which higher cognitive processes operate and results in more precocious development of inhibition and attentional abilities.

However, inhibition itself is not a unitary process. A distinction is sometimes made between two types of inhibition: *interference control* (or interference suppression), which refers to suppression of interference due to stimulus competition and *behavioral inhibition* (or response inhibition) which is suppression of prepotent motor responses (Harnishfeger, 1995). The studies discussed above mainly compared monolingual and bilingual children's performance on interference suppression tasks and demonstrated a processing advantage for bilinguals in tasks that present the target information along with salient but misleading input and require cognitive control to attend to the relevant properties of the target. Fewer studies have studied the bilingual influences on response inhibition in children (Bonifacci, Giombini, Bellocchi, & Contento, 2011; Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008). Response inhibition is typically measured in go/no-go paradigms which require participants to produce a motor response to selected stimuli and to refrain from responding when no-go stimuli are presented. In addition, response inhibition is measured by tasks that ask children to control impulses or delay gratification.

To examine whether the bilingual advantage documented in previous research is present for both interference suppression and response inhibition, Martin-Rhee and Bialystok (2008) conducted three studies that used tasks such as the Simon task, Stroop picture naming task, and univalent and bivalent arrows task. The Stroop picture naming task is a modified computerized version of the day-night Stroop task (Gerstadt, Hong, & Diamond, 1994) that presented children with four types of pictures (i.e., day, night, cat, dog) and asked children to either name the picture as fast as possible or to say the name of its pair as fast as possible (i.e., "night" for day and "dog" for cat and vice-versa). This task provided a measure of response inhibition because pictures were presented one at a time, and thus there was no conflict between competing perceptual cues. Instead, the main demand was to overcome the prepotent response of naming the picture when asked to provide the name of its pair. The task has additional working memory demands given that children are required to hold in mind pairs of names plus the rule.

The univalent arrows task was designed to measure processes similar to the Stroop naming task and presented children with displays of an arrow that appeared in the center of the screen and pointed either to the left or to the right. Again, there were two types of trials that asked children to press a key indicating either the direction in which the arrow was pointing or the opposite direction. To perform successfully, children had to inhibit the prepotent response indicating the actual direction of the arrow, making the task an index of response inhibition.

In contrast, the bivalent arrows task was designed to measure processes similar to the Simon task and presented children with displays of an arrow that appeared on one side of the screen and children had to press a key indicating the direction in which the arrow was pointing. The processing required by this task is different from the univalent arrows task because the stimuli are characterized by two properties – location on the screen and pointing direction. However, only the pointing direction needs to be considered to perform the task because the arrow's location is irrelevant and has to be ignored; thus the task indexes interference suppression, similar to the Simon task.

The results showed a clear dissociation with a bilingual advantage present only in the Simon task and the bivalent arrows task and equivalent performance for monolingual and bilingual children on the Stroop naming task and the univalent arrows task. In other words, the exercise of speaking two languages appears to selectively impact interference suppression processing but not response inhibition.

A similar result was found in a study by Carlson and Meltzoff (2008). They administered nine executive function tasks to 50 kindergarten children who were English-speaking monolinguals, English-Spanish bilinguals, or were in a language immersion elementary school. The major finding was that the native bilingual children performed better on the executive function battery than both other groups, once differences in age, vocabulary and parents' education and income levels were statistically controlled. The effects were specific to certain aspects of control: there were no bilingual advantages in the control of impulses (response inhibition) but advantages emerged on conditions requiring memory and inhibition of attention to irrelevant information (interference suppression). In other words, on tasks that required children to refrain from peeking at or opening a nicely wrapped gift, bilingual children did not differ from monolinguals. However, on tasks that required children to focus on selected information such as the middle fish in an array of five fish, and ignore the distractors (i.e., the four fish flanking the middle fish), bilingual children surpassed monolinguals.

Finally, Bonifacci and colleagues (2011) tested bilingual children (age 6 to 12 years) and adolescents (age 14 to 22 years) on a battery of tests of choice reaction time, response inhibition, working memory and anticipation. Response inhibition was measured with a go/no-go task that presented two separate images of a hand and a foot in a random sequence. On the go trials, participants were asked to press the keys "H" or "F" corresponding to the first letters of the words "hand" and "foot". On the no-go trials a sound was played simultaneously with the picture and it signaled withholding the motor response. At both ages, bilingual children performed similarly to monolinguals, showing no enhancement of response inhibition abilities. Taken together, these three studies (Bonifacci et al., 2011; Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008) suggest that the experience of speaking two languages does not impact the ability to delay gratification, to control impulses or to withhold a habitual or prepotent response.

Bilingualism effects go beyond inhibitory processes. Studies on the effects of bilingualism on executive functions have focused on interference suppression to test the hypothesis of a general bilingual inhibitory control advantage. One unexpected but robust finding coming from these studies revealed a bilingual advantage for both congruent and incongruent trials. This pattern was observed in the performance of both bilingual children (e.g., Bialystok, Barac, Blaye, Poulin-Dubois, 2011; Martin-Rhee & Bialystok, 2008) and adults (e.g., Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009). This finding is puzzling and difficult to explain within the framework of the inhibitory control hypothesis given that the congruent trials do not have significant inhibitory demands.

In a recent review of the empirical data from the literature on non-linguistic interference tasks in bilingual children and adults, Hilchey and Klein (2011) found scant evidence for a bilingual cognitive advantage in inhibitory processing based on the incongruent trials of interference tasks such as Simon task and flanker. However, there was robust evidence for a bilingual advantage on both congruent and incongruent trials, and instead the authors proposed a *general executive processing advantage*. This interpretation is in line with more recent research which demonstrated that the bilingual advantage in children extended to executive functions such as task switching, planning, monitoring, and working memory (Barac & Bialystok, 2012; Bialystok, 2010; Calvo, 2011). For instance, Bialystok (2010) tested 6-year-old monolingual and bilingual children on the switching, updating, and monitoring components of executive control using the trail-making and the global-local tasks. The trail-making task consists of two parts: one in which the stimuli are numbers (Trail A) and the other in which the stimuli represent numbers and letters (Trail B), randomly arranged on a page. The children's task was to connect the stimuli in ascending order, thus moving from number 1 onwards in Trail A (1-2-3-4, etc.) and alternating between numbers and digits in Trail B (1-A-2-B-3-C, etc.). In the Global Local Task, participants are presented with a global stimulus (e.g., a capital letter, H), made up of smaller letters that are the same (congruent trials) or different (incongruent trials) from the global stimulus. The children's task was to identify the stimuli, either at the global or the local level. Bilingual children outperformed monolinguals in all conditions, that is, trails A and B of the trail-making task, and the congruent and incongruent trials of the global-local task. However, when the congruent trials were presented in a single block, there were no group differences, ruling out an explanation based solely on processing speed differences. Thus, the study demonstrates that language experience influences aspects of executive processing such as planning, switching and monitoring skills.

Similarly, Barac and Bialystok (2012) examined differences in switching abilities between 6-year-old monolingual and bilingual children. In the task switching test used in the Barac and Bialystok study (in press), children were presented with images of cows and horses colored in red or blue and they were instructed to sort the stimuli either by color or by shape. Children performed the two sorting tasks either in separate blocks (i.e., sort by color only, and sort by shape only), and in mixed blocks (i.e., sort by color or by shape as indicated by a cue). The performance of bilingual children was less affected by the two tasks being mixed together, indicating that bilingual children have better abilities to select, maintain and switch between tasks than same age monolingual children.

These results suggest that bilingualism has the power to shape a range of executive functions in the general control network supported by the prefrontal cortex. However, as noted earlier, not all executive functions tested were influenced by bilingualism: monolingual and bilingual children showed equivalent performance on measures of response inhibition (e.g., Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008). One possible explanation for this finding is that experimental tasks might need to have a threshold level of executive demands or complexity, and recruit a certain subset of executive processes in order to discriminate between the two language groups. Thus, if a certain degree of complexity is not reached, the task might not discriminate between the two language groups. Accuracy was around 95% in Martin-Rhee and Bialystok study (2008, study 3), suggesting that the tasks used might not have been difficult enough to differentiate the groups.

Another explanation, related to the issues of task complexity and task impurity could be that although various experimental tasks are believed to index the same underlying process, in reality this may not be the case. Response inhibition, for instance is measured by go/no-go tasks but also by other tasks that ask participants to control impulses and delay gratification. Recently, some researchers argued against the idea that these different tasks - go/no-go, delay of gratification - index similar processing and differentiated between simple response inhibition and complex response inhibition based on the working memory demands of the tasks (Garon et al., 2008).

Simple response inhibition is measured in tasks such as delay of gratification and Gift Delay and requires withholding or delaying of a prepotent or automatic response. In contrast, complex response inhibition involves holding a rule in mind and responding based on this rule, in addition to the demand of inhibiting a prepotent response. For instance, tasks such as reverse categorization in which children sort "baby" toy animals in big buckets and "mommy" toy animals in small buckets was proposed to tap complex response inhibition because they have additional working memory demands. This distinction between simple and complex response inhibition is important because it reflects the pervasive issue of task impurity in the study of executive functions and it enriches interpretations of data coming from these tasks. Thus, going back to the lack of differences in performance between monolingual and bilingual children on the Gift Delay task in the Carlson and Meltzoff (2008) study, Gift Delay is a measure of simple response inhibition because it involves delaying or stopping a response without relying heavily on working memory resources. The Simon Says task recruits inhibitory processes and working memory, which makes it more demanding than the Gift Delay task. However, the working memory demands are low, thus the Simon task can also be considered a measure of simple response inhibition. Consequently, a possible explanation for the lack of bilingual effect could be that the task did not engage a specific subset of executive processes such as inhibition, working memory, monitoring and switching (in the case of Gift Delay), or even when these processes were recruited, the executive demands of the tasks might have been too low to differentiate the two language groups (in the case of Simon Says, which recruited inhibitory processes, but very low working memory resources).

This idea is supported by a recent study showing that when the task is complex and engages a cluster of specific executive processes, bilinguals show superior response inhibition than monolinguals (Barac, Calvo, Feng, & Bialystok, 2010). The study conducted by Barac et al. (2010) extended previous findings by showing that 6- to 7-year old bilingual children outperformed monolinguals on go/no-go trials measuring response inhibition, but only when the go/no-go trials were incorporated within an experimental block that contained three other types of trials (Barac et al., 2010). The task was a modified version of the flanker task in which children had to press a mouse button indicating whether the target stimulus – the central arrow – was pointing to the left or to the right. There were four different types of trials: go/no-go (the target was surrounded by four x, two on each side), simple distraction (the target was flanked by four diamonds, two on each side), congruent (the target was surrounded by four arrows all pointing in the same direction), and incongruent (the flanking arrows were pointing in the opposite direction from the target).

Results showed that bilingual and monolingual children had similar performance when the go/no-go trials appeared in a separate block, but there was a bilingual advantage when the go/no-go trials were combined with the other types of trials in a mixed block. It may be the case that in this study, bilingual children showed an advantage mainly because the go/no-go trials were embedded in a block of mixed trials, increasing the executive demands and the complexity of the task. However, the interpretation is not straightforward because this experimental manipulation also reduced the purity of the executive processes engaged by the go/no-go trials which likely indexed additional executive functions such as monitoring, inhibition, and switching, along with response inhibition.

Length of bilingual experience resulting in cognitive benefits. The benefits of the bilingualism experience on children's cognitive development have been documented at various ages ranging from 3 to 8 years. Recently, this pattern has been extended to infants and toddlers (e.g., Kovács & Mehler, 2009; Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011). For instance, Kovacs and Mehler presented 7-month-old infants with a verbal cue followed by a visual reward. The verbal cue consisted of meaningless trisyllabic cues and the visual reward was a toy that always appeared on the same side of the screen. Infants had to learn that the verbal cue predicted the location of the toy reward. One way to know if infants learned this is by recording their anticipatory looks. That is, if infants learned that the verbal cue predicted the location of the toy on the screen, then they should look at the place where they expect the reward to appear, even before it is shown. Monolingual and bilingual infants were equally good at learning this relation. However, in the second part of the task, the rule was changed so that the toy reward appeared on the opposite side of the screen. Thus, again, infants had to learn that the cues predicted the location of the toy, but to do so they needed to overcome the old response, the tendency to look to the side of the screen that was previously rewarded. In this sense, infants needed to rely on executive functions to switch to the new location. Kovacs and Mehler (2009) found that 7-month old infants raised in bilingual households were better able to switch responses after a rule shift than were their peers raised in monolingual households. These results suggest that the experience with two languages changes the cognitive system from very early on. However, one limitation of this study is that only minimal information was reported about the infants' language exposure.

Generality of the bilingual advantage. Although the bilingual advantage in executive functions is a robust effect supported by a large body of empirical evidence, understanding the effect is complicated by the fact that bilingualism is often correlated with variables that may themselves influence performance. For example, Morton and Harper (2007) claimed that the reported bilingual advantage was due to socioeconomic differences between bilingual and monolingual children. There is no doubt that socioeconomic status is a powerful influence on executive control, but it does not undermine the body of literature for which bilingual advantages have been recorded (Bialystok, 2009). Similarly, claims for cultural effects favoring Asian children on tests of executive control (e.g., Sabbagh, Xu, Carlson, Moses, & Lee, 2006) must be separated from the role of bilingualism in shaping this performance.

These issues were addressed in a recent study examining three groups of bilingual children (Chinese-English, French-English, and Spanish-English) and one group of English monolinguals performing verbal and nonverbal tasks (Barac & Bialystok, 2012). The bilingual children differed in terms of similarity between English and their other language, cultural background, and educational experience (the French-English bilinguals were schooled in French, but all the other groups received instruction in English). However, despite these differences, all three bilingual groups performed similarly on the executive control task measuring task switching and exceeded monolinguals. Thus, executive control outcomes for bilingual children are general and do not depend on the relationship between the two languages or on the language of school instruction.

In summary, these studies demonstrate that the experience of building and accessing representations from two linguistic systems tunes the executive function system, as demonstrated by its precocious development in bilingual children. Moreover, an extensive body of behavioral evidence demonstrates that these effects apply to a range of executive functions such as inhibition, monitoring, task switching and working memory, lending strong support to the idea of a *general executive processing advantage* in bilinguals. Despite being a general processing advantage, it appears that some executive processes are less likely to be molded by the bilingualism experience than others; in particular, aspects of response inhibition such as impulse control and withholding prepotent responses appear unchanged by the experience of speaking two languages.

Bilingualism Effects: Electrophysiological and Neuroimaging Findings

The condensed summary of several decades of bilingualism research is that the experience of speaking two languages shapes higher cognition, as measured by behavioral performance on a wide range of executive functions tasks. This conclusion is in line with research examining the effects of other forms of expertise, life experience or training on behavior. To date, several studies have demonstrated that training a particular ability results in changes in the behavioral performance on structurally similar (i.e., near transfer) or dissimilar tasks (i.e., far transfer). For instance, training in switching, a component of the executive function, led to benefits to other executive functions and fluid intelligence across the lifespan (Karbach & Kray, 2009). Similarly, working memory training improved fluid intelligence in children with ADHD (Klingberg, Forssberg, & Westerberg, 2002) and in young adults (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). Thorell and colleagues showed that training inhibition or visuo-spatial working memory for 5 weeks in preschool children resulted in different outcomes: while both types of training improved performance on the trained tasks, only working memory training benefits transferred to non-trained verbal and spatial working memory and attention tasks (Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). Finally, playing video games extensively has been found to enhance several aspects of visual processing (Green & Bavelier, 2007), and music training was related to gains in verbal intelligence in preschool children (Moreno et al., 2011).

What is most remarkable about these results is that the behavioral changes are accompanied by both functional and structural brain changes. In other words, training through expertise in various life experiences leads to neuroplasticity, also referred to as brain plasticity, cortical plasticity or cortical re-mapping (Jancke, 2009). Several studies have documented alterations of brain structure after prolonged experience of driving taxi in London (Maguire et al., 2000), playing the piano (Bengtsson et al., 2005), and working memory training (Takeuchi et al., 2010). Bengtsson and colleagues (2005), for instance, investigated the effects of piano training starting at different ages (i.e., childhood, adolescence, adulthood) on white matter microstructure using diffusion tensor imaging. The authors found that regardless of the starting age there were significant increases in myelination as practice time increased. Moreover, these increases in myelination specifically affected certain pathways depending upon the time in development when the piano practice occurred. These findings were interpreted as showing that training-induced white matter plasticity is possible and may be detected when the specific white matter fibers involved are still undergoing maturation.

Other studies have demonstrated other experiences that modify functional brain responses. For instance, 6- to 9-year-old children with reading disabilities who received an evidence-based intervention targeting phonological skills for one year showed improved reading skills at the behavioral level and increased activation in regions of the left hemisphere (Shaywitz et al., 2004). One year post-intervention, children were activating bilateral inferior frontal gyri and left superior temporal and occipitotemporal regions. In another study, five-week working memory training in adults was related to increases in task-related prefrontal and parietal activity and decreases in the anterior cingulate, postcentral gyrus and inferior frontal sulcus (Olesen, Westerberg, & Klingberg, 2004). Similarly, music training in preschool children led to brain modifications (increased amplitudes) in processing of an inhibition task (Moreno et al., 2011), and differences in vocabulary size in infants in the second year of life were related to different patterns of brain responses (more bilateral for low vocabulary, left-lateralized for larger vocabularies) (Mills, Conboy, & Paton, 2005).

Although a great deal still needs to be learned about the mechanisms underlying these structural and functional brain changes, and why exactly "practice makes perfect" (Jonides, 2004, p. 11), these studies nevertheless show that variations in experience lead to reorganization and remapping of the brain structure and activity. Kolb summarized this as "The brain's plasticity reflects more than mere maturational change, however, as it includes the ability to change with experience. Indeed, the capacity to alter brain structure and function in response to experience provides the nervous system with the ability to learn and remember information. Some experiential changes are self-evident, such as the acquisition of specific bits of knowledge, whereas other changes are more subtle such as perceptual learning and the development of different problem-solving strategies. Nonetheless, regardless of the nature of the experiential change, the brain has altered its form and function." (Kolb, 1995, p. 5).

Bilingualism is a life experience and ultimately, a form of training, so it is reasonable to expect that bilingualism shapes the brain as well. In what follows, the effects of bilingualism on the brain's physical and functional characteristics are examined initially in children, and then in adults.

Bilingualism effects on brain function in children. To date, no studies have investigated the neural correlates of non-verbal executive processing in bilingual children. However, a few studies have looked at how childhood *bilingualism* changes brain structure (Mohades et al., 2011) and brain functioning in verbal tasks (Conboy & Mills, 2006; Rinker, Alku, Brosch, & Kiefer, 2010). Additionally, two other studies examined the functional brain changes in children processing linguistic tasks after *short-term exposure to a second language* (Conboy & Kuhl, 2011; Takahashi et al., 2011). Together, these studies demonstrate that experience with two linguistic systems changes the way in which language is organized in the brain. Furthermore, these functional brain changes are present very early on, after only limited bilingualism experience, suggesting that setting up representations in two linguistic systems through exposure to two languages, and not only language production, drives functional plasticity in bilingual children. Similarly, changes in white matter microstructure were reported in simultaneous and sequential bilingual children between 8 and 11 years of age in two of the four white matter tracts investigated (i.e., left inferior occipitofrontal fasciculus and the anterior part of the corpus callosum projecting to the orbital lobe than monolingual children) (Mohades et al., 2011). In this study by Mohades and colleagues, the strongest effect was found in bilingual children who learned the second language at an earlier age, that is simultaneous bilinguals, with sequential bilinguals showing a neural profile intermediate to that of the other two language groups.

Bilingualism effects on brain responses to linguistic tasks. The task of building up linguistic knowledge in two languages, in other words creating and accessing phonological, lexical and semantic representations was shown to induce functional brain plasticity in children. For instance, in one study, 19- to 22-month-old Spanish-English bilingual children were tested by recording ERPs to known and unknown words in both languages (Conboy & Mills, 2006). The results demonstrated that language experience altered the organization of language in the brain as indicated by differences in ERP responses between infants with low and high vocabularies and between the patterns elicited by infants' dominant and non-dominant languages. Latency analyses showed that processing of known and unknown words occurred earlier in the dominant language than in the non-dominant language.

Similarly, Rinker and colleagues found that language experience influenced the electrophysiological brain responses of 5-6-year-old German monolinguals and Turkish-German bilinguals in their study comparing ERPs to vowel contrasts unique to German or common to both German and Turkish (Rinker et al., 2010). The study focused on one ERP component, the mismatch negativity, which is particularly sensitive to differences in processing between native and non-native phonemes. The bilingual children showed a less pronounced brain response for the German-specific contrast but did not differ from the monolingual children on the contrast that exists in both Turkish and German.

Effects of short-term second language exposure on brain responses to linguistic tasks. Two recent studies (Conboy & Kuhl, 2011; Takahashi et al., 2011) did not look directly at the impact of bilingualism on linguistic processing but rather at the neural signature of short-term exposure to a second language. These studies investigated phonological or semantic performance in infants or pre-school children. Both studies showed that having limited experience with a second language changed the brain responses to verbal tasks. The results of these studies are important because they demonstrate that even very limited exposure to a second language shapes brain responses in young children.

Conboy and Kuhl (2011) tested English monolingual infants at 9 and 11 months, before and after a month of naturalistic exposure to Spanish. The authors collected ERPs from infants who were presented with contrasts that were phonemic either in English or in Spanish. At 9 months, before exposure to a second language, infants showed the typical mismatch negativity in response to English contrasts, but no discrimination of the Spanish contrasts. However, after only one month of exposure to Spanish, infants showed the neural signature of a second language phonetic learning illustrated by the presence of a mismatch negativity response to the Spanish contrast. Importantly, this second language phonetic learning did not come at the cost of native language phonetic learning – in fact, post-exposure to Spanish, infants showed improved processing of the native contrast as indicated by earlier latency of the brain responses to the English phonemes.

In the other study, Takahashi and colleagues focused on semantic processing indexed by the N400 component to Japanese sentences that had congruous ("My father eats an apple") and incongruous ("My father eats a bathtub") endings. The authors tested four groups of Japanese-speaking children: 4- and 5-year old children who were never exposed to English, 4-year-olds with about 30 hours of English exposure and 5-year-olds with about 290 hours of English exposure in a kindergarten setting. The results indicated that in children with longer exposure to a second language, the N400 showed an earlier onset and more distributed brain topography, suggesting again that systematic exposure to a second language alters the brain processing of the native language.

Training effects on brain responses to non-verbal executive control tasks. Although at present there is no direct evidence for bilingual influences on brain function related to executive processing in children, there is evidence for changes in neural function following executive control training (e.g., Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). In the Rueda et al. (2005) study, behavioral and electrophysiological data were recorded from 4- and 6-year-olds before and after they received five-day long attention training. The training consisted of multiple exercises that targeted aspects of cognition that were thought to be related to executive attention such as stimulus discrimination, conflict resolution and response inhibition. For example, in the response inhibition training exercise, children were told to help a farmer bring sheep inside a fence by clicking a mouse button as fast as possible. However, some of the animals outside the fence were wolves, and in these cases children had to refrain from producing a motor response to let them in. In the pre- and post-training sessions, children were tested with the child ANT in order to assess training-related changes in executive attention.

Children's behavioral performance on the child ANT improved after training at both ages and the training effects transferred to aspects of intelligence captured by the matrices subtest of the Kaufman Brief Intelligence Test. This is an important finding because it demonstrates that training a specific ability (executive function) results in changes in performance on tests of that ability, but it also transfers or generalizes to related skills. Additionally, the electrophysiological data for the child ANT showed changes in spatial distribution of the ERPs characterized by more frontal, adult-like activation. Interestingly, this more frontal scalp distribution of the ERPs is similar to changes in ERP topography as a result of development: trained 4-year-olds showed a similar pattern of brain responses compared to untrained 6-year-olds, and the ERPs scalp distribution of trained 6-year-olds approximated that of adults. Thus, training executive functions in children results in improved behavioral performance and changes in brain function that mimic speeded developmental changes.

Bilingualism effects on brain in adults.

Bilingualism effects on brain responses to linguistic tasks. One of the basic issues in the neuroscience of bilingualism that is largely explored in adults and to a lesser extent in children (e.g., Conboy & Mills, 2006; Tan et al., 2011) is whether the two languages of bilinguals are processed through the same neural mechanisms. Substantial neuroimaging evidence demonstrates that the brain regions supporting the processing of the first (L1) and second language (L2) in bilinguals are at least partially overlapping (Chee, Soon, & Lee, 2003; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Perani & Abutalebi, 2005). When solving grammatical tasks in L2, bilingual adults activated areas typically supporting grammatical processing in L1 such as Broca's area and the basal ganglia. Additionally, other areas were activated when processing grammar in L2, particularly when the proficiency in L2 was low and when L2 was acquired later in life (Perani & Abutalebi, 2005). In their review, Perani and Abutalebi (2005) concluded that "grammatical processing of L2 is acquired and carried out through the same computational brain devices underlying L1 grammatical processing. There are differences in terms of additional resource demands, but these are within the same neural system." (p. 204).

Similar to the findings from research with children, very limited exposure to a second language has also been found to change brain activity in response to second language processing (McLaughlin, Osterhout, & Kim, 2004). Adult learners of a second language showed differential ERPs to words and pseudo-words in a second language after only 14 hours of instruction in that second language. Not surprisingly then, several studies have shown that systematic and prolonged experience with two languages - bilingualism and variations in factors related to bilingualism, such as age of acquisition and language proficiency - influence the characteristics of various ERP components related to semantic and syntactic processing (e.g., the amplitude, latency and topography of N400, a marker of semantic integration, and P600, an electrophysiological index of syntactic violations) (Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Hahne, 2001; Hahne & Friederici, 2001; Moreno & Kutas, 2005; Weber-Fox & Neville, 1996; etc). For instance, in a study comparing ERPs to correct, semantically incorrect and syntactically incorrect sentences in monolingual speakers of German and German-Russian bilinguals, there was a delay in latency for both N400 and P600 components in bilinguals, suggesting reduced automaticity of linguistic processing (Hahne, 2001).

In addition, bilingualism was found to influence performance on linguistic tasks that recruit different degrees of cognitive control as well. A recent study contrasted monolinguals' and bilinguals' ERP characteristics on two sentence judgment tasks that required different levels of executive function involvement (Moreno, Bialystok, Wodniecka, & Alain, 2010). Monolingual and bilingual young adults were presented with the four types of sentences typically used in the research with children: sentences that were completely correct, grammatically incorrect but meaningful, grammatically correct but silly, or both grammatically and semantically incorrect. There were two tasks: in the simple task, the instructions were to decide if the sentence was okay or if there was anything wrong with it ("Apples grow on noses" would be incorrect); in the difficult task, the instructions were to decide only if the sentence was grammatically correct regardless of the meaning ("Apples grow on noses" would be correct). The conflict between form and meaning is only a problem for the difficult task. Importantly, on the simple task, monolinguals and bilinguals showed equivalent responses in ERP signals, but on the more difficult conflict task, the bilinguals produced different signals than the monolinguals, indicating less conflict to these sentences on the P600 waveform considered to reflect conflict in syntactic processing. This difference shows that the bilinguals processed the sentence and dealt with the conflict more efficiently than the monolinguals. These findings demonstrate that bilingual experience influences brain processing of sentence-level linguistic stimuli. The key component is the ability to control attention to attend to relevant features when there is strongly misleading information that needs to be ignored. Bilinguals find this easier to do than monolinguals.

Language control in the bilingual brain. These studies provide strong evidence for the idea that bilingualism impacts the way in which the brain processes linguistic information in each of the two languages. But separate from the issue of whether the functional brain responses are similar for the two languages is the way in which the brain manages the two linguistic systems and performs the processes of language selection and switching. This question is particularly important given that (a) the neural systems for the two languages are highly overlapping (e.g., Perani & Abutalebi, 2005) and (b) behavioral and neural evidence indicates that both the target and the non-target languages are active to some extent at all times in bilinguals (Schwartz & Kroll, 2006; Spivey & Marian, 1999; Thierry & Wu, 2007). Thierry and Wu (2007) demonstrated that the first language, Chinese, was accessed by Chinese-English bilingual adults who performed the task of deciding whether pairs of English words were related in meaning or not. The testing was performed exclusively in English but the authors used an ingenious experimental design that included a manipulation unknown to the participants: half of the words contained a character repetition when translated to Chinese. For instance, the words "train" and "ham", which are not semantically related, correspond to "Huo Che" and "Huo Tui" in Chinese (i.e., the character "Huo" is repeated). This manipulation did not affect the behavioral performance, but participants showed smaller amplitudes for the N400 component when there was a character repetition. What these results show is that when participants performed a task exclusively in the second language, they automatically and unconsciously activated the translation equivalents in the native language.

The overlap of the neuroanatomical representations of the two languages in bilinguals and their simultaneous activation during language production and comprehension require explanations about possible mechanisms that allow bilinguals to selectively access words from the relevant language and resolve interference from the other language. To address this issue, Abutalebi and Green (2008) conducted a qualitative review of the research examining bilingual language processing and identified a language control network that includes both cortical and subcortical areas: left prefrontal cortex, left anterior cingulate cortex, bilateral supramarginal gyri, and left caudate nucleus. The authors proposed that this cortical-subcortical system supports bilingual language processing by monitoring the use of the two languages, selecting the appropriate language and suppressing the irrelevant language. This finding is consistent with the results of a recent quantitative meta-analysis (Luk, Green, Abutalebi, & Grady, 2011) that identified a similar neural system supporting language switching in bilinguals, based on ten neuroimaging studies: left inferior frontal gyrus, left middle temporal gyrus, left middle frontal gyrus, right precentral gyrus, right superior temporal gyrus, midline pre-supplementary motor area, and bilateral caudate nuclei. Abutalebi and Green (2008) further proposed that this neural system supporting language control in bilinguals is also engaged in cognitive control tasks that are not language-specific but rather domain-general. For instance, the anterior cingulate cortex is activated to overcome interference in Stroop tasks (Melcher & Gruber, 2009) and in error detection (Ide & Li, in press). The dorsolateral prefrontal cortex and the supramarginal gyrus are part of the fronto-parietal network of attention (Toro, Fox, & Paus, 2008). The caudate nucleus was found to be engaged in tasks that require control of motor responses (Boehler, Appelbaum, Krebs, Hopf, & Woldorff, 2010) and goal-directed behavior (Grahn, Parkinson, & Owen, 2008). The fact that the control network engaged in bilingual language processing overlaps, at least in part, with the control network engaged in other high-order cognitive tasks indicates that bilingual language use therefore recruits the same general control system that is used for a range of nonverbal tasks.

Bilingualism effects on brain responses to non-linguistic tasks. These findings support the behavioral evidence showing that bilingualism changes not only the processing of linguistic tasks, but also of non-verbal tasks that rely on the executive function system. The finding of bilingualism-induced brain plasticity in non-verbal tasks is in line with the behavioral evidence reviewed in the previous section demonstrating that bilinguals profit from the experience of managing two languages and show a general processing advantage in executive control tasks. Evidence for functional brain plasticity in non-verbal executive control tasks comes from a few studies using different imaging methods - magneto-encephalography (MEG), functional magnetic resonance imaging (fMRI), and ERPs. In a MEG study by Bialystok and colleagues (Bialystok et al., 2005), the authors found that monolingual and bilingual young adults performing a Simon task used different brain regions to solve non-verbal conflict. For bilinguals there was a significant correlation between faster reaction times and amount of activation in a left frontal region corresponding to Broca's area. Using fMRI, Luk and colleagues (Luk, Anderson, Craik, Grady, & Bialystok, 2010) compared monolingual and bilingual young adults performing a modified flanker task that measured both response inhibition (go/no-go trials) and interference suppression (incongruent trials). Results showed that bilingualism selectively affected the neural correlates of these two inhibitory processes, with differences on interference suppression but not response inhibition. For monolinguals, the incongruent trials activated a restricted set of regions on the left side (temporal pole and superior parietal regions), whereas for bilinguals a broader network was engaged that included bilateral frontal, temporal, and subcortical regions. Similarly, Garbin and colleagues found that bilinguals relied on a different neural system than monolinguals when performing a non-verbal task switching task that involved switching between sorting geometric figures by color or by shape (Garbin et al., 2010). Monolinguals activated the right inferior frontal cortex and the anterior cingulate whereas bilinguals activated the left inferior frontal cortex and the left striatum, and achieved better behavioral performance (i.e., smaller switching costs). Interestingly, the brain areas engaged by the bilingual participants in this non-verbal control task are part of the cortical-subcortical network that supports language control, suggesting a relationship between language control and domain-general control. Finally, in a study by Moreno, Bialystok, Wodniecka, and Alain (in preparation), ERPs were recorded as bilingual and monolingual young adults performed a non-verbal go/no-go task. The authors found no differences in the behavioral performance of monolingual and bilingual adults on the go/no-go task. However, at the neural level, there were significant language group differences for two components: the P3 component which is related to inhibition, and the late positivity component, which follows the P3 component and provides a measure of task re-analysis and updating of mental representations. Greater amplitudes by bilinguals on these ERP components indicate that the neural basis of executive functioning is changed by the bilingual experience.

What these studies show is that for bilingual adults, performance on executive functions tasks is related to activation of cognitive control areas in a different way than it is for monolinguals. At the same time, it is important to note that, parallel to the children's findings, behavioral studies with adults have shown bilingual advantages in executive function tasks that require ignoring distracting and conflicting information (e.g., Bialystok, Craik, & Ryan, 2006; Costa, Hernández, & Sebastián-Gallés, 2008). Relating these behavioral and neuroimaging findings from non-verbal control tasks back to Abutalebi and Green's proposal (2008), one possible interpretation is that: (a) bilinguals engage a control network in order to manage the two linguistic systems; (b) this control network is not language-specific but rather supports domain-general functions, (c) as a result of systematic bilingual experience this control system is trained and possibly re-organized, and (d) this translates into better behavioral performance in tasks with high executive demands (linguistic and non-linguistic) and generally more diffuse brain activation.

Bilingualism effects on structural brain plasticity. In addition to the evidence for functional plasticity described above, there is also evidence indicating structural plasticity (Filippi et al., 2011; Luk, Bialystok, Craik, & Grady, 2011; Mechelli et al., 2004). In the first study of structural brain differences in bilinguals, Mechelli and colleagues (2004) tested monolinguals, early bilinguals who learned a second language before the age of 5, and late bilinguals who learned a second language during adolescence. Gray matter density in the left inferior parietal cortex, as measured by voxel-based morphometry, was greater in bilinguals than in monolinguals, regardless of when the second language was acquired. Using a different sample of bilinguals, the authors investigated the relationship between brain structure and two variables related to bilingualism: age of second language acquisition and language proficiency. Gray matter density in the same brain area as found in the first study, the left inferior parietal cortex, correlated positively with language proficiency and negatively with age of second language acquisition. Although voxel-based morphometry does not allow one to specify the nature of the structure change - changes in neuropil, neuronal size, dendritic or axonal arborization – the results are important because they demonstrate that the experience of learning a second language restructures the brain.

More recently, Filippi and colleagues (2011) found that differences in the gray matter density of a subcortical structure, the posterior paravermis of the right cerebellum, are related to differences in controlling verbal interference. This is in line with other evidence from functional neuroimaging and patients with aphasia demonstrating that subcortical structures such as the striatocapsular area (Azarpazhooh, Jahangiri, & Ghaleh, 2010), posterior paravermis of the right cerebellum (Filippi et al., 2011), and left head of the caudate (Ali, Green, Kherif, Devlin, & Price, 2010; Crinion et al., 2006) are involved in controlling interference when processing language.

In contrast with these studies examining gray matter density in young adults, Luk and colleagues (2011) took a different approach and measured white matter integrity in older adults (mean age 70 years) with lifelong bilingual experience. White matter integrity typically deteriorates with age (e.g., Madden et al., 2009); however, the authors proposed that preserved white matter integrity, that is, better connectivity, might be related to the previously documented finding that bilingual adults engage a different, and more distributed neural system when performing verbal and non-verbal tasks with high executive demands. The results confirmed this hypothesis: Older adults, who used two languages regularly for a span of decades, better maintained the integrity of white matter in the corpus callosum extending to the superior and inferior longitudinal fasciculi. These results were interpreted to suggest that greater white matter integrity in bilinguals might contribute to the cognitive reserve and this way support superior performance on cognitively demanding tasks.

In sum, the bilingualism experience, and even shorter exposure to a second language, results in reorganization and reshaping of the brain structure and function across the lifespan. This is consistent with the effects of other types of training, expertise and life experiences. Consistent with the reliable behavioral findings of different linguistic and nonlinguistic performance in bilinguals, neuroimaging and electrophysiological evidence also shows different functional brain responses than monolinguals on both linguistic and non-linguistic tasks. A possible explanation is that managing two linguistic systems engages a cortical-subcortical neural circuit that is not specific to language processing but is involved in general cognitive control processes. As a consequence, establishing representations in a second language and using two languages in a sustained manner presumably relies on this neural network supporting general cognitive control, and through prolonged training it gets further reorganized.

Theoretical Models of Bilingualism

The studies with both children and adults provide evidence that monolinguals and bilinguals differ in terms of brain structure as well as in the functional brain responses to verbal and non-verbal executive function tasks. “If properly interpreted, these brain data may be very informative for models of bilingual language processing. Regarding the key question of language control and selection, neuroimaging research may not only provide crucial insight but also an indication of the nature of the mechanisms involved in control” (Abutalebi & Green, 2008, p. 560). This issue is explored in this subsection with the goal of providing a brief overview of the main theoretical models and mechanisms of bilingualism. Ideally, models of bilingualism need to account for or to align with the main empirical findings consistently documented in bilingualism research and outlined in the previous subsections: (a) improved executive control abilities as measured in both linguistic and nonlinguistic control tasks, and (b) reorganization of the brain circuits supporting cognitive control. In addition, theoretical explanations of bilingualism effects need to account for a third consistent empirical finding, which is reduced language proficiency skills in bilinguals compared to monolinguals. The issue of language proficiency in bilingual children will be presented and followed by a discussion of the main theoretical views on bilingualism.

Language abilities in bilingual children. The evidence is compelling that on average bilingual children know significantly fewer words in each language than comparable monolingual children who speak only that language. A careful investigation of children between 8 and 30 months old examining the number of words children could understand and produce in each language confirmed that, on average, this number was smaller in each language for bilingual children than for monolingual learners of that language (Pearson, Fernandez, & Oller, 1993). Nevertheless, an analysis of the total number of concepts showed no differences between monolingual and bilingual children (Pearson et al., 1993; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, in press). For instance, Poulin-Dubois and colleagues (in press) showed significant differences between 24-month-old monolingual and bilinguals' expressive vocabulary size in the first language but no differences in total vocabularies. The number of words in the total vocabulary of a bilingual child, however, is difficult to estimate: Do proper names count for one language or two? Do cognates (words that are very similar in both languages, such as "table" in English and "la table" in French) count once or twice, especially if the pronunciation is unclear? Do childish sounds that are not quite words count as a word if they have a consistent meaning?

A clearer illustration of the relative vocabulary size of monolinguals and bilinguals comes from a study of children who were older than those in the Pearson et al. analysis. Bialystok, Luk, Peets, and Yang (2010) measured the receptive vocabulary of over 1700 children between the ages of 3 and 10 years old. Receptive vocabulary was assessed by the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997) in which the child is shown a page with four pictures while the experimenter says a word, and the task is to point to the picture that best illustrates that word. All the bilingual children spoke English and another language, with English being the language of the community and school for all children. Across the sample and at every age studied, the mean standard score on the English PPVT was reliably higher for monolinguals than bilinguals. At least in one of the two languages, and importantly, the language of schooling, monolingual children had an average receptive vocabulary score that was consistently higher than their bilingual peers.

It is important to note, however, that the disparities were not equivalent for all words. In a subset of 6-year-olds in the sample, all children achieved comparable scores on words associated with schooling (e.g., astronaut, rectangle, writing) but significantly lower scores for words associated with home (e.g., squash, canoe, pitcher). Because all the children attended schools in which English was the language of instruction, their experiences in learning English in this context were more equivalent than their experiences learning words that refer to home and social contexts. This is a reasonable result given that English is not used as extensively in bilingual homes as it is in those of monolinguals. Thus, bilingual children are not typically disadvantaged in academic and literacy achievement (e.g., Bialystok, Luk, & Kwan, 2005) or academic uses of spoken language (Peets & Bialystok, 2009) because the linguistic basis of those activities is well established. In this sense, the smaller vocabulary for bilingual children in each language is not an overall disadvantage but rather an empirical description that needs to be taken into account in research designs, especially in tasks that involve verbal ability or lexical processing. Moreover, the vocabulary deficit for home words in English in the bilingual children is almost certainly filled by knowledge of those words in the non-English language, making it likely that the total vocabulary for bilingual children is in fact greater than that of monolinguals. Therefore, the nature of the smaller bilingual vocabulary than monolingual speakers of each language is complex (Bialystok et al., 2010). Similarly, other researchers commented that the issue of linguistic deficits in bilinguals is not a straightforward finding (e.g., Akhtar & Menjivar, 2012; Yan & Nicoladis, 2009). Akhtar and Menjivar (2012), for instance, emphasized that an interpretation of the linguistic (and non-linguistic) outcomes in bilingual children needs to be informed by variables such as timing of the second language, proficiency in both languages, relative dominance and contexts of exposure to the two languages.

Models of bilingualism. Models of bilingualism need to account for the documented costs in language processing, advantages in executive control and reorganization of the neural systems supporting the linguistic and non-linguistic performance. Thus the key is to identify parsimonious explanations that can account for the discrepant cognitive characteristics of bilinguals. One model, the "weaker links" hypothesis, was designed as an account of the bilingual deficits in lexical access. Gollan and colleagues argued that the subtle differences in language production between monolinguals and bilinguals are related to differences in the frequency of using representations in L1 and L2 (Gollan, Montoya, Cera, & Sandoval, 2008). Given that both languages rely on the same modality, only one language can be used at a time, which means that bilinguals use each language less frequently than a monolingual speaker of that language. Consequently, words in L1 and L2 in bilingual speakers receive less practice, affecting the strength of the links between semantics and phonology within each linguistic system. Furthermore, because these links are weaker, the access to words is slower in each language relative to a monolingual speaker. The authors argue that the strength of this hypothesis comes from the fact that the proposed mechanism, frequency of usage, is common to both monolinguals and bilinguals, and no unique mechanism needs to be postulated to account for the observed language processing differences. Empirical evidence confirms that access to low frequency words (relative to high frequency words) is indeed slower in monolinguals. Similarly, bilinguals take longer to access words in picture naming tasks, in both the dominant and non-dominant language (Gollan et al., 2008). It is specifically access to words and not concepts that is impacted by the frequency of use, as demonstrated by the finding that performance costs are observed in picture naming tasks, but not in picture classification tasks (Gollan, Montoya, Fennema-Notestine & Morris, 2005). Additionally, words that have the same label in both languages are not affected, presumably because the links between phonology and semantics are not weakened (Gollan, Bonanni, & Montoya, 2005). Thus, the "weaker links" hypothesis offers a reasonable and intuitively appealing explanation for the subtle but consistent language processing costs documented in bilinguals. However, the model offers no account of the bilingual benefit in executive functions.

Other psycholinguistic models of language production (e.g., the Inhibitory Control model, IC) and comprehension (e.g., the Bilingual Interactive Activation Plus model, BIA+) in bilinguals postulate the existence of both a language processing system and a task or decision system (Dijkstra & van Heuven, 2002; Green, 1998). Green (1998) proposed that the activation of a particular thought or concept leads to parallel activation of the lexical candidates or lemmas in the two linguistic systems. Parallel activation produces competition between the two lexical items, given that only one lemma is relevant and has to be selected. Therefore, Green (1998) argued that it is necessary to postulate the existence of a control mechanism in bilinguals with the function of regulating the activation of the two linguistic systems. The proposed mechanism is a Supervisory Attention System (SAS), initially conceptualized by Norman and Shallice (1986) that responds reactively by inhibiting the irrelevant lemma. For the relevant lexical item to be selected and the irrelevant one to be inhibited, lemmas have selection features, linguistic "tags" that link them to a particular language. Thus, for bilinguals, there are two processes that unfold in a continuous manner: first, the inhibition of the language "tag" in order to select the appropriate language whenever conversations are initiated or a language switch occurs, and second, the inhibition of the actual lexical items from the irrelevant language, with the amount of inhibition being proportionate to the amount of lexical activation.

This idea of competition between lexical items in the two linguistic systems is consistent with the empirical evidence indicating verbal processing costs in bilinguals such as slower times to name pictures (Gollan et al., 2005), lower verbal fluency (Portocarrero, Burright, & Donovick, 2007), and more frequent tip-of-the-tongue (Gollan & Acenas, 2004). Moreover, the assumption of lexical competition is in line with the intriguing finding of asymmetrical costs when switching from a dominant to a nondominant language. For instance, in a task of naming numbers aloud, bilinguals were slower to switch from the non-dominant to the dominant language, compared to trials in which they switched to the nondominant language (Meuter & Allport, 1999). This asymmetric switch was interpreted by the authors as indicating that the dominant language requires more inhibition to be suppressed, and consequently takes longer to be re-activated. Importantly, in contrast to the "weaker links" hypothesis, the IC model proposed by Green (1998) is also consistent with the robust empirical evidence showing executive functions benefits. The lexical competition between words in the two languages which leads to costs in verbal processing requires a control mechanism to monitor and regulate this linguistic conflict. As already discussed, the proposal is that this control mechanism is domain-general (e.g., Abutalebi & Green, 2008) and the extensive need to engage this type of control tunes in the executive control system and leads to benefits in performance. Thus, a single mechanism, competition between lexical items from the two languages, is proposed to underlie the unique cognitive profile of bilinguals.

Finally, the BIA+ model (Dijkstra & van Heuven, 2002; van Heuven & Dijkstra, 2010), focuses on bilingual language comprehension using a connectionist perspective. Similar to the IC model, BIA+ posits the existence of a language processing system and a task/decision system. However, in contrast to the IC model which assumes that the executive system operates through top-down reactive inhibition, in the BIA+ the task/decision system is part of a larger control system that is conceptualized to operate bottom-up. Lemmas from the two languages have different degrees of activation, with the degree of activation being regulated by language tags, represented as language nodes in the network. The model also assumes competition between lexical items, both within and between-languages, but the competition is resolved by local, lateral inhibition, meaning that the lemma with highest degree of activation ends up being selected, and the other lemmas are suppressed. Although both models put forth the existence of two distinct systems, a word identification system and a task/decision system, as van Heuven and Dijkstra (2010) note in their review "So far, the task/decision system of BIA+ has not been described in much detail." (p. 116). The authors further argue that the task/decision system operates in a fundamentally different manner in language comprehension (BIA+) and language production (IC). Specifically, the BIA+ proponents explain that it is conceivable to see top-down inhibition play a role in the selection of the intended word in the target language, but it is less likely for this kind of inhibition to be involved in language comprehension.

Thus, the BIA+ decision system appears to be more language-specific than the IC decision system, and consequently, within the BIA+ framework it is difficult to explain why there are advantages in the non-verbal executive tasks in bilingual speakers. Moreover, in contrast to the IC model which includes both linguistic and cognitive components, the "weaker links" hypothesis only addresses the linguistic aspects of the bilingual profile. In response to this issue of the right model of bilingual language processing, Rodriguez-Fornells and colleagues (2006) argued that it is important to postulate the existence of both local, bottom-up inhibition that operates between languages, and global, top-down inhibition that controls these local inhibitory processes.

In other words, based on the observation of Rodriguez-Fornells et al. (2006), the right model of bilingual language processing is a combination of IC and BIA+.

Methodological Aspects: ERPs and Response Inhibition

The ERP technique. Over the last decades, the ERP technique has been increasingly used to answer questions in cognitive psychology and neuroscience. Its beginnings go back to a series of separate experiments conducted between 1920s and 1930s by Berger and Adrian (as cited in Luck, 2005) who showed that the electrical activity of the human brain can be measured by attaching a pair of electrodes to the scalp and amplifying the electrical signal detected. This output reveals rhythmic variations in voltage as a function of time and it represents the electroencephalogram or EEG (Coles & Rugg, 1996; Luck, 2005). These fluctuations in voltage are characterized by magnitude or amplitude measured in microvolts (μV) (e.g., EEG ranges between -100 and +100 μV), latency, indicating the time dimension of these magnitudes, and topography or location where the signal is recorded on the scalp (e.g., anterior versus posterior sites).

When a participant is presented with a series of experimental stimuli and these voltage fluctuations are measured for a specific segment of time before and after the stimulus presentation, the resulting output are called ERPs and it is time-locked to the stimulus. ERPs are believed to reflect variations in electrical activity of the brain that *also* capture the brain activity involved in stimulus processing. In contrast to early conceptualizations which proposed that these voltage fluctuations reflected *only* brain activity elicited or evoked by the stimuli (thus the early name of evoked potentials), it is currently accepted that the variations in electricity reflect a variety of processes, some of which related to the experimental stimuli (thus, the current name of ERPs). In fact, some of the difficulties in using ERPs to understand cognitive processes stem from this issue of ERPs representing a *sum of multiple* sources of electrical activity. Thus, although the scientific community accepts that ERPs reflect processes originating in the brain, at present it is not fully clear how these processes originating in the brain are related to what is recorded at the level of the scalp. What we know is that the electric potentials recorded at the scalp reflect the activity of large populations of pyramidal neurons that are synchronously active and form an open field, meaning that they must have a specific geometric arrangement that allows the formation of a field with positive and negative charges (Picton et al., 2000). Moreover, the electrical activity recorded at the scalp level is believed to represent post-synaptic, dendritic potentials related to the release of neurotransmitters, rather than axonal action potentials, which represent voltage that travels from the beginning to the end of the axons, where neurotransmitters are released (Coles & Rugg, 1996). Action potentials are extremely brief in duration, about one millisecond, whereas the duration of post-synaptic potentials can last between tens and hundreds of milliseconds (Luck, 2005). Because the electrical activity recorded at the scalp is dependent on the configuration of neurons, ERPs mostly capture the activity of the cerebral cortex than that of subcortical structures because in the cortical layers the neurons share a similar orientation and the electrical fields created are less likely to cancel each other out (Coles & Rugg, 1996).

A great advantage in using ERPs is that it provides an online measure of brain activity and therefore it is possible to examine, with a precision of milliseconds, what stages of cognitive processing are affected by the experimental manipulations. Even more, with ERPs it is possible to obtain information about processing even when no behavioral responses are required from participants such as experiments in which participants are passively listening to sentences that contain syntactic anomalies or are grammatically intact.

There are also several disadvantages to using ERPs. Despite the excellent temporal resolution, ERPs have very poor spatial resolution, meaning that it is difficult to establish the exact neural source of the voltage recorded at the scalp level. This is known as the "inverse problem" and refers to the fact that when given the observed voltage distribution at the scalp level and asked to determine the locations and orientations of the dipoles, it is impossible to find a unique solution to the problem. In fact, mathematically this is an underdetermined problem and researchers have suggested that there are an infinite number of dipole arrangements that can potentially fit the observed voltage distribution (Luck, 2005). In recent years, there have been several attempts to find unique solutions to the "inverse problem" using software that analyzes ERPs data, such as the Brain Electrical Source Analysis procedure (BESA), but much more research is needed to refine these techniques and to compare these results with those from studies using methods with excellent spatial resolution such as the magnetic resonance imaging.

Another disadvantage in using ERPs comes from the difficulty of making precise functional interpretations of the ERP components given that typically several cognitive processes occur in parallel. ERPs are very small in magnitude compared to the background EEG signal and in general researchers average across individual ERP trials related to certain experimental stimuli in order to separate the ERP signal from the EEG noise. The resultant averaged ERP waveforms show clear peaks and troughs, and these positive or negative deflections of the averaged ERP waveforms are referred to as ERP components or peaks. Generally, the earlier these components occur in time, the more likely they are to be influenced by external factors such as stimulus characteristics (i.e., exogenous components), and the later they occur in time, the more likely they are to depend on internal factors (i.e., endogenous components). To date, researchers have identified and described several ERPs components such as the C1, P1, N1, and P2 related to visual sensory processing, N1 and the mismatch negativity reflecting auditory sensory responses, N400 and P600 linked to language processing and others. In the following sections, two components, typically associated to response inhibition, are discussed in more detail.

ERPs components and response inhibition. As described above, response inhibition is conceptually distinct from interference suppression. In an fMRI study, Bunge and colleagues found that these two types of inhibition followed different developmental trajectories and recruited different areas of the prefrontal cortex, strengthening the validity of the distinction between them (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Specifically, response inhibition recruited posterior association areas and interference suppression relied on the left ventrolateral prefrontal cortex and the insular cortex.

Increasing evidence supports the idea that response inhibition, as an executive function process, is dependent on the basal ganglia-prefrontal cortex network. For instance, research using fMRI has shown that children performing go/no-go tasks showed greater activation than adults in regions of the prefrontal cortex (ventrolateral prefrontal cortex and anterior cingulate), as well as in subcortical areas (left caudate nucleus, thalamus and the hippocampo-amygdaloid region bilaterally) (Booth et al., 2003; Durston, Thomas, Worden, Yang, & Casey, 2005). Adults with Parkinson's disease, who are characterized by pathological basal ganglia changes, showed deficiencies in pre-motor response inhibition (Beste, Willemssen, Saft, & Falkenstein, 2010). Similarly, patients with lesions to the superior medial parts of the frontal lobes make frequent false alarm responses in a simple go/no-go task, suggesting that these areas support response inhibition (Picton et al., 2007).

Two ERP components have been found to be reliably related to inhibition of responses measured in a go/no-go paradigm: the N2 and P3 components. The N2 component is a negative deflection recorded at approximately 200 to 400 ms after the stimulus onset, and it is typically larger for no-go than go trials, although this is not always the case (e.g., Davis, Bruce, Snyder, & Nelson, 2003). Moreover, the N2 component 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). Consistent with fMRI research, source analyses studies have shown that children and adults engaged sources in the medial frontal cortex, adjacent to the anterior cingulate, and additionally, children engaged posterior neural sources as well (e.g., Jonkman, Sniedt, & Kemner, 2007).

The N2 component was proposed to represent response inhibition, conflict monitoring, and perceptual mismatching (Botvinick, Braver, Carter, & Cohen, 2001; Ciesielski, Harris, & Cofer, 2004; Duan et al., 2009). For instance, Nieuwenhuis and colleagues found variations in N2 amplitude in adults as a function of changes in go to no-go trials ratio (Nieuwenhuis et al., 2003). The N2 amplitude was measured in three distinct conditions: high conflict monitoring demands (20% no-go trials), moderate conflict monitoring (50% no-go trials), or low conflict monitoring (80% no-go trials). In most experiments using the go/no-go paradigm the majority of trials are go trials, creating a strong tendency to make a behavioral response and typically the no-go N2 amplitude is larger than the go N2 amplitude. In the Nieuwenhuis et al. (2003) study, the N2 amplitude for the no-go trials was largest in the experimental condition with high conflict monitoring demands and lowest when the majority of trials were no-go. In fact, the go N2 was larger than the no-go N2 when no-go trials occurred 80% of the time. Thus, the authors proposed that variations in N2 amplitude reflect the need to monitor and overcome conflict.

P3 is the second ERP component typically observed when participants perform a go/no-go task. In adults, the P3 component 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). Studies using go/no-go paradigms with children have indicated less consistent results. For instance, Jonkman, Lansbergen, and Stauder (2003) showed that 9- and 10-year-old children made more false alarm responses than adults, in the absence of a fronto-central no-go P3 component, but showing a no-go N2 component with adult-like characteristics.

In terms of processing, P3 was proposed to reflect later stages of inhibition such as response evaluation or monitoring the outcome of inhibition because of its long latency (Duan et al., 2009; Schmajuk, Liotti, Busse, & Woldorff, 2006) or response inhibition (Freitas, Azizian, Leung, & Squires, 2007). Freitas and colleagues (2007) examined changes in N2 and P3 amplitude as participants performed a go/no-go task involving digits. On the no-go trials, when participants had to withhold a response to a digit that previously appeared as a target in a selective attention task, the no-go P3 amplitude was much higher than if the digit was previously ignored. In contrast, N2 amplitude was not affected by these manipulations. This finding suggests that the N2 component may index conflict monitoring, and the P3 component reflects response inhibition (Jonkman, 2006). Although there is no consensus in the literature regarding the exact interpretation of the processes underlying these ERP components, it is generally accepted that they index some aspects of executive control (Lamm, Zelazo, & Lewis, 2006; Smith, Johnstone, & Barry, 2007).

Developmental studies have shown that both the amplitude and the latency of various ERP components decrease with age. These electrophysiological changes occur in parallel with improvements in behavioral performance. However, the interpretation of this developmental pattern is unclear given that the thickness and density of the scalp increase with age as well. To address this issue, Lamm and colleagues examined whether behavioral performance on several measures of executive functions is associated with neural activity above and beyond age effects (Lamm et al., 2006). Results showed that better performance on the Iowa Gambling Task and Stroop tasks predicted smaller N2 amplitudes in children between 7 and 16 years of age, but was not related to N2 latencies. The authors divided children in two groups, based on the behavioral performance on the battery of executive function tasks and examined the neural generators of the N2 component as a function of behavioral performance. Interestingly, the characteristics of the neural sources of N2 varied as a function of behavioral performance on the control tasks: the cingulate source was more anterior in children with high executive function performance regardless of age and the orbitofrontal generator was relatively left lateralized in younger children and in children with low executive skills. However, interpretations of the size of the amplitude in ERPs research are not straightforward and smaller amplitudes do not unequivocally indicate enhanced performance. In contrast to studies showing amplitude reductions with age, other studies have demonstrated that within a single age group, better behavioral performance is often associated with larger amplitudes (e.g., Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; Pliszka, Liotti, & Woldorff, 2000). For instance, Pliszka and colleagues (2000) showed that controls had larger amplitudes and better accuracy than children with ADHD in a go/no-go task.

The Present Dissertation

The literature reviewed so far demonstrates that bilingualism is associated with improved executive functioning for children and adults on tasks that require participants to resolve conflict between stimuli, ignore irrelevant information, or switch efficiently between tasks. A small number of neuroimaging studies have also revealed structural and functional differences between monolingual and bilingual adults at the brain level. However, no studies to date have examined the neural correlates of non-verbal executive control in bilingual children. Therefore, there is no direct evidence for bilingual influences on brain function and brain plasticity in children for nonverbal executive control. This means that although substantial evidence demonstrates that bilingual children process executive control tasks differently than monolinguals, an understanding of the mechanisms underlying these differences is only tentative. Thus, examining the neural basis of the bilingual advantage is the key to understanding how sustained experience with two languages results in neurocognitive differences and how brain plasticity is related to behavioural performance.

The present study is the first to address this issue and uses both electrophysiological and behavioural measures of executive control processing. The behavioral performance of monolingual and bilingual children on tasks measuring executive functions is first examined in order to attempt to understand previous findings showing differential effects of bilingualism. We then test the main question of the current study; that is, the neural correlates associated with executive functions performance will differ between bilingual and monolingual children. Monolingual and bilingual pre-school children matched on non-verbal IQ, age, and socio-economic status performed behavioural tasks measuring different forms of inhibition (simple response inhibition: Gift Delay, Simon Says; interference suppression: flanker task). Electrophysiological data were recorded to analyse ERPs for a go/go-no task (complex response inhibition).

In the go/no-go task, children were presented with geometric shapes that appeared one at a time, and they were required to either press a mouse button or suppress the button press based on the color of the shape. In addition to response inhibition, performance on this task requires working memory and monitoring abilities. Thus, using the go/no-go task is an excellent way to demonstrate that response inhibition processing *is* influenced by the bilingual experience when certain executive processes are recruited to a great extent. The go/no-go paradigm was chosen for the present ERP study for several other reasons. First, as already noted, bilingualism has been found to influence the brain ERP patterns related to a non-verbal go/no-go task in adults (Moreno et al., in preparation). Secondly, two components have been found to be reliably related to inhibition of responses measured in a go/no-go paradigm: N2 and P3. Importantly, these components have been also identified in electrophysiological studies of children's executive functions development (e.g., Cieselski, et al., 2004; Lahat, Todd, Mahy, & Zelazo, 2010; Lamm et al., 2006), which makes the task appropriate for use with young children. Thirdly, N2 and P3 index aspects of executive functions (Lamm et al., 2006), which makes the go/no-go a good candidate task to be influenced by bilingualism. Further evidence supporting this possibility comes from functional magnetic resonance imaging studies using go/no-go paradigms showing that successful performance on the task required the activation of several areas of the prefrontal cortex such as the ventrolateral prefrontal cortex and the anterior cingulate (Bunge et al., 2002; Durston et al., 2002), areas found to be involved in language switching in bilinguals (Abutalebi & Green, 2008; Hernanadez et al., 2001).

Based on the findings of neuroplasticity in bilingual adults and the observation that training executive functions in children leads to changes in functional brain responses, the hypothesis is that bilingualism shapes the electrophysiological correlates of non-verbal executive control tasks in children. Although some developmental data have shown decreases in amplitudes with age and improved behavioral performance, between-subject designs comparing children within the same age group generally reveal a pattern of increased electrical activity associated with enhanced behavioral performance. Given that the present study uses a between-subject design examining monolingual and bilingual children of equivalent age, one prediction regarding the electrophysiological characteristics of the N2 and P3 components is that bilinguals will show greater amplitude in the go/no-go task.

For the go/no-go behavioral performance, the prediction is that a bilingual advantage will be found for the bilingual children. This prediction may seem surprising given that go/no-go task is a measure of response inhibition and previous studies showed no differences in performance on measures of response inhibition in children. However, as already discussed, in these past studies the tasks likely have not engaged a specific set of executive processes to discriminate between the two languages groups (i.e., Gift Delay task) and if they did, these processes were not engaged to a great extent (i.e., Simon Says). In the present study, it is expected to see a bilingual advantage because working memory, response inhibition and monitoring processes are highly engaged in the go/no-go task, particularly for the age group examined.

The behavioral measures for simple response inhibition (Gift Delay and Simon

Says) and interference suppression (the child ANT) were included to better characterize the bilingualism-induced plasticity of executive control processes. Although all are measures of executive control, the tasks differ in the executive demands and in the main processes investigated. The Gift Delay and the Simon Says tasks have low control demands and do not rely heavily on monitoring and working memory resources: Gift Delay has almost null working memory demands and Simon Says poses very low demands on the working memory resources. The child ANT was chosen because it allows for the evaluation of attention and inhibitory processing in different conditions: with distractors that provide facilitating or conflicting information (that is, congruent and incongruent trials), and without distractors (control trials). Based on previous findings, it is expected that bilinguals outperform monolinguals on the interference suppression task when distractors are present, but are equivalent to monolinguals on the measures of simple response inhibition.

By investigating the effect of bilingualism on executive control processing using both behavioral and electrophysiological measures, the present study brings a significant contribution to existing research by showing a) whether limited bilingualism experience changes the neural basis of executive control and b) how these neural differences translate into behavioral differences. Although the picture of behavioural differences between monolingual and bilingual children has becomes increasingly detailed and refined over the last decade, at present, the key to understanding the mechanisms underlying these behavioural differences lies in investigations of bilingualism-related neural plasticity. Given that most children become bilinguals for a variety of reasons related to life circumstances, rather than because of special language talents, bilingual children provide strong evidence for plasticity in brain development. By addressing the issue of neuroplasticity in bilingual children for the first time, the present study aims to bring new insights with respect to the neural basis of the bilingual advantage in children and its behavioural correlates.

Method

Participants

Participants were 62 5-year-old children (M = 63.9 months, SD = 5.6, range 53-76 months). Past studies with children of similar age using comparable or smaller sample sizes yielded reliable ERP findings (e.g., Lahat et al., 2010). Children were recruited from similar neighborhoods across the Greater Toronto Area to ensure that they matched in socioeconomic background. 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 (see Appendix A). The level of education was quantified using 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). All children attended public schools. Additional inclusion criteria required participants to be right-handed, to have normal or corrected-to-normal vision, to be free of psychiatric diagnoses and medication, and to attend kindergarten programs where the language of instruction was English. Previous research has indicated that bilingual children's performance on verbal tasks is affected if the language of testing does not match the language of instruction (Barac & Bialystok, 2012).

Children were assigned to one of the two language groups (English monolinguals, N = 37 children, and bilinguals, N = 25 children) based on the parents' answers to a detailed language background questionnaire about children's comprehension and production of language(s). An additional 13 children were tested but not included in the analyses because they could not be unambiguously assigned to one of the two language groups.

The English monolingual group (M = 62.9 months, SD = 5.7, range = 54.0 – 76.0 months) included 24 girls and 13 boys. The bilingual group (M = 65.3 months, SD = 5.2, range = 53.0 – 75.0 months) included 10 girls and 15 boys. Bilingual children formed a heterogeneous group speaking a total of twelve 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 of the children in the bilingual group (n = 9) were simultaneous bilinguals (i.e., started learning both languages at the same time), another third had English as a first language (n = 8), and the rest of the children (n = 8) spoke the non-English language first. The majority of the bilingual children were 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 at the Cognitive Development laboratory at

York University during a single session lasting about two hours. Children were allowed to take short breaks and play in the playroom after each task. Written informed consent was obtained from parents (e.g., Appendix B) and, additionally, children provided verbal assent before testing. All tasks were administered in English. The testing battery consisted of two background measures (Language and Social Background Questionnaire and the Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition), three behavioral EF tasks (Attention Network Task, Simon Says, Gift Delay) and one ERP EF measure (the go/no-go task). The tasks were administered in a randomized order. After the completion of each task, children were given stickers and small gifts.

Language and Social Background Questionnaire (LSBQ). The questionnaire was filled out 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. To be included in the bilingual group, children were expected to speak and be exposed to a second language for about half of the time spent at home. An additional variable, home language environment was created by adding up the scores for four variables included in the LSBQ: language the child speaks to siblings, language the child speaks to friends, language the parents use to communicate with each other, and language parents use to read stories to the child. Each of these four variables ranged between 1 (English language used exclusively) and 5 (non-English language used exclusively) and consequently the minimum score for the variable home language environment was 4 and the maximum was 20. The mean score and standard deviation for this variable are presented in Table 1. Other questions on the LSBQ asked information about parents' occupation, immigration history, languages used in the community and extended family, child's attendance of a language program, and child language proficiency. LSBQ has been designed specifically for the purpose of gathering data regarding participants' social and language background and has been used in multiple studies conducted by Bialystok and colleagues (e.g., Bialystok et al., 2010, with over 1700 children; Bialystok & Luk, 2011, with over 1600 adults). There is no data on the reliability and validity of this instrument, but its utility has been demonstrated in the previously mentioned studies.

Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition (WPPSI-III). Children received only the Vocabulary and the Block Design subtests of the WPPSI-III in order to estimate the scores for verbal and nonverbal reasoning. The administration and scoring of the two subtests followed the guidelines outlined in the manual (Wechsler, 2002).

The stimuli for the Vocabulary subtest consisted of 25 items. The first five items were pictures of objects, animals or vegetables such as "car", "clock", "fork", "turtle", and "pumpkin". The remaining twenty were verbal items representing words that children had to define in the absence of a visual aid. Children were asked to name the set of 5 pictures and to explain orally the meaning of the 20 words (e.g., "What is a letter?" or "What does courage mean?"). During the administration of the Vocabulary subtest the experimenter wrote down the child's answers verbatim and for some answers specified in the manual (e.g., saying "phone" when asked "What is a telephone?") the experimenter had to further query the child (i.e., "Can you tell me more about it?").

The first 7 items could receive a score of 0 or 1 and each of the remaining 18 items could receive a score of 0 for incorrect responses, 1 for vague definitions, or using the word in a sentence instead of explaining its meaning, etc., or 2 for offering a good synonym. Testing started with the administration of item number 6 as indicated in the manual for their age. According to the basal rule, children had to obtain a perfect score on the first two items. If that was not the case, testing continued by administering the preceding items in reverse order until the child obtained two consecutive perfect scores. Testing discontinued when the child obtained 5 consecutive scores of 0. The maximum total raw score a child could obtain for this subtest was 43.

On the Block Design subtest to measure nonverbal reasoning, children were asked to duplicate a series of 15 to 20 spatial designs using red and white plastic blocks. Depending on the level of difficulty of the item, the time limit was 30 seconds, 60 seconds or 90 seconds. For the first 12 items, the experimenter created the model and the child was asked to reproduce it as fast as possible. For item number 13 the experimenter created a model, and then handed the same blocks to the child whose task was to recreate it based on a picture representing that pattern. Finally, for the remaining 7 items the child was asked to duplicate the pattern based only on the picture.

For the first 6 items the child was given a second chance to solve the problem if they did not get it right or they were not fast enough on the first trial. More specifically, for the initial 6 items the child could obtain one of the following scores: 0 if time limit was exceeded or the pattern was incorrect even after 2 trials, 1 if the pattern was correctly reproduced within the allowed time but only on the second trial, or 2 if the pattern was correctly reproduced within the time limit on the first trial. For the remaining 14 items, there was only one trial and the child could obtain a score of 0 if the pattern was incorrect or the time limit was violated, or 2 if the pattern was correctly reproduced within the time limit.

The stimuli for the first half of the subtest included a total of 8 blocks, 4 of which were completely red and the remaining 4 were completely white. The stimuli for the second half included a total of 4 blocks, whose faces were either completely red, or completely white or half red half white. Similar to the administration of the Vocabulary subtest, testing started with the administration of item number 6 and the first two items had to receive a perfect score. Testing discontinued when the child obtained 3 consecutive scores of 0. The maximum total raw score a child could obtain for this subtest was 40.

Scaled scores for each of the Vocabulary and Block Design subtests were obtained based on the raw scores and children's chronological age. These scaled scores were used to estimate a full-scale IQ (Sattler, 2002). The short form of WPPSI-III based on the combination of these two subtests has high reliability (r_{xx} = .906) and validity (r = .855).

Simon Says. This behavioral task is a measure of response inhibition (Carlson & Meltzoff, 2008; Strommen, 1973). It consists of five Simon trials and five non-Simon trials which were administered in random order with the restriction that there could not be more than three consecutive same-type trials. For all trials the child stood opposite the experimenter and the experimenter executed a simple motor action: wave your hands, touch your nose, touch your knees, stamp your feet, touch your tummy, step back, touch the floor, arms up, step forward, put your hands on your head. The child was instructed to either imitate the experimenter for the Simon trials ("Whenever I say 'Simon Says' you do what I say"), or to stay still for the non-Simon trials ("When I don't say 'Simon Says' you shouldn't do anything at all").

The ten test trials were preceded by a maximum of three practice trials to ensure that the child understood the task rules. The child was given a hypothetical example and was asked to explain verbally or demonstrate the behavioral response required by the rule: "For example, what would you do if I say 'Simon says clap your hands'? But what if I only say 'Clap your hands', what would you do?" If the child made a mistake, the experimenter repeated the rule emphasizing the absence of the "Simon Says" cue and another non-Simon practice trial was presented until the child showed correct performance (i.e., inhibited a behavioral response). Following the original procedure, children could be presented with up to three practice non-Simon trials and if they failed to inhibit a behavioral response after these three examples testing was discontinued. During testing, the pace of trial presentation was a function of children's responses and a new trial was presented about 2 seconds following the child's response and after about 5 seconds if the child did not produce any behavioral response.

Children's behavioral responses for all ten trials were coded and recorded by the experimenter. Scoring was done by assigning a number between 0 and 3, following the criteria described by Carlson and Meltzoff (2008). Specifically, for each non-Simon, that is non-imitation trial, the child could receive a score of 0 (fully executed movement), 1 (partially executed movement), 2 (wrong movement or flinch) or 3 (no movement). For each of the five Simon or imitation trials the child could receive a score of 0 (failure to move), 1 (wrong movement or flinch), 2 (partial correct movement), or 3 (full correct movement). The variable of interest was the total score obtained on the non-Simon trials, which could range between 0 and 15 (Carlson & Meltzoff, 2008). Additionally, for the purpose of analyses, a mean score per non-Simon trial was obtained by dividing the total score by the number of trials (i.e., five). Performance on the non-Simon trials indexes response inhibition. Similar calculations (i.e., total score across the five trials and mean score per trial) were carried out for the remaining five Simon trials which provided a measure of children's understanding of the task and their ability to follow rules, execute commands and imitate a model action.

A great advantage of this task is its strong ecological validity. With respect to reliability, there are no studies of how Simon Says relates to other standardized measures of executive control, but a couple of studies have examined the relationship between Simon Says and other experimental executive control tasks (Carlson & Meltzoff, 2008; Kochanska, Murray, & Coy, 1997). For instance, Kochanska and colleagues (1997) administered a battery of seven non-standardized inhibitory control tasks, including Simon Says and tasks of effortful attention, cognitive reflectivity, and slowing down of motor activity to preschool children. The authors found that the tasks appeared to tap a common process, as indicated by Cronbach's alpha of .75. In another study, Carlson and

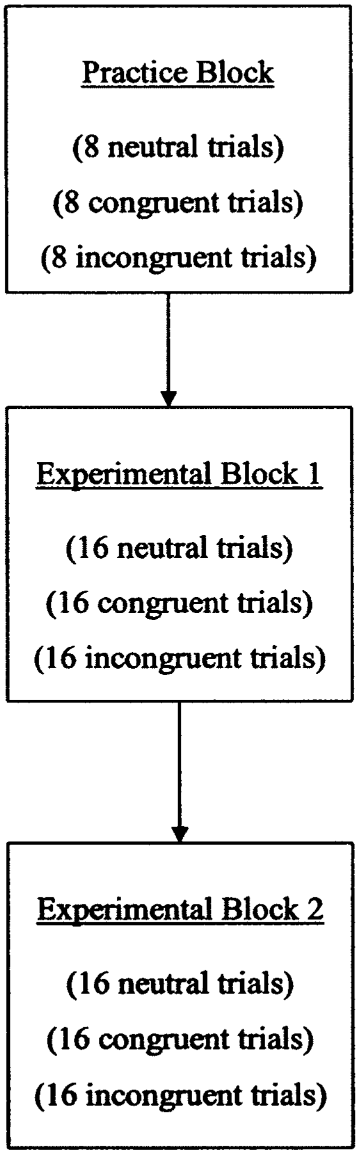
Meltzoff (2008) conducted a factor analysis based on a battery of nine executive function tasks and found two main factors: a conflict factor (tasks that primarily required conflict resolution: Simon says, Visually Cued Recall, ANT, Dimensional Change Card Sorting Task, etc.) and a delay factor (tasks that required control of impulses).

Gift Delay with cover. This is a type of 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 away from the room. The child sat at a table and the experimenter placed a colorful gift box on the table in front of the child and told the child that inside the box there was a gift for the child. At that moment, the experimenter pretended to notice that the cover of the gift box on one side was broken and it was partially covered by a piece of felt. Following the procedure described by Carlson and Meltzoff (2008), the experimenter explained: "I think the cover must be broken! It's falling off. I really want this gift to be a good surprise, so I'm going to go get another cover for the window. I'm going to get a cover that hides the whole window, so no one can peek inside." The experimenter arranged the window at a 90-degree angle from the child's seat. Next she said, "Let's play a game again. Try not to touch this box until I come back, and try not to peek inside, OK? So, see how long you can stay in your seat without touching the box or looking inside it, OK?" The experimenter left the room for three minutes and after that she returned with a new cover and encouraged the child to open the present.

The whole 3-minute interval 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 Pearson's correlation coefficient and results showed high reliability between the independent coders, $r(60) = 0.89$, $p < .01$.

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 left button of either the left or the right mouse to indicate the direction that the target fish (i.e., the middle fish) was pointing. Children were told that a target 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. The experimenter explained the instructions with the aid of three drawings depicting the images on the screen corresponding to the different trial types. There were two experimental blocks, each including 48 trials, preceded by a practice block of 24 trials (see Figure 1).

Figure 1. Schematic presentation of the ANT: Block presentation with number of trials in parentheses.



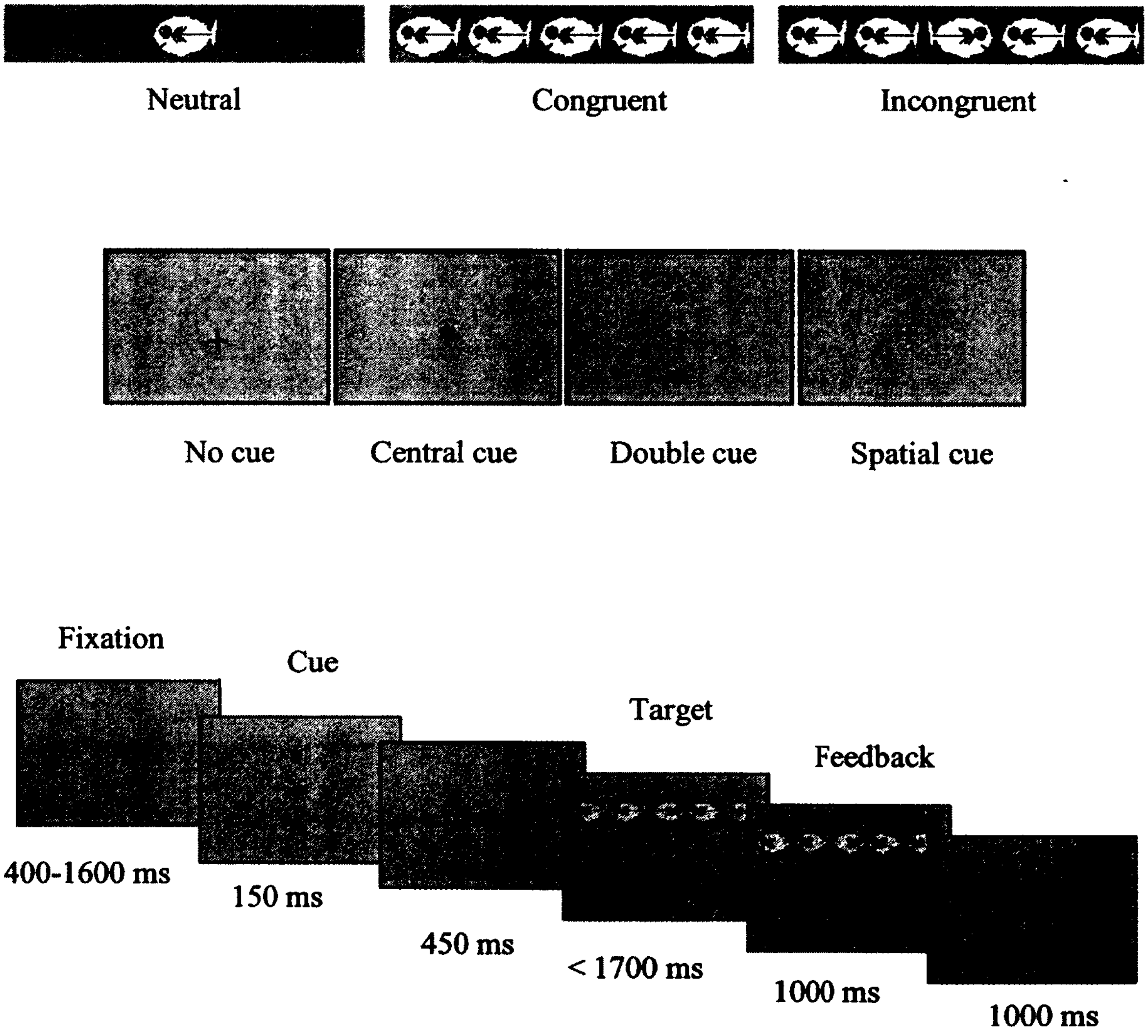
Before each block, children were reminded to press the button as fast as possible without making mistakes. Children could take breaks between the experimental blocks. Within each block, there was an equal number of three types of trials: neutral (the target fish appeared alone), congruent (the target fish and the flanking fish pointed in the same direction) and incongruent trials (the flanking fish pointed in the opposite direction from the target fish). These three types of trials were presented randomly in each block. Each trial consisted of the following sequence of events: 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. Figure 2 represents a schematic description of this sequence of events.

If the child's response was correct they heard a "whoo-hoo" sound and simultaneously saw bubbles coming up from the fish's mouth to signal that the target fish was happy. If the child made an error, the feedback consisted of a "bang" sound and no animation of the fish. 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 in order 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.

Reliability data on this task are scarce. Fan and colleagues, for instance, reported some reliability data for each of the three attention networks and the executive control network showed the strongest test-retest reliability, $r = 0.77$ (Fan, McCandliss, Sommer, Raz, & Posner, 2002). In another study, split-half reliabilities of reaction times for each attention network indicated that again the executive control network was the most reliable component (MacLeod et al., 2010).

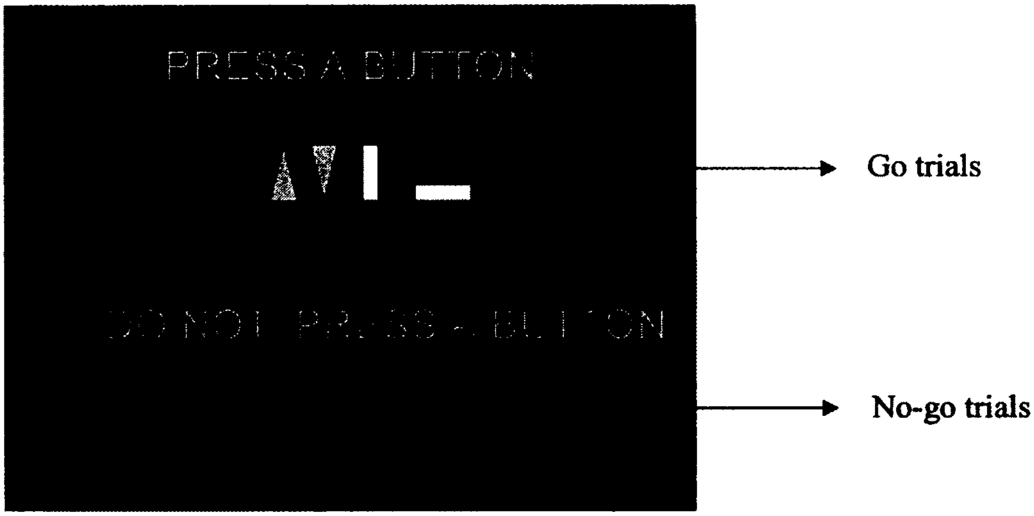
Figure 2. Schematic presentation of the ANT: Examples of stimuli and cues and event presentation within each trial. The example shown here is an incongruent trial.



Go/no-go task and ERP recording. This task assesses children's ability to inhibit a prepotent behavioral response. 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 diagonal LCD monitor. Participants 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. Children were presented with one geometrical shape at a time: a triangle or a rectangle. The shapes appeared in the center of the screen in randomized order. Two types of triangles and two types of rectangles were presented to reduce stimuli repetition effects: the triangles were either pointing upwards or downwards and the rectangles appeared in vertical or horizontal position. In addition to the manipulation of the position of the stimuli, there was a color manipulation which indicated whether the stimuli were go or no-go. The shapes were either white, the go stimuli that required a mouse button press, or purple, the no-go stimuli that required withholding the button press response. All shapes appeared against a black background (see Figure 3).

Children were instructed to press the mouse button when the shape on the screen was white and to refrain from pressing when the shape was purple. Each trial consisted of the following sequence of events: a white cross on a black background appeared for 500 ms, followed by a blank screen for a variable duration between 0 and 500 ms before the stimulus, then a shape appeared in the centre of the screen for 300 ms. Finally, a blank-screen interval of 900 ms separated trials, a duration that corresponded to the post-stimulus interval. Thus, from the moment the stimulus appeared on the screen participants 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. The 200 trials were presented in random order in a single block. This ratio was chosen to create a prepotent tendency to respond. The experimental block was preceded by a practice block of 20 trials to familiarize children with the stimuli and the task rules. Children were reminded of the rules between the practice and the experimental block. During the task, participants did not receive any feedback on their performance. Accuracy rates and ERPs were recorded for go and no-go trials, and reaction times were recorded for the go trials only.

Figure 3. Schematic presentation of the go/no-go task: Examples of stimuli.



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). Children were given a brief explanation about the EEG system and they watched an animated movie during the time that the experimenters applied the cap. 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 signal was digitized at a 500-Hz sampling rate. Impedances were maintained below 20 µV. Trials containing ocular and movement artifacts, amplifier saturation or too much noise were excluded from the averaged ERP waveforms (mean = 9.5%). Similarly, channels with low signal were not included in the analyses (i.e., an average of two channels). 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. The bandpass was 0.01—30 Hz and additionally a 60Hz notch filter was also used on the data. 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. On-line recordings were referenced to the Common Mode electrode and were re-referenced off-line to the algebraic average of all electrodes. ERPs were then averaged separately for each condition and electrode site (Duan et al., 2009). Error trials were not included in the analyses. ERP data from go and no-go trials were baseline corrected using the initial 200 ms of each segment. Baseline correction is a procedure typically performed in ERP experiments in order to ensure that stimuli-related signal is not present in the electric signal prior to the presentation of the stimuli. Baseline correction is performed by calculating the mean signal for the pre-stimulus interval and subtracting it from the signal at all time points. ERPs data for the go and no-go trials were analyzed in terms of the amplitude and latency of the N2 and P3 waveforms.

Results

Background Measures

LSBQ. The first set of analyses compared the monolingual and bilingual children on background measures, including home language use, age and SES scores. Table 1 presents the mean and standard deviations for the background measures.

Table 1

Mean and standard deviation for background measures by language group

Variables	Monolinguals	Bilinguals
Age (in months)	62.90 (5.70)	65.30 (5.20)
SES[a]	3.73 (1.07)	3.60 (0.82)
*Home language child speaks[b]	1.0 (0)	2.88 (1.24)
*Home language child listens[b]	1.0 (0)	3.16 (1.37)
*Home language environment[b]	4.33 (0.68)	8.77 (3.18)
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)

[a] SES based on maternal level of education was quantified using 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)

[b] Measures of home language experience obtained from a Language and Social Background Questionnaire (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 home language environment was based on four variables, thus the minimum score was 4 and the maximum was 20.

Note: variables preceded by * show a significant group difference.

The main variables from the LSBQ reflecting children's language experience at home were language(s) spoken to the child at home and language(s) spoken by the child at home. On both variables monolingual children obtained a score of 1, indicating exclusive use of the English language at home. Because there was no variability in the home linguistic experience of the monolingual group, the two language groups could not be compared directly on the scores obtained for the variables "language spoken by" and "language spoken to" the child at home. Nonetheless, to understand the home linguistic experience of the bilingual children, two one-sample *t*-tests were performed comparing the scores for languages spoken to the child at home and languages spoken by the child at home to the score of 3.0 (i.e., a balanced use of the two languages). Results indicated that bilingual children used ($t(24) = - 1.2$, n.s.) and were exposed to ($t(24) = 0.58$, n.s.) both languages relatively equally at home. Additionally, a one-way ANOVA for the composite measure of home language environment with language group as a between-subject factor showed that bilingual children were immersed in a more mixed language environment than monolinguals, $F(1, 60) = 73.09, p < .0001$. Taken together, these results show that bilingual children had indeed a different home linguistic experience than monolingual children as reflected by the language spoken by children and to children at home and by the greater score for the variable home language environment.

Bilingual and monolingual children had similar age and SES background as measured by highest level of maternal education: a one-way ANOVA with language group as a between-subject factor indicated no difference in SES between groups, $F < 1$.

Similarly, a one-way ANOVA for age showed no differences between monolinguals and bilinguals, *F*(1, 60) = 3.01, n.s.

WPPSI-III. Data for one monolingual child on the WPPSI-III are missing because the child refused to perform the task. A one-way ANOVA for WPPSI-III estimated full-scale scores with language group as a between-subject factor indicated no difference between monolinguals and bilinguals, F < 1. Two more analyses were performed to examine performance on verbal and non-verbal scales separately. The one-way ANOVA for the verbal scaled scores with language group as a between-subject factor showed that monolingual children obtained higher expressive vocabulary scores than bilinguals, *F*(1, 59) = 4.13, $p < .05$. In contrast, the one-way ANOVA for the non-verbal scaled scores (i.e., block design scores) with language group as a between-subject factor showed no difference between monolingual and bilingual children, *F*(1, 59) = 3.13, n.s.. Since all the experimental tasks in the study were measuring non-verbal executive control processes, vocabulary scores were not covaried out from the subsequent analyses.

Behavioral EF Measures

Simon Says. Table 2 presents the mean scores and standard deviations for the two measures of simple response inhibition: Simon Says and Gift Delay. Data for two monolingual children are missing because they refused to perform the task. Data for the Simon trials showed a ceiling effect and therefore were not analyzed further. Mean scores for the non-Simon trials were not normally distributed and consequently the two language groups were compared using a non-parametric test (i.e., the Mann-Whitney test). The two groups performed similarly on the non-Simon trials, *W*(1) = 781, n.s.

Gift Delay. Scores for the Gift Delay task were analyzed by a one-way ANOVA for language group and showed no difference between monolingual and bilingual children, $F(1, 60) = 1.47$, *n.s.*

Table 2

Mean and standard deviation for simple response inhibition measures by language group

Variables	Monolinguals	Bilinguals
Simon Says Task		
Simon trials – mean score per trial[a]	2.90 (0.16)	2.84 (0.54)
Simon trials – total score across trials[a]	14.51 (0.82)	14.22 (2.71)
Non-Simon trials - mean score per trial[b]	2.03 (1.00)	2.08 (1.00)
Non-Simon trials – total score across trials[b]	10.17 (5.01)	10.40 (4.99)
Gift Delay Task[c]	2.92 (1.38)	2.52 (1.08)

[a] Scoring was done by assigning a number between 0 and 3: 0 (failure to move), 1 (wrong movement or flinch), 2 (partial correct movement), or 3 (full correct movement). Mean score per trial was obtained by dividing the total score by the number of trials. Total score for the five trials could range between 0 and 15.
[b] Scoring was done by assigning a number between 0 and 3: 0 (fully executed movement), 1 (partially executed movement), 2 (wrong movement or flinch) or 3 (no movement). Mean score per trial was obtained by dividing the total score by the number of trials. Total score for the five trials could range between 0 and 15.
[c] Based on 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).

ANT. Data from the ANT task were recorded in E-prime on a touch-screen tablet computer. Central tendencies for RT data were calculated for correct trials only. Individual trials with RTs less than 200 milliseconds were excluded because they likely reflected anticipatory responses. These anticipatory trials constituted less than 1% of the total number of trials. In addition, data for participants with accuracy lower than 50% for each trial type were not included in the analyses. As a result, two children were excluded from analyses of performance on neutral trials and five children were excluded from analyses of the incongruent trials. Mean accuracy and RTs for all types of trials (i.e., neutral, congruent, incongruent trials) are presented in Table 3.

Accuracy data were analyzed by running two separate ANOVAs: one to examine group differences on the neutral trials that served as a control condition, and one for the congruent and incongruent trials. The one-way ANOVA on the accuracy scores for neutral trials with language group as a between-subject factor indicated no difference between monolingual and bilingual children, $F < 1$. The two-way ANOVA with trial type as a within-subject factor (congruent, incongruent) and language group as a between-subject factor showed a main effect of language group, $F(1, 55) = 5.66, p < .03$, with bilingual children outperforming monolinguals, a main effect of trial type, $F(1, 55) = 24.59, p < .0001$, with fewer errors on the congruent trials than incongruent trials, and no interaction, $F < 1$.

Response times for all trial types were long, with the majority of children (32 monolinguals and 22 bilinguals) obtaining mean RTs longer than 1000 milliseconds. Similar to the accuracy data, RTs were analyzed by running a one-way ANOVA on the neutral trials and a two-way ANOVA on the congruent and incongruent trials. The one-way ANOVA for neutral trials RT showed no differences between monolingual and bilingual children, $F < 1$. The two-way ANOVA with trial type as a within-subject factor (congruent, incongruent) and language group as a between-subject factor indicated a main effect of trial type, $F(1, 55) = 66.72$, $p < .0001$, with faster RTs on the congruent trials than incongruent trials. There was no main effect of language group and no interaction. Response time data were further analyzed by examining the scores for the three attentional functions: alerting, orienting and conflict. Table 3 presents the mean and standard deviations for these three attentional functions. Separate one-way ANOVAs for language group showed no effect of language group on any of the three attentional functions: alerting $F < 1$, orienting $F < 1$, and conflict $F(1, 59) = 2.43$, *n.s.*

Data were examined for a possible speed-accuracy trade-off by performing a bivariate Pearson correlation between the overall accuracy on the task calculated as the average accuracy across the three types of trials and the overall RT on the task calculated as the average RT across the three types of trials. Across subjects in both language groups there was a large negative correlation between accuracy scores and RTs on the ANT task, $r(60) = -0.49$, $p < .0001$, which rules out the possibility of a speed-accuracy trade-off. When the same correlation was performed for each of the two language groups separately, a similar pattern was found for both monolinguals, $r(35) = -0.56$, $p < .0005$, and bilinguals, $r(23) = -0.40$, $p = .05$.

Table 3

Mean and standard deviation for the ANT task by language group

Variables	Monolinguals	Bilinguals
Accuracy (% correct)		
Neutral trials	0.80 (0.11)	0.82 (0.13)
*Congruent trials	0.80 (0.11)	0.86 (0.11)
*Incongruent trials	0.71 (0.14)	0.79 (0.12)
*Overall	0.75 (0.12)	0.81 (0.11)
Reaction Time (ms)		
Neutral trials	993 (127)	1005 (86)
Congruent trials	1041 (126)	1016 (102)
Incongruent trials	1108 (127)	1113 (83)
Overall	1050 (120)	1046 (81)
Attentional Functions Scores (ms)		
Alerting	41 (63)	49 (83)
Orienting	15 (74)	29 (64)
Conflict	68 (81)	101 (78)

Note: variables preceded by * show a significant group difference.

ERP Measures

Go/no-go task behavioral analyses. Performance on the go/no-go task was measured by variables related to either go trials and no-go trials considered separately, or taking into account performance on both types of trials. Performance on go trials was indexed by mean percentage hits (i.e., mean percentage correct, namely pressing the button when instructed to press it) and mean and median RT on correct go trials. Response time data were additionally examined in terms of performance variability by calculating the intra-individual standard deviation (ISD) and intra-individual coefficient of variation (ICV) (Stuss, Murphy, Binns, & Alexander, 2003). ISD represents the standard deviation (SD) of each subject's RTs for correct go trials. ICV was calculated for each subject by dividing the ISD by the mean RT and it offers a measure of performance that is controlled to some degree for speed of response. Go RTs below 200 ms were excluded from the analyses because these times were too short and may not reflect the cognitive processes of interest. As a result of this filtering, for the whole sample 1.1% of the go trials have been excluded. Additionally, data for one bilingual child were not included in the analyses because 17% of the RTs on the go trials were faster than 200 ms and were considered anticipatory responses. Performance on no-go trials was indexed by the mean number of false alarms or commission errors representing cases in which children pressed the button when they were not supposed to make a response, and mean percentage correct no-go trials, when children correctly refrained from responding.

Three additional scores were calculated to reflect the extent to which participants' performance was taxed on the no-go trials relative to the go trials or to take into account performance on both accuracy and RT. First, following Lahat et al. (2010), a *no-go accuracy cost* was calculated as the difference between proportion of correct go trials and proportion of correct no-go trials, divided by the proportion of correct go trials. The no-go accuracy cost was proposed to represent a more pure measure of executive processing than the simple no-go accuracy (Lahat et al., 2010). The second score was the discriminability index measured by d^l and was calculated based on signal detection theory which aims to model how a participant decides whether a signal is present or not. Macmillan and Creelman (2005, p. 6) argue that "the hit rate, or any measure that depends on responses to only one of the two stimulus classes, cannot be a measure of sensitivity." The d^l scores reflect perceptual sensitivity to the go and no-go conditions, with higher values indicating better perceptual sensitivity. More specifically, d^l scores range from 0, indicating inability to discriminate between the experimental stimuli, to 4.65, considered to be "effective ceiling" (Macmillan & Creelman, 2005, p. 8). To calculate d^l scores, z-scores for the proportions of hits and false alarms were obtained and the d^l score for each participant was calculated as z(hits) – z(false alarms) (see Schulz et al., 2007). Finally, *inverse efficiency scores* were computed by dividing the mean RTs of the correct go trials by the percentage of accurate responses on the go trials (Townsend & Ashby, 1978). Thus inverse efficiency scores represent an index of performance efficiency that takes into account both speed and accuracy of responses independent of possible speed-accuracy tradeoffs. A higher value for this variable indicates poorer performance. Behavioral data for these go/no-go variables are summarized in Table 4.

Table 4

Mean and standard deviation for the go/no-go task by language group

Variables	Monolinguals	Bilinguals
Go trials		
* Percentage correct (% hits)	73.19 (11.04)	81.32 (10.92)
* RT (mean)	677 (84)	624 (55)
*RT (median)	652 (91)	592 (59)
*Intra-individual standard deviation (ISD)	197 (25)	176 (16)
Intra-individual coefficient of variation (ICV)	0.29 (0.05)	0.28 (0.03)
No-go trials		
Number of false alarms	6.90 (5.27)	6.11 (4.16)
*Percentage correct	81.87 (13.89)	84.16 (10.82)
No-go accuracy cost	-0.16 (0.31)	-0.05 (0.19)
*Discriminability index *(d')*	1.75 (0.53)	2.16 (0.84)
*Inverse efficiency scores	9.53 (2.16)	7.80 (1.24)

Note: variables preceded by * show a significant group difference.

Three children (1 monolingual and 2 bilinguals) refused 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 examined for performance on the go/no-go task included 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) who performed the ERP task, $F(1, 48) = 1.87$, *n.s.*

Five sets of ANOVAs were carried out to examine differences in performance between the two language groups on the main go/no-go variables (go/no-go accuracy and go RT) and the scores derived from those variables (no-go accuracy cost, $d^{\prime}$ scores and inverse efficiency scores). The first analysis examined accuracy performance on the go and no-go trials. The mixed ANOVA for accuracy on go and no-go trials with language group as a between-subject factor showed a main effect of condition, $F(1, 48) = 4.33, p < .05$, with higher performance on the no-go trials, a main effect of language group, $F(1, 48) = 6.09, p < .02$, with bilinguals outperforming monolinguals, and no interaction.

The second set of analyses examined RT data for go trials. The one-way ANOVA for RTs on go trials with language group as a between-subject factor showed a main effect of language group, $F(1, 48) = 6.00, p < .02$, with bilingual children being faster than monolinguals. The go RT data were also analyzed in terms of performance variability. The one-way ANOVA for intra-individual standard deviation showed that bilingual children had less variable performance than monolinguals, $F(1, 48) = 10.21, p < .003$, and the one-way ANOVA for intra-individual coefficient of variation showed no differences between the two language groups, $F < 1$.

The next three analyses were performed on the scores calculated from go accuracy and RT and no-go accuracy: no-go accuracy cost, d^{l} scores and inverse efficiency scores. The one-way ANOVA for no-go accuracy cost with language group as a between-subject factor showed no main effect of language group, $F(1, 48) = 1.74$, *n.s.* The one-way ANOVA for d^{l}scores with language group as a between-subject factor showed that bilingual children obtained larger d^{l}scores than monolinguals, $F(1, 48) = 4.52$, $p < .04$. Lastly, the one-way ANOVA for inverse efficiency scores with language group as a between-subject factor showed more efficient performance in the bilingual children, $F(1, 48) = 10.14$, $p < .003$.

Pearson correlations among the go/no-go variables were calculated to examine possible speed-accuracy tradeoffs. Results are summarized in Table 5. For the monolingual children there was a large negative correlation ($r(29) = -0.79$, $p < .0001$) between the number of false alarms and RT on the go trials indicating a speed-accuracy tradeoff in this sample. Likewise, the correlation between the no-go accuracy cost and go RT in monolingual children showed the same pattern ($r(29) = -0.67$, $p < .0001$). However, for the bilingual children neither of these two correlations was significant.

To better understand the behavioral performance on the go/no-go task, an additional analysis was performed on the false alarms data by controlling for the effect of the RT on go trials. An analysis of covariance (ANCOVA) was performed on the number of false alarms with language group as a between-subject factor and go RTs as a covariate. Results showed that after adjustment for RTs, bilingual children made fewer false alarms (adjusted $M = 4.62$) than monolingual children (adjusted $M = 7.81$), $F(1, 47) = 8.27, p < .007$.

Table 5

Correlations among variables in the go/no-go task in a) monolingual and b) bilingual children

a)

	Number of false alarms	No-go accuracy cost	d-prime	Go RT
Go percentage correct	0.48*	0.84***	0.19	-0.46**
Number of false alarms		0.86***	-0.73***	-0.79***
No-go accuracy cost			-0.36*	-0.67***
d-prime				0.46**

b)

	Number of false alarms	No-go accuracy cost	d-prime	Go RT
Go percentage correct	-0.14	0.69**	0.72**	0.19
Number of false alarms		0.60**	-0.74**	-0.38
No-go accuracy cost			0.02	-0.14
d-prime				0.32

* p < .05 ** p < .01 *** p < .0001

In sum, these results showed that bilingual children demonstrated better behavioral performance on the go/no-go task than monolinguals, as indicated by higher accuracy and faster go RT, less variable performance, improved sensitivity to the experimental stimuli and more efficient performance.

Go/no-go task ERP analyses. All analyses were performed on correct trials only. The mean number of trials contributing to the event-related potentials for the monolingual children was 109.32 (SD = 21.81) for the go trials and 29.10 (SD = 5.51) for the no-go trials. The mean number of trials contributing to the event-related potentials for the bilingual children was 115.84 (SD = 25.22) for the go trials and 28.32 (SD = 7.13) for the no-go trials. There were no differences between the two language groups on either the number of go trials, t(48) = -0.97, *n.s.*, or no-go trials, t(48) = 0.43, *n.s.*

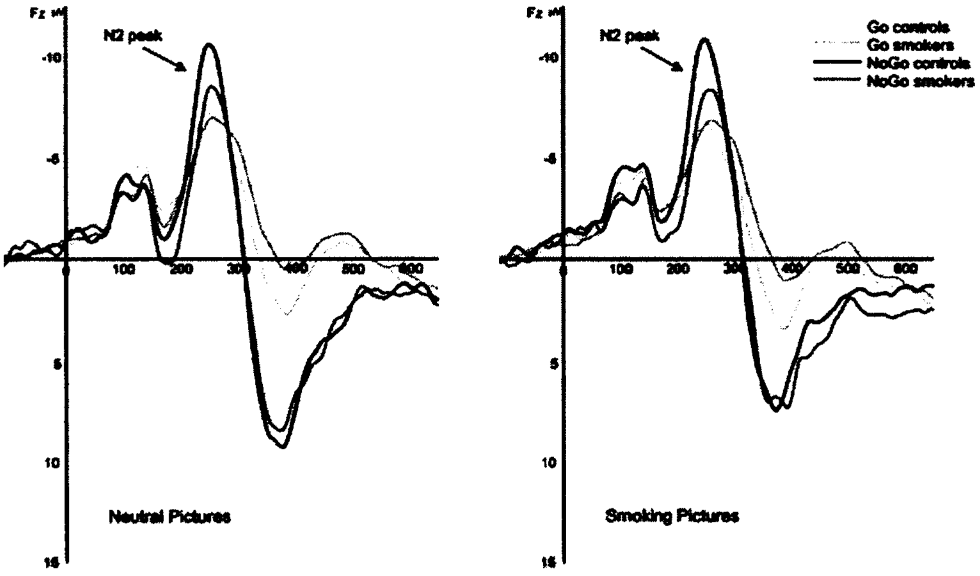
To facilitate identifying the waveforms, Figures 4a and 4b show typical N2 and P3 waveforms from a different study that used a go/no-go paradigm (Luijten, Littel, & Franken, 2011). Similar to the present study, negativity is plotted up, and positivity is plotted down. As seen in Figure 5, the visual stimuli in the present go/no-go task elicited a series of positive and negative deflections that were broadly distributed over the scalp. This series of deflections correspond to the components N1 (peaking at about 150 ms), P2 (peaking at about 270 ms), N2 (peaking at about 400 ms) and P3 (peaking at about 650 ms). The waveform components of interest for the present study were N2 and P3.

ERP amplitudes and latencies can be measured by calculating peak amplitude, mean amplitude, peak latency, fractional area latency and others. In the present study, both ERP components were analyzed in terms of mean amplitude and peak latency for the time windows defined below. Mean amplitude for each component was calculated as the mean voltage (in microvolts, µV) in a specified time window. Mean amplitude was chosen over peak amplitude, or the maximum amplitude in a defined time window, because it is less sensitive to high-frequency noise, to the level of noise in general and to the length of the measurement time window (Luck, 2005, pp. 234-235). Peak latency for each component was computed in milliseconds from the time the stimulus was presented to the time the maximum positive or negative peak was recorded within the defined time window. Peak latency is sensitive to high-frequency noise and changes systematically as a function of noise level. However, given that there are not many alternatives to using peak latency, "it is often the best measure" of latency (Luck, 2005, p. 239). To attenuate the shortcomings of peak latency, high-frequency noise in the waveforms was filtered out and waveforms for the two language groups were inspected to ensure that they have similar noise levels. Similarly, same strict artifact removal procedure has been used for both groups.

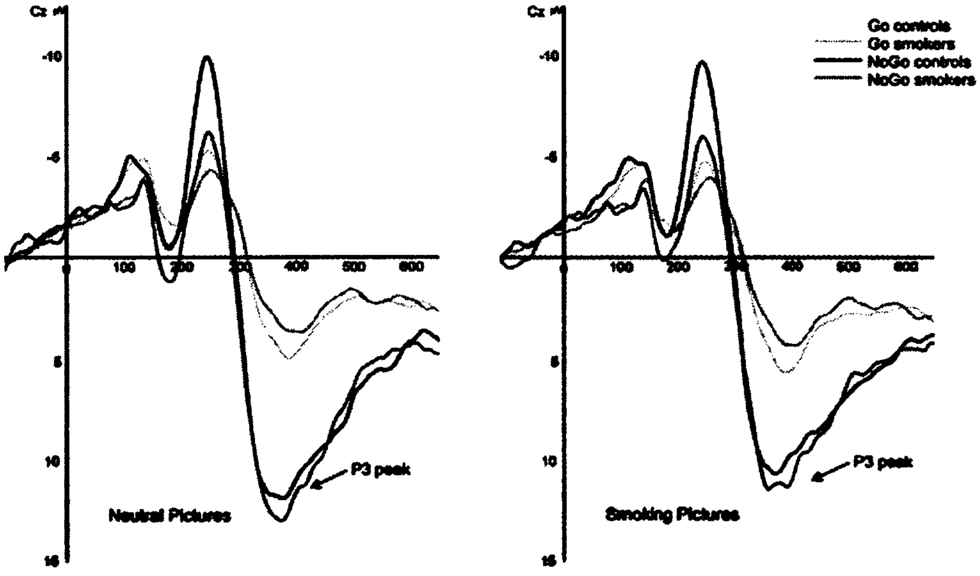
Grand-average ERP waveforms in the two language groups and in the go and no-go conditions at F1, F2, Fz, F3, F4, FC1, FC2, FCz, FC3, FC4, C1, C2, Cz, C3, C4, CP1, CP2, CPz, CP3, CP4, P1, P2, Pz, P3, P4 are depicted in Figure 5 and selected electrodes are presented in Figures 6a and 6b. ERP amplitudes and latencies for each of the two components were analyzed using four-way mixed ANOVA with laterality (5 levels, two on the left, midline, two on the right), anterior-posterior electrode position (5 levels, frontal, frontal-central, central, central-parietal, parietal), and condition (2 levels, go, no-go trials) as within-subject factors and language group (2 levels, monolinguals, bilinguals) as a between-subject factor.

Figure 4. Illustration of the a) N2 and b) P3 components.

a) N2 component



b) P3 component



(Images reproduced from Luijten, M., Little, M., Franken, I. H. A. (2011) Deficits in Inhibitory Control in Smokers During a Go/NoGo Task: An Investigation Using Event-Related Brain Potentials. *PLoS ONE, 6*: e18898. doi:10.1371/journal.pone.0018898)

Figure 5. Grand-averaged ERP waveforms for go and no-go trials for monolingual and bilingual children at all electrode sites.

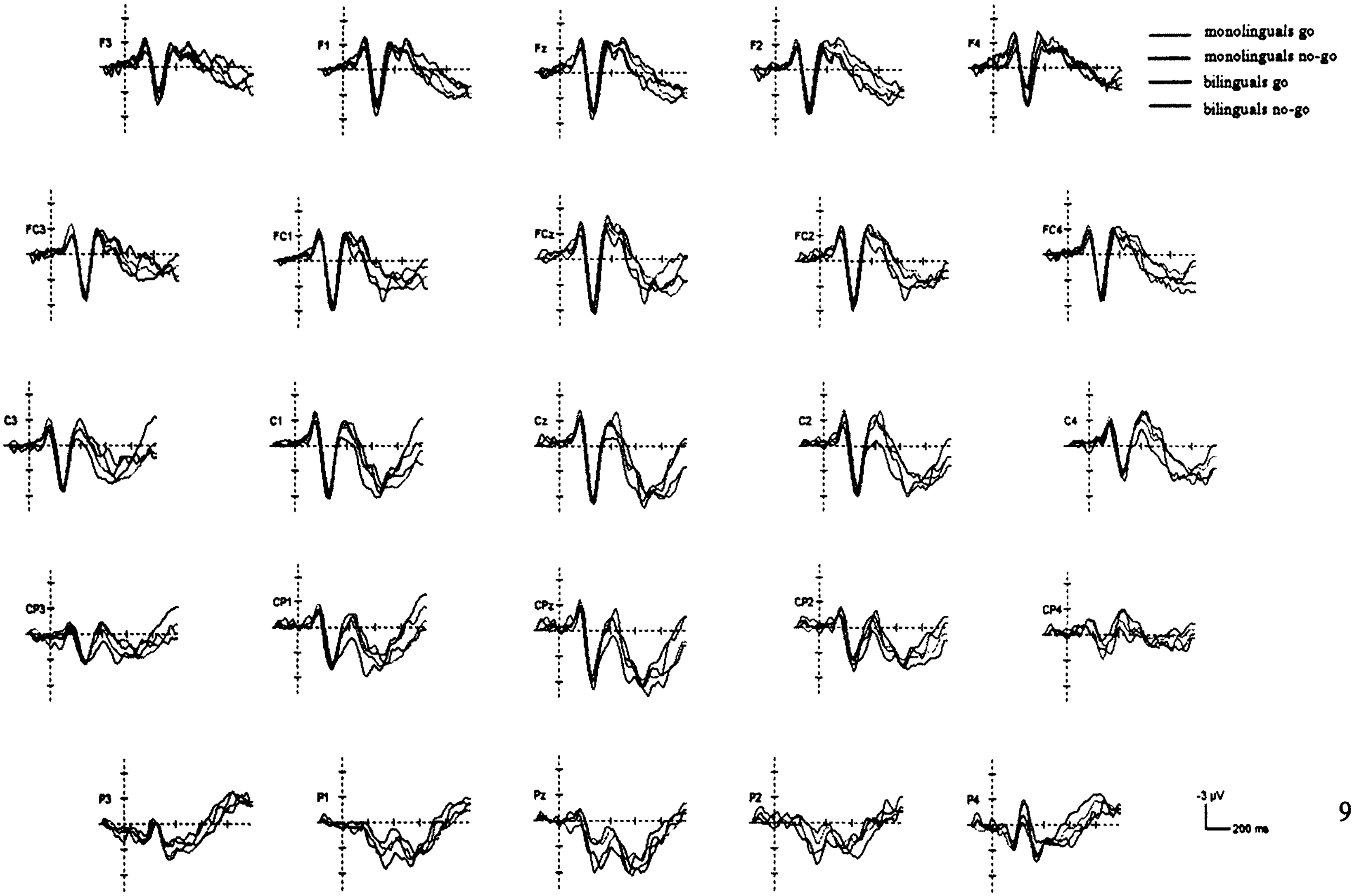
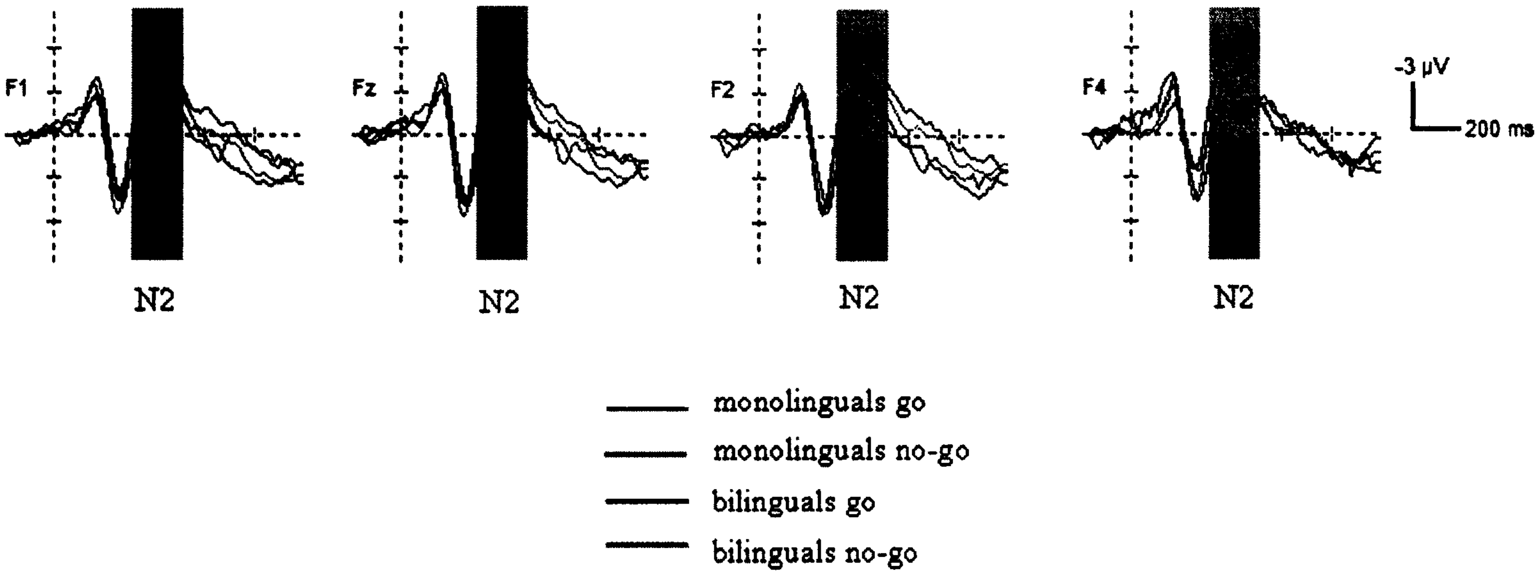
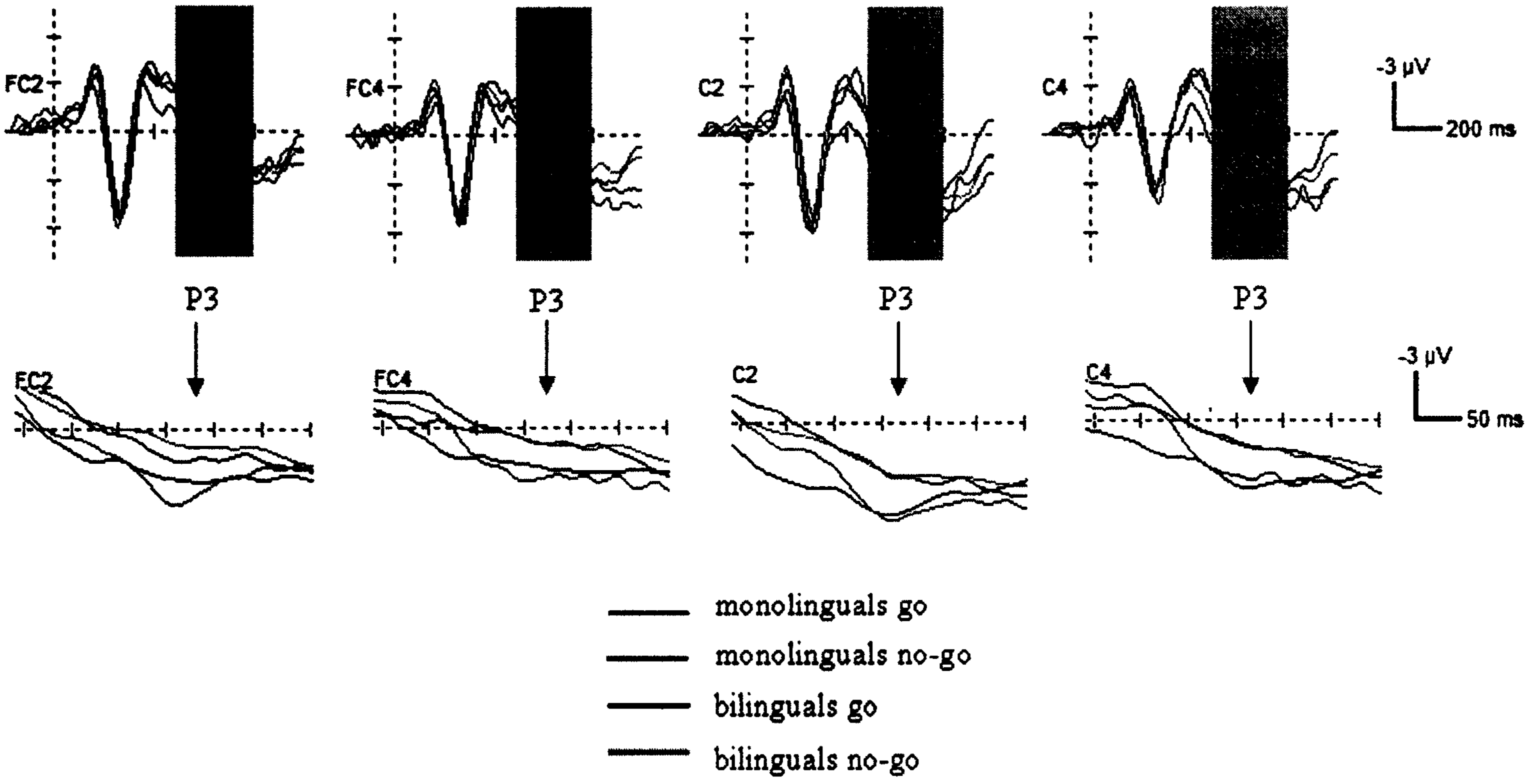


Figure 6. Grand-averaged ERP waveforms for go and no-go trials for monolingual and bilingual children at selected electrode sites.

a) Shorter latencies for bilinguals for the N2 component



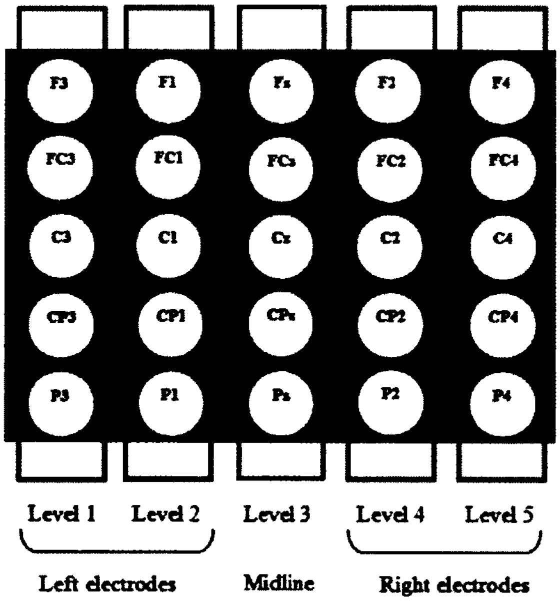
b) Larger mean amplitudes for bilinguals for the P3 component



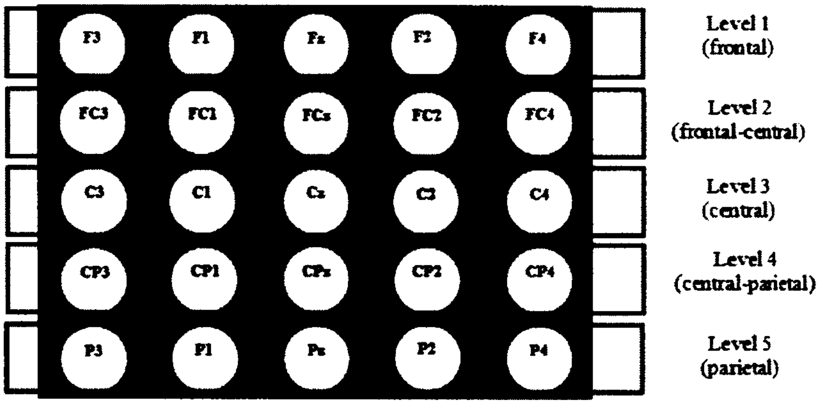
Figures 7a and 7b illustrate the layout of the 25 electrodes used for statistical analyses and highlight each level of the factors laterality and anterior-posterior. Figure 7c shows a schematic representation of the position of these 25 electrodes on the scalp relative to the rest of the electrodes. For the statistical analyses, Greenhouse-Geisser epsilon adjustment was used when appropriate in order to correct for the violation of the assumption of sphericity.

Figure 7. Electrode sites included in the analyses for the factors laterality and anterior-posterior electrode position.

a) Laterality (5 levels)



b) Anterior-posterior electrode position (5 levels)



c) Schematic distribution of all electrodes on the scalp (Biosemi system). Highlighted are the electrodes used for analyses.

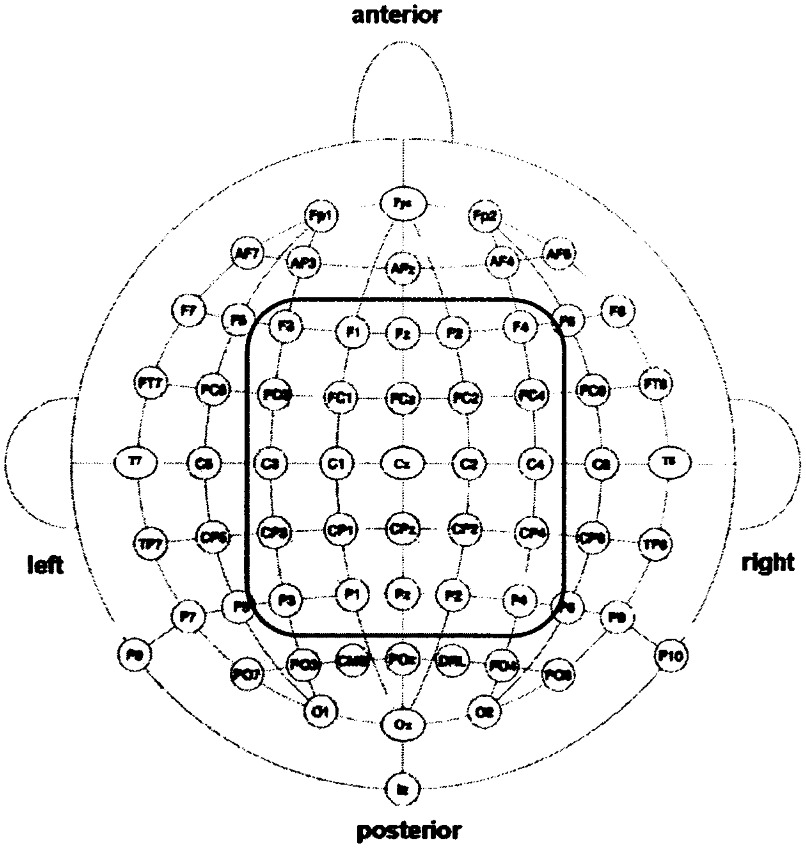


Image Reproduced from BioSemi Corporate Website (Amsterdam): http://www.biosemi.com/headcap.htm

N2 component. The mean amplitude and peak latency for the N2 component were calculated for the time window between 300 and 500 ms post-stimulus. Data for amplitude and latency for N2 were analyzed in two separate four-way ANOVAs.

First, the four-way ANOVA for mean amplitude with laterality (5), anterior-posterior electrode position (5), condition (2) and language group (2) showed a main effect of condition, $F(1, 48) = 10.50, p < .003$ with the no-go trials (M = -1.03, SD = 3.66) showing more negativity than the go trials (M = 0.06, SD = 2.82), a main effect of anterior-posterior electrode site, $F(4, 192) = 27.86, p < .0001$, and a main effect of laterality, $F(4, 192) = 4.53, p < .002$. Post-hoc contrasts for the variable anterior-posterior electrode site showed N2 amplitude was largest over frontal and central electrodes (anterior-posterior levels 1-3). Post-hoc contrasts for the variable laterality showed that N2 amplitude was largest over right electrodes (laterality levels 4-5).

Two interactions were significant: condition x anterior-posterior electrode position, $F(4, 192) = 6.33, p < .0001$, and laterality x anterior/posterior electrode position, $F(16, 768) = 2.01, p < .02$. Simple effects for the condition x anterior posterior interaction showed that for the frontal, t(49) = -0.82, *n.s.*, and frontal-central electrode sites, t(49) = 0.43, *n.s.*, there were no differences between the go and no-go trials, whereas for the central, t(49) = 2.67, $p < .01$, central-posterior, t(49) = 4.19, $p < .0001$ and posterior electrode sites, t(49) = 2.92, $p < .006$, the no-go trials elicited more negativity than the go trials. Simple effects for the laterality x anterior-posterior interaction showed that for the frontal electrodes there was no laterality effect, $F(4, 196) = 1.24$, *n.s.*, but for the frontal-central, central, central-parietal and parietal electrodes there was a laterality effect, which was further examined by running post-hoc contrasts. The results showed that N2 amplitude was largest over the right electrodes at the frontal-central, central and central-parietal sites, but at the parietal sites it was largest over the left electrodes.

Importantly, the four-way ANOVA for mean amplitude showed no main effect of group and no interaction between group and any of the other three factors. There were no significant three-way or four-way interactions.

Second, the four-way ANOVA for peak latency with laterality (5), anterior-posterior electrode position (5), condition (2) and language group (2) showed a main effect of condition, $F(1, 48) = 13.75, p < .0005$ with the go trials (M = 408, SD = 30) showing shorter latency than the no-go trials (M = 422, SD = 30), a main effect of anterior-posterior electrode position, $F(4, 192) = 21.24, p < .0001$, and a main effect of laterality, $F(4, 192) = 2.71, p < .04$. Post-hoc contrasts for the laterality factor showed that N2 latency was shortest over the left electrodes (levels 1-2). Post-hoc contrasts for the anterior-posterior factor showed that the frontal electrodes had the longest latency, and were significantly different from the frontal-central, central, central-parietal and parietal electrodes, which displayed the shortest latency.

There was no main effect of group but there was a significant interaction between group and anterior-posterior electrode position factor, $F(4, 192) = 2.98, p < .03$ (see Figure 6). Simple effects analyses showed that bilingual children had marginally shorter latencies than the monolingual children on the frontal, $t(48) = 1.86, p = .07$, and frontal-central electrodes, $t(48) = 1.86, p = .07$, but they did not differ on the central, $t(48) =$

0.96, *n.s.,* central-parietal, *t*(48) = 0.04, *n.s.,* and parietal *t*(48) = -0.92, *n.s.* electrodes. Peak latencies for the N2 component at each level of the anterior-posterior factor are presented in Table 6. No other interactions were significant.

Table 6

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

Anterior-posterior site	Monolinguals	Bilinguals
*Frontal electrodes	442 (43)	419 (41)
*Frontal-central electrodes	432 (38)	411 (41)
Central electrodes	423 (35)	414 (29)
Central-posterior electrodes	416 (28)	415 (31)
Posterior electrodes	377 (34)	387 (39)

Note: variables preceded by * show a significant group difference.

In sum, for the N2 component, bilingual children did not differ from monolinguals in the size of amplitude but showed shorter latencies at more anterior electrode sites (i.e., frontal and frontal-central electrodes), sites which also showed maximal amplitudes for this component.

P3 component. The mean amplitude and peak latency for the P3 component were calculated for the time window between 500 and 800 ms post-stimulus. Data for amplitude and latency for P3 were analyzed in two separate four-way ANOVAs.

First, the four-way ANOVA for mean amplitude with laterality (5), anterior-posterior electrode position (5), condition (2) and language group (2) showed four main effects: condition, $F(1, 48) = 13.31, p < .0007$, anterior-posterior electrode site, $F(4, 192) = 18.53, p < .0001$, laterality, $F(4, 192) = 16.05, p < .0001$ and language group, $F(1, 48) = 3.88, p = .055$. The main effect of condition indicated that the go trials (M = 2.73, SD = 2.99) elicited a larger amplitude response than the no-go trials (M = 1.21, SD = 4.44). The main effect of anterior-posterior electrode site showed that the frontal and frontal-central electrodes had the smallest amplitudes and were significantly different from all the other electrodes, whereas the central-parietal and parietal electrodes showed the largest amplitudes. The main effect of laterality indicated that the midline electrodes showed the largest amplitudes and were significantly different from levels 1, 4 and 5. Finally, the main effect of group indicated that bilingual children (M = 3.17, SD = 3.38) showed larger amplitude than the monolingual children (M = 1.23, SD = 3.39) (see Figure 6).

The analysis also showed three two-way interactions: condition x anterior-posterior, $F(4, 192) = 3.49, p < .009$, condition x laterality, $F(4, 192) = 3.55, p < .009$, and anterior-posterior x laterality, $F(16, 768) = 3.42, p < .0001$, all of which were followed up by simple effects analyses. The condition by anterior-posterior interaction showed that the go trials elicited larger amplitudes than the no-go trials but only at the central and central-posterior locations. The condition by laterality interaction showed that the go trials had larger amplitudes than the no-go trials on all electrodes except the right electrodes (level 5 of laterality factor). Finally, the anterior-posterior by laterality interaction indicated that for the frontal and frontal-central electrodes there was no laterality effect, whereas at the central, central-parietal and parietal sites, the midline electrodes (level 3 of laterality factor) showed the largest amplitude. There were no significant three-way or four-way interactions.

Second, the four-way ANOVA for peak latency with laterality (5), anterior-posterior electrode position (5), condition (2) and language group (2) showed three main effects: anterior-posterior electrode site, $F(4, 192) = 34.93, p < .0001$, laterality, $F(4, 192) = 15.38, p < .0001$ and language group, $F(1, 48) = 3.71, p = .059$. The main effect of anterior-posterior electrode site showed that the parietal electrodes displayed the shortest latency, and were significantly different from the frontal, frontal-central, central and central-parietal electrodes. The main effect of laterality indicated that longer latencies were observed over midline-right electrodes (levels 3 and 4). Finally, the main effect of group indicated that bilingual children (M = 677, SD = 29) showed shorter latencies than the monolingual children (M = 696, SD = 35).

The analysis also showed two significant two-way interactions: condition x anterior-posterior site, $F(4, 192) = 10.90, p < .0001$, and anterior-posterior x laterality, $F(16, 768) = 2.88, p < .0001$, which were followed up by simple effects analyses. The condition by anterior-posterior interaction showed that the latencies for the go trials were longer than the no-go trials latencies at the frontal, $t(49) = 2.91, p < .006$, and frontal-central, $t(49) = 2.34, p < .03$ sites, were shorter than the no-go trials at the parietal sites, $t(49) = -3.45, p < .002$, and were no different from each other at the central, $t(49) = 1.70$, *n.s.* and central-parietal sites, $t(49) = -1.33$, *n.s.* The anterior-posterior by laterality interaction indicated that the left electrodes (level 1 of laterality factor) showed the shortest latency, and it was significantly different from levels 2, 3, and 4 at the frontal and parietal sites, shorter than levels 3 and 4 and the central and central parietal sites, and shorter than levels 2 and 3 at the frontal-central sites.

Finally, the analysis also showed two three-way interactions that involved language group: condition x anterior-posterior x group, $F(4, 192) = 2.66, p < .04$, and anterior-posterior x laterality x group, $F(16, 768) = 1.86, p < .03$. Peak latencies for P3 for monolingual and bilingual children are presented in Table 7. Simple effects analyses for the condition by anterior-posterior by language group interaction showed that bilingual children had shorter latencies than monolingual children only for the go trials at the central, $t(48) = 2.20, p < .04$, central-parietal, $t(48) = 3.55, p < .001$ and parietal sites, $t(48) = 1.83, p = 0.07$. The anterior-posterior x laterality x group interaction showed that bilinguals had significantly or marginally shorter latencies than monolinguals at the level 3 of the frontal-central sites, $t(48) = 1.90, p = .06$, levels 1, $t(48) = 2.18, p < .04$ and 2, $t(48) = 3.40, p < .002$ of the central sites, levels 2, $t(48) = 4.17, p < .0001$, 3, $t(48) = 3.23$, $p < .003$ and 4, $t(48) = 1.83, p = .07$ of the central-parietal sites, and levels 3, $t(48) = 1.80$, $p = .078$ and 4, $t(48) = 1.70, p = .095$ of the parietal sites.

Table 7

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

	Monolinguals		Bilinguals	
Anterior-posterior site	Go trials	No-go trials	Go trials	No-go trials
Frontal electrodes	705 (88)	682 (70)	731 (71)	667 (83)
Frontal-central electrodes	721 (69)	709 (65)	730 (49)	687 (49)
*Central electrodes	743 (55)	724 (43)	711 (41)	706 (54)
*Central-posterior electrodes	704 (59)	705 (62)	644 (55)	674 (71)
Posterior electrodes	620 (64)	646 (60)	591 (46)	632 (68)

Note: variables preceded by * show a significant group difference.

In sum, for the P3 component, bilingual children showed larger amplitude than monolinguals regardless of the laterality and anterior-posterior electrode position and they showed shorter latencies at central and posterior electrode sites (i.e., central, central-parietal and parietal sites), sites which showed the maximal amplitudes for this component.

Behavior – brain relationships. Pearson bivariate correlation analyses were performed to better understand the relationship between behavioral performance and ERP measures. For the mean amplitude of the P3 component, most correlations did not reach statistical significance but were suggestive of an interesting pattern. For monolinguals, the correlations between $d^{\prime}$ scores or percentage accuracy on no-go trials and amplitude at the C2 and C4 sites all had negative coefficients, whereas for bilingual children all these correlation coefficients were positive. Moreover, in the bilingual sample two of these correlations were significant ($d^{\prime}$ scores and amplitude at C4 site for go trials, $r(17) = 0.47$, $p < .05$) or marginally significant (no-go accuracy and amplitude at C4 site for no-go trials, $r(17) = 0.40, p = .09$). This suggests that in the bilingual children larger amplitudes are associated with better performance and enhanced discrimination of the experimental stimuli.

Likewise, correlations between peak latency of the P3 component and $d^{\prime}$ scores indicate a similar pattern. In bilinguals, shorter latencies were associated with larger $d^{\prime}$ scores, in other words with better behavioral performance (correlation between $d^{\prime}$ scores and F3 go latency, $r(17) = -0.51, p = .03$, F4 go latency, $r(17) = -0.42, p = .07$, CP2 go latency, $r(17) = -0.39, p = .09$, P2 go latency, $r(17) = -0.70, p < .001$, with one exception, FC2 no-go latency, $r(17) = 0.41, p = .08$). In contrast, in monolinguals the correlation coefficients were positive, with shorter latencies being associated with smaller $d^{\prime}$ scores, that is, worse behavioral performance: correlation between $d^{\prime}$ scores and C1 go latency, $r(29) = 0.32, p = .08$, P1 go latency, $r(29) = 0.31, p = .09$, Fz no-go latency, $r(29) = 0.54, p = .002$, F2 no-go latency, $r(29) = 0.31, p = .09$, F4 no-go latency, $r(29) = 0.45, p = .01$, FC4 no-go latency, $r(29) = 0.31, p = .08$.

For the N2 component, correlations between accuracy on no-go trials and peak latency at various sites showed a pattern consistent with the P3 results. Again, longer latencies were associated with better performance in monolingual children (at CP3 site,

$r(29) = 0.30, p = .09$, at Cz site, $r(29) = 0.36, p < .05$), and shorter latencies were associated with better performance in bilinguals (at FC4, $r(17) = -0.40, p = .09$, at C4, $r(17) = -0.45, p = .05$).

Since many of these correlations are marginally significant, perhaps due to lack of power, 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 are suggestive of a pattern in which for bilingual children larger amplitudes and shorter latencies reflect better behavioral performance.

Discussion

Substantial *behavioural evidence* has demonstrated the plasticity of executive functions as a result of bilingualism, but at present we know very little about the *neurocorrelates of these executive control* processes for monolingual and bilingual children. Examining the neural basis of the bilingual advantage provides a window into understanding how sustained experience with two languages influences neurocognitive performance and how brain plasticity is related to behavioural performance.

The present dissertation investigated for the first time the neural basis of the bilingual advantage in executive control in children. Five-year-old monolingual and bilingual children with similar SES background and general cognitive level were tested on executive control tasks using both behavioural and electrophysiological indices of cognitive performance. The behavioural tasks measured different forms of inhibition (simple response inhibition: Gift Delay task and Simon Says; interference suppression: flanker task). Based on previous findings, the prediction was that bilinguals would outperform monolinguals on the interference suppression task when distractors were present, but would be equivalent to monolinguals on the measures of simple response inhibition.

Electrophysiological data were recorded to analyse ERPs for a go/go-no task (complex response inhibition). For this task, a behavioural advantage was predicted for bilingual children, as well as differences between the two language groups in the N2 and P3 waveforms. Specifically, greater amplitudes were expected on the N2 and P3 components of the go/no-go task.

Summary of Findings

Analyses of background measures indicated that bilingual children formed a heterogeneous group, speaking English at daycare or school and English plus one of twelve other languages at home. Most bilingual children spoke and were exposed to the two languages relatively equally at home. In contrast, for monolinguals the language used at home and school was exclusively English.

For the other background measures, results showed that bilingual and monolingual children had similar SES background based on maternal education: in both language groups, for most participants the highest degree of education corresponded to college diploma or a bachelors' degree. Children were also matched on age, non-verbal reasoning based on the Block Design scale of the WPPSI-III, and general cognitive ability based on the estimated full-scale scores on WPPSI-III. However, on the measure of expressive vocabulary, monolingual children outperformed bilinguals.

Performance on the behavioural measures of executive control indicated that bilingual and monolingual children performed similarly on the two measures of simple response inhibition: Gift Delay and Simon Says. This is consistent with previous research. In contrast, on the ANT flanker task measuring interference suppression, bilinguals were more accurate than their monolingual peers. This bilingual advantage was found only on trials where distractors were present along with the target stimulus (congruent and incongruent trials), and not on trials where the target appeared by itself (neutral trials). This result confirms previous research reporting a bilingual advantage in conflict tasks.

Analyses of the ERP task showed a clear bilingual advantage on the behavioural performance as indexed by higher accuracy on both go and no-go trials and faster RTs on the go trials. Behavioural performance on the go/no-go task was also measured by d^l scores and inverse efficiency scores, both providing a more detailed analysis of the task performance. The d^l scores reflect perceptual sensitivity to the go and no-go conditions and inverse efficiency scores represent an index of performance efficiency that takes into account both speed and accuracy of responses independent of possible speed-accuracy tradeoffs. Analyses of both scores again showed better performance by the bilingual children.

Finally, analyses of the ERPs waveforms looked at mean amplitude and latency of the N2 and P3 components. These two waveforms are generally accepted to index aspects of executive control, such as conflict monitoring (N2; Nieuwenhuis et al., 2003) and later stages of response inhibition (P3; Freitas et al., 2007). For the N2 component, bilingual children did not differ from monolinguals in amplitude but showed shorter latencies at more anterior electrode sites (i.e., frontal and frontal-central electrodes). For the P3 component, in contrast to the N2 component, bilingual children showed larger amplitude than monolinguals regardless of laterality and anterior-posterior electrode position. Bilingual children also showed shorter latencies at central and posterior electrode sites (i.e., central, central-parietal and parietal sites). Moreover, correlations between the behavioural performance and the electrophysiological indices showed that for bilinguals larger amplitudes and shorter latencies were associated with more efficient task performance. This pattern of functional brain responses for the N2/P3 complex indicates that bilingual children show more mature brain responses than monolingual children, a point that is discussed in more detail below.

In sum, the experience of processing two languages led to a) enhanced behavioural performance on tasks with high executive demands (child ANT and the go/no-go task), and b) changes in the electrophysiological correlates of non-verbal executive control task, the go/no-go task. The behavioural results are discussed first, followed by the electrophysiological data.

Bilingualism Effects on Behavioural Performance

Vocabulary. Past research has shown that speaking two languages leads to a cost in performance on linguistic tasks across lifespan (e.g., Bialystok & Luk, 2011; Fernández et al., 1992; Oller, Lewis, & Cobo-Lewis, 2007; Oller & Eilers, 2002). Bialystok and colleagues, for instance, showed that bilingual children between the ages of 3 and 10 years obtained lower scores than comparable monolingual children on the

Peabody Picture Vocabulary Test, which is a measure of receptive vocabulary (Bialystok et al., 2010). Consistent with this pattern, in the present study, bilingual children showed lower expressive vocabulary scores in English, despite equivalent performance in nonverbal reasoning. Bilingual children divide their language production and language comprehension experience across two languages and the quantity of linguistic input is an important factor determining vocabulary acquisition (Hoff & Naigles, 2002). Thus, it is not surprising that bilingual children show smaller vocabularies in one language compared to monolingual speakers of that language.

In the present study, vocabulary was measured only in English. Thus, it is possible that the bilingual disadvantage would not be present if vocabulary was measured in both languages. The advantage of measuring vocabulary in both languages is that it allows calculating the number of concepts children have acquired across languages - the total conceptual vocabulary - rather than the number of labels in each language (Conboy & Mills, 2006; Junker & Stockman, 2002; Pearson et al., 1993). This way, total conceptual vocabulary offers a more complete measure of bilingual children's overall linguistic knowledge.

Executive control. Children were administered four measures of executive control: bilingualism enhanced performance on two of these measures, whereas performance on the other two remained unaffected by the experience of speaking two languages.

When the bilingual advantage is not present. On the two measures of simple response inhibition - Gift Delay and Simon Says - bilingual children performed similarly to monolinguals. This is in line with the results of Carlson and Meltzoff (2008) study indicating that bilingualism selectively influences performance on tasks that require managing conflicting attentional demands, but not on measures of impulse control. In their study, Carlson and Meltzoff (2008) compared three different groups of 6-year-old children (monolinguals, bilinguals, children attending language immersion programs) in terms of their performance on nine measures of executive control. When controlling for parent education, age and language ability, bilinguals outperformed at least one of the other two groups on Visually Cued Recall, the Advanced Dimensional Change Card Sort, and the Comprehensive Test of Nonverbal Intelligence, which all require inhibition of attention to misleading stimulus dimensions. However, in line with the present findings, the groups were equivalent on Simon Says and Gift Delay tasks.

In the Carlson and Meltzoff (2008) study, the Simon Says and Gift Delay tasks were both unaffected by bilingualism, yet the two tasks appeared to recruit different executive processes. The authors conducted a factor analysis which revealed that the nine executive control tasks loaded on two main factors: conflict and delay. The Simon Says task correlated with performance on the ANT and it loaded on the conflict factor, along with five other tasks: Comprehensive Test of Nonverbal Intelligence, Kansas Reflection-Impulsivity Scale, Visually Cued Recall, Dimensional Change Card Sort and the ANT. In contrast, the Gift Delay task was correlated with paternal education and loaded highly on the delay factor, along with Statue and delay of gratification. Thus, given that performance on Gift Delay and Simon Says was not correlated and that the two tasks loaded on two different factors in the Carlson and Meltzoff study, it appears that there is a dissociation in the executive control processes underlying the Simon Says task and the Gift Delay task. Similarly, in the present study, there were no correlations between performance on Gift Delay, Simon Says, and any of the ANT variables, regardless of whether the analyses were run for the overall sample or separately by language group. This result suggests again that these three tasks tap onto different cognitive resources.

In line with this pattern, developmental data examining performance on several measures of executive control in children between 22 and 83 months indicated that Gift Delay and Simon Says differed in terms of their relative difficulty: in the age range 5 to 6 years, the Simon Says task had a probability of passing of about 50% whereas the Gift Delay task had a probability of passing of about 75% (Carlson, 2005). Based on these developmental trends and relative task difficulty indices, Carlson suggested that the different executive control tasks can be conceptualized in terms of their inherent demands such as primarily inhibitory demands, primarily working memory demands or a combination of the two. Gift Delay is an example of a task containing mainly inhibitory demands, whereas Simon Says contains both inhibitory and working memory demands (i.e., holding in mind an arbitrary rule) (Carlson, 2005; Garon et al., 2008), and developmental data has shown that this combination of different executive demands makes the task more challenging for children.

Thus, past research has demonstrated that Simon Says and Gift Delay are both measures of executive control that differ in the underlying processes measured. Furthermore, both the present study and the previous study by Carlson and Meltzoff (2008) show that bilingualism does not affect the performance of either task. The question that arises, then, is what is it that these two tasks have in common that makes both of them less permeable to bilingualism influence despite their different demands? One possible answer from the present dissertation is that what the tasks have in common is that they are simple measures of executive control. Gift Delay measures response inhibition and Simon Says measures response inhibition and to some extent working memory. Because of this combination of response inhibition and working memory, it can be argued that Simon Says can be expected to produce a bilingual advantage. However, working memory involvement in this task is small: there is one rule to remember, and although the rule is somewhat arbitrary (act only when you hear "Simon Says") it is nonetheless more intuitive and easy to remember than selecting responses based on random color assignment (press if white, do not press if purple). One possibility is that increasing the working memory demands of the Simon Says task might lead to a bilingual advantage in performance. Moreover, neither task imposed strict timing constraints, making the monitoring demands very low. Thus, in other words, neither of the two tasks contains complex enough cognitive processing demands to be able to discriminate between the two language groups.

When the bilingual advantage is present. If this argument is correct, then bilingual advantages should be found only on more complex tasks that recruit a different set of executive control processes than those required in the simple tasks. Additionally, complex tasks may tap similar processes as in the simple tasks, such as response inhibition, working memory and monitoring in the case of Simon Says, but involve those processes to a greater extent. This is exactly the finding of the present dissertation showing that bilingual children outperformed monolingual children on the child ANT task and on the go/no-go task. The child ANT is considered a measure of interference suppression but successful performance on the task recruits several executive control processes such as selective attention, conflict monitoring, and conflict resolution. Conflict monitoring is involved in detecting the presence of conflict and signalling and adjusting the behavioural demands as a function of the presence or absence of conflict. Conflict resolution, which includes the inhibitory control component, is needed when the task activates simultaneously two different representations that are associated with different responses (Costa et al., 2008).

Bilingualism has been shown to improve performance on the ANT/ flanker task in both children (e.g., Mezzacappa, 2004; Yang et al., 2011) and adults (Costa et al., 2008; Costa et al., 2009; Luk, 2008). 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, such as the monitoring demands, by manipulating the ratio of congruent to incongruent trials, influences performance and a bilingual advantage is present only in the conditions that require a great deal of monitoring activity (Costa et al., 2009). The present findings showed enhanced performance in 5-year-old bilingual children on the congruent and incongruent trials, but not on the control trials. The lack of language group differences on the control trials, where the target stimulus was 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.

In the go/no-go task the main requirement was to suppress the motor response for selected, infrequent stimuli and the task is considered a measure of response inhibition. Bilinguals outperformed monolinguals on both go and no-go trials, on measures of accuracy, reaction time, performance efficiency and perceptual sensitivity. Similar to the ANT and unlike other measures of response inhibition such as Gift Delay, the go/no-go task also involved a cluster of executive processes such as selective attention, working memory and monitoring. These processes were particularly recruited in the go/no-go task used in the present study given that the stimuli were geometric figures that differed in shape (i.e., rectangles and triangles) and color (i.e., white and purple), but the decision to suppress the response was based solely on color. Thus, a bilingual advantage was found on the go/no-go task presumably because the version of the go/no-go task used in the present study indexes a set of executive processes.

The present findings are consistent with the results of a previous study in which 6-year-old bilingual and monolingual children performed a non-verbal working memory task. In line with the present argument, bilingual children outperformed monolinguals on the two conditions from the total of four that carried the highest executive demands (Feng, Diamond, & Bialystok, 2007). Children were shown a 3x3 matrix and were told that each of the nine cells represented a pond in which a frog could be resting. Children's task was to remember all the ponds in which frogs had been resting. Thus, although all four conditions measured children's ability to maintain information in mind, they required different degrees of cognitive control, such as ignoring interference and manipulating the information. For instance, in one condition, children were presented with the 9 ponds, and in some of the ponds frogs were resting. Children were asked to indicate the ponds where they saw the frogs. However, between the stimuli presentation and children's response, another screen popped up that contained distracting information, namely frogs presented at other locations than the initial ones. Children were instructed to ignore this information and only report the frog positions they saw initially. In this condition, bilingual and monolingual children performed similarly, perhaps because the distracting information was not sufficiently misleading: the distracting frogs always appeared in the same positions which made the distracting information easier to ignore. In the fourth condition, however, a bilingual advantage was recorded. This was the condition with the highest executive demands: children were presented with one frog at a time, at various positions in the 3x3 matrix pond and the task was to remember the spatial positions of the frogs and to re-order them according to an arbitrary rule set by the experimenter. The rule was that regardless of the order of presentation, children had to indicate the frog positions following a path indicated by the experimenter.

A similar pattern was found in a study investigating response inhibition in 6- to 7-year-old children using a task that combined a go/no-go task with a flanker task. Children were instructed to press a mouse button indicating the direction of the target stimulus, which was an arrow that pointed to the left or to the right. In one block, the go trials (the target was flanked by four diamonds, two on each side) were combined with no-go trials (the target was flanked by 4 Xs, two on each side). In a different block, the go/no-go trials were combined with two other types of trials: congruent (the target was surrounded by four arrows all pointing in the same direction), and incongruent (the flanking arrows were pointing in the opposite direction from the target) (Barac et al., 2010). A strong bilingual advantage on the go/no-go trials was recorded only in the block that included all trial types, in other words the block in which task complexity was at its highest.

To summarize, the pattern of performance on the four executive control tasks in the present study in which there is a bilingual advantage in ANT and the go/no-go task, and equivalent performance on Simon Says and Gift Delay, supports the interpretation that bilingual children excel at managing executive resources in cognitive tasks with high control demands. It has been suggested that what appears to make an executive function measure more difficult than another is the combination of different executive processes such as inhibition and working memory (e.g., Carlson, 2005). In the present dissertation it is argued that the bilingual advantage is recorded in tasks that recruit a set of executive resources, with specific involvement of processes such as selective attention, conflict resolution, inhibition, and monitoring. In addition, it is argued that a bilingual advantage is present when these specific executive resources are involved to a great extent. Thus, consistent with the data, the present position is that bilinguals outperform monolinguals when the task engages a certain combination of executive processes and when more intense use of these processes is required. This position is in line with Costa and colleagues' (2009) interpretation that bilinguals outperform monolinguals when the task draws on a set of executive processes and when these executive processes are heavily engaged. In the study by Costa and colleagues (2009), bilinguals and monolinguals performed two versions of the same flanker task that involved a combination of conflict resolution and either high or low monitoring skills. Bilinguals excelled only in the version with high monitoring skills, indicating that it is not just the need to inhibit or to monitor that makes a difference, but rather their combination, in a high dose.

It is nonetheless possible that a bilingual advantage is present when there is highly intense involvement of only one of these processes but at present no data convincingly supports this position. Interpretations are further complicated by the fact that determining which tasks have complex processing demands and are likely influenced by bilingualism is not a straightforward issue given that performance on executive function tasks is also influenced by age, resulting in a very dynamic performance map.

Nonetheless, the present study brings more clarity to understanding the locus of the bilingual advantage in non-linguistic task performance and indicates that the bilingual benefits are present not when the tasks have low executive demands, but rather when the task demands are complex and rely on a range of executive processes and more intense executive involvement. In a recent review of the topic of the bilingualism advantage, Hilchey and Klein (2011) concluded that bilingualism has a general influence on the "central executive system" (p. 654) rather than on a purely inhibitory mechanism. In the 13 studies of Simon and Flanker tasks included in the meta-analysis, the authors found a general bilingual processing advantage, with bilinguals outperforming monolinguals in both congruent and incongruent conditions. Hilchey and Klein interpreted this finding to show that for bilinguals, having representations in two linguistic systems activated simultaneously results in intense reliance on the conflict monitoring system which subsequently, with practice, becomes strengthened and more efficient. Thus, bilinguals show an enhanced ability to focus on task-relevant information, rather than inhibit task irrelevant information. This is why the bilingual advantage is found on cognitively demanding and complex conditions, regardless of whether inhibitory demands are present or not.

Bilingualism Effects on Brain Function

The experience of speaking two languages resulted in improved performance on tasks of executive control with complex processing demands. In addition, the present dissertation demonstrated that bilingualism induced brain modifications in the neurocorrelates of executive control, namely the N2 and P3 components. A recent DTI study showed structural differences between the brains of monolingual and bilingual children (Mohades et al., 2011). In this study, Mohades and colleagues (2011) found that simultaneous and sequential bilingual children between 8- and 11-years of age showed different characteristics of the white matter microstructure in the left inferior occipitofrontal fasciculus and in the anterior part of the corpus callosum projecting to the orbital lobe than monolingual children, with the stronger effect being reported in children who learned the second language at an earlier age. Moreover, previous research has shown bilingualism-related brain changes in linguistic processing (e.g., Conboy & Mills, 2006). However, in the present results functional brain changes were recorded when the brain was engaged in a *non-verbal measure of executive control.* This finding of functional brain plasticity in children as a consequence of speaking two languages is consistent with previous research demonstrating experience-related functional plasticity, such as the effect of music training on brain function (Moreno et al., 2011; Shahin, Roberts, Pantev, Trainor, & Ross, 2005; Shahin, Bosnyak, Trainor, & Roberts, 2003; Trainor, Shahin, & Roberts, 2003).

For both monolingual and bilingual children, the go/no-go paradigm elicited the N2/P3 complex. However, the characteristics of these two components differed as a function of language group: in bilingual children, the N2 and P3 components showed faster latencies, and P3 showed larger amplitudes. What larger amplitude means, however, is not straightforward. Increased amplitude has been interpreted as an increased neuronal representation due to training (e.g., Recanzone, Schreiner, & Merzenich, 1993) and/or increased neural synchrony (e.g., Tremblay, Kraus, McGee, Ponton, & Otis, 2001). In fMRI studies, a similar issue is related to the interpretation of the different patterns of practice-related changes in brain activation, namely increases, decreases or a combination of the two and, as with ERPs, the interpretations are neither simple nor unequivocal (Kelly & Garavan, 2005). Although it is difficult to pinpoint the exact mechanism underlying this functional plasticity, the correlations between electrophysiological data and behavioural performance give some direction with respect to what larger amplitudes and shorter latencies potentially indicate. In bilingual children, shorter latencies and larger amplitudes were associated with more efficient behavioural performance and better discrimination between the experimental stimuli. In contrast, for monolingual children, shorter latencies correlated with less efficient behavioural performance, with no relation between amplitude and performance.

This pattern of findings – enhanced task performance related to larger amplitudes on the N2/P3 complex – is in line with past research indicating that typically developing children were more accurate than children with ADHD on a go/no-go task, and showed increases in the amplitudes for the P3 component (Pliszka et al., 2000). In another 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). Furthermore, the results of two additional studies comparing the neurocognitive functions of gifted and average children (e.g., Duan et al., 2009; Liu, Xiao, Shi, Zhao, & Liu, 2011) support the interpretation of the present findings. In one study, gifted children achieved more accurate performance on a go/no-go task, as indexed by fewer commission and omission errors, and shorter P3 latency than average intelligence children (Duan et al., 2009). In the second study, gifted children outperformed children with average intellectual levels on a flanker task, and showed larger P3 amplitudes over central–parietal regions and faster P3 responses over their frontal regions (Liu et al., 2011). The shorter latencies and larger amplitudes for P3 responses in gifted children were found for both congruent and incongruent trials. Together, these results were interpreted to suggest that gifted children have a more mature and efficient control network, supporting the neural efficiency hypothesis of intelligence. The neural efficiency hypothesis of intelligence posits that intelligence is not a function of how hard the brain works but rather how efficiently it works (Duan et al., 2009).

Similarly, the present results suggest that when monolingual and bilingual children are engaged in a task with complex demands that require high levels of cognitive resources for monitoring, response selection and response inhibition, bilingual children show a more efficient use of their neural systems. The interpretation of more efficient use of neural resources by bilinguals is based on the finding of shorter latency for N2 and P3 and larger amplitude for P3. Shorter latencies for bilingual children on the N2 component, particularly at the frontal electrode sites is an interesting result in the 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 it can be speculated that the anteriorization of responses in bilingual children in the present study suggests a more mature, adult-like pattern of brain function. This is evidence that bilingual children are more precocious in their developmental trajectory or in other words, bilingual children reach certain level of ability and development earlier than their monolingual peers. These results speaking to functional brain development are consistent with a large body of behavioural evidence indicating earlier maturation of executive processes in bilingual children.

In the current study, the N2 and P3 components were not influenced by bilingualism in the same way: the go/no-go task evoked shorter latencies for N2 in bilinguals, whereas for P3 both the amplitude and the latency were modified by bilingualism. This finding is not surprising given that N2 and P3 show different developmental trajectories (Jonkman et al., 2003) and likely reflect different executive processes (Enriquez-Geppert, Konrad, Pantev, & Huster, 2010). For instance, the N2 component was similar in 9-to10-year-old children and adults, whereas the P3 component showed different characteristics as a function of age (Jonkman et al., 2003). Moreover, although there is no general consensus on this point, N2 has typically been proposed to index mainly conflict monitoring processes, and P3 generation is believed to be evoked by motor inhibition processes (Enriquez-Geppert et al., 2010). Thus, the N2 and P3 capture different aspects of executive control, and these aspects are not uniformly influenced by bilingualism.

Another point that requires further discussion is the length of training or experience that is needed to produce neural plasticity. Based on the present findings it appears that several years of sustained experience with two linguistic systems are sufficient to modify relevant cognitive functions and their underlying electrophysiological correlates. This is consistent with other findings revealing that brain plasticity is possible and measurable with only limited experience or training. For instance, Scholz and colleagues found white matter changes after 6 weeks of training of complex visuo-motor skills, with five training days per week (Scholz et al., 2009), and Takeuchi and colleagues did so after 2 months of daily working memory practice (Takeuchi et al., 2010). In children, a month of exposure to a second language resulted in modifications of neural function in a task of language perception (Conboy & Kuhl, 2011) and one month of music training induced changes in brain responses in a non-verbal executive control task (Moreno et al., 2011). These are all dramatic examples of the potential of the brain to transform as a result of (sometimes very limited) experience, regardless of age and type of experience or training involved. At the same time, the present demonstration of bilingualism-induced functional brain plasticity after a few years of dual language experience is congruent with behavioural results indicating that from very early on, starting in infancy bilinguals perform differently than monolinguals (e.g., Kovacs & Mehler, 2009). Furthermore, the present findings of bilingualism-induced plasticity at the brain and at the behavioral levels is in line with the IC and BIA+ theoretical models in that they emphasize the need to posit the existence of both a linguistic system and a decision/ control system. However, the BIA+ model is more language-specific than the IC model, and it makes it somewhat difficult to explain advantages on non-verbal tasks in bilingual speakers. The IC model, on the other side, postulates mainly inhibitory mechanisms to be responsible for solving the competition between lexical items in the two simultaneously activated linguistic systems. The present findings of a processing advantage on a range of executive processes fit with a model similar to the IC, but having the locus of control not limited exclusively to inhibitory processes, but rather extended more generally to the central executive system.

Thus, practice, training, expertise, and various life experiences lead to functional brain plasticity. But how do practice or life experience change neural function? Based on animal and human plasticity research, Kolb (1995) hypothesized that "the effect of experience has been to remodel the brain to make it more responsive to subsequent experiences. Stated differently, plastic changes have made the brain more plastic" (p. 28). Commenting on the effects of practice in general, Jonides (2004) proposed that practice can result either in greater skill at applying the initial strategy, which at a physiological level is supported by increased neural efficiency, or in the development of a new strategy which is supported by cortical functional reorganization. With respect to the present findings, it is difficult to pinpoint the exact mechanism of change, and in general, in the field as a whole, it is not clear how the mechanism underlying plasticity at the level of synapses is related to changes in neuronal networks and cognitive processes and behavioural performance. As a future direction, Kelly and Garavan (2005) proposed that the key to understanding this fundamental issue is studying the relationship between functional changes and changes in neural connectivity between different brain areas. Although the present study did not look at connectivity analyses, it offers nonetheless a beginning in this direction since it examined correlations between behavioural performance and brain function.

The present study has several limitations. For the bilingual children, language proficiency was measured only in one language, English. This offers a limited picture of the linguistic abilities of the bilingual children and possibly underestimates their vocabulary knowledge. Measuring language proficiency in the non-English language allows for estimations of the total conceptual vocabulary across the two languages, which is a more precise indication of the linguistic abilities of the bilingual children. Furthermore, including more measure of language processing would allow investigating the relationship between the non-verbal and verbal performance in the bilingual children. Due to testing constraints and the age of the participants, no more tasks could have been added to the present testing battery but this is an important future direction. Additionally, as acknowledged in the Method section, examining peak latency, although the most common measure of latency, has limitations in that it is very sensitive to movement artifacts.

Conclusion

In conclusion, the present findings offer evidence for the idea that bilingualism is a form of cognitive training that involves the executive control system, and as a consequence of this sustained executive control training there is experience-induced brain plasticity. This experience-induced plasticity was observed in bilingual children both in terms of more accurate and faster behavioural performance and more efficient use of neural function when engaged in processing of a complex executive control tasks. More generally, these results can be interpreted to suggest that bilingualism acts as a potentiator of a general processing executive network. Thus, the present findings are the first to demonstrate that sustained language training – bilingualism - influences the electrophysiological correlates of non-verbal executive control processes, likely through shared brain resources that are common across cognitive tasks.

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Appendix A

Language Background Questionnaire

YORK UNIVERSITÉ UNIVERSITY

Language Background Questionnaire

To Be Completed by Parents

PART A:

The following information refers to the CHILD:

First name:____________________ Last name:_________________________

Date of birth (DD/MM/YY):_______________________________ Gender:

____

Country of birth:__________________________

If not born in Canada, when did your child come to Canada? (MM/YY) _____________

The following information refers to PARENTS:

Country of birth of MOTHER: ___________________ If not born in Canada, when did the mother come to Canada? (MM/YY) _________________

Country of birth of FATHER: ___________________ If not born in Canada, when did the father come to Canada? (MM/YY) _________________

Please indicate the highest level of education for each parent:

Mother	**Father**
_____No high school diploma	_____No high school diploma
_____High school graduate	_____High school graduate
_____Some college or college diploma	_____Some college or college diploma
_____Bachelor's Degree	_____Bachelor's Degree
_____Graduate or professional degree	_____Graduate or professional degree
Occupation: ________________	Occupation: ________________

PART B:

Please answer the following questions about your child's language abilities:

1. a) Does your child attend any language or school program other than regular school?

Yes **No**

b) If **YES**, what program? ____________________

If **YES**, how often? Once a week Everyday Other

2. a) Does your child *understand* any language other than English?

Yes **No**

If so, what language(s)? ________________

b) Does your child *speak* any language other than English?

Yes **No**

If so, what language(s)? ________________

3. What language did your child first speak? __________________________________

4. At what age did your child first start to speak **English**?_________________________

5. Where did your child learn **English**? Home School Community Other

6. Where does your child speak **English**? Home School Family Other

7. At what age did your child first start to speak the **Other Language**?

________________ N/A

8. Where did your child learn the **Other Language**? Home School Community Other N/A

9. a) How often does your child speak the **Other Language**?

Daily Weekly Monthly Occasionally Other N/A

b) Where does your child speak this **Other Language**?

Home School Family Other N/A

10. a) How would you rate your child's <u>understanding</u> of the **Other Language**?

Poor Fair Good Very good Excellent N/A

b) How do you rate your child's <u>speaking ability</u> in this **Other Language**?

Poor Fair Good Very good Excellent N/A

11. Outside of school, does your child use **both** languages on a daily basis? YES NO N/A

12. While at home, how often does your child **switch** between using the two languages?

Never Rarely Sometimes Frequently Very frequently N/A

PART C:

We would like to know more about the languages used in your home. Please use the 5-point scale below to indicate the balance between the two languages for each activity.

Legend for the 5-point scale:

1 = all English
2 = mostly English
3 = both languages equally
4 = mostly Other Language
5 = all Other language

	All English				No
English					
1. Language spoken by your child	1	2	3	4	5
2. Language spoken among adults at home	1	2	3	4	5
3. Language spoken to child at home	1	2	3	4	5
4. Language spoken among siblings *N/A*	1	2	3	4	5
5. Language YOU watch TV/videos in	1	2	3	4	5
6. Language your child watches TV/videos in	1	2	3	4	5
7. Language YOU read Newspaper/Books, etc.	1	2	3	4	5

8. How often do adult(s) read to your child in:

a) **English**

Never Rarely Sometimes Frequently Very frequently

b) **Other Language**

Never Rarely Sometimes Frequently Very frequent

Appendix B

Sample Consent Form

INFORMED CONSENT

Study Name: Inhibition of responses in young monolingual and bilingual children: Evidence from ERP

Researcher: Raluca Barac, PhD student, Atkinson Building room 508, phone 416 736 2100 ext. 66217 under the supervision of Dr. Ellen Bialystok, Behavioral Science Building room 234, phone 416 736 2100 ext. 66109

Purpose of the Research. Our research in the past few decades has shown that bilingual children outperformed monolingual peers on several behavioural measures of nonverbal cognitive abilities. Research with monolingual and bilingual adults demonstrated the same results at the behavioural level, and additionally, it showed that the brain processing related to these tasks was influenced by the bilingualism experience. The purpose of the study is to build on the current findings and examine whether the brain processing of non-verbal cognitive tasks is also different in bilingual children compared to monolinguals, finding already confirmed in the adult samples.

What You will be Asked to Do in the Research

The child participant will be asked to complete some paper-based and computer-based cognitive tasks, for example:

- To watch a pattern made with colored blocks and reproduce the pattern
- To say what different words mean
- To watch a computer screen and make decisions about various stimuli that are presented (e.g., whether the five fish on the screen swim in the same or in different directions, etc.)

- To watch a computer screen and respond to some stimuli (e.g., white geometric shapes) but refrain from responding for other stimuli (purple geometric shapes)

All the tasks are developmentally appropriate and will be administered by trained research assistants. During this study, for the task that was described last, we will record the electrical responses of the brain. The recordings that we take are similar to those of routine clinical "electroencephalogram" (brain-wave recording). Prior to the recording, several electrodes will be placed on the scalp, face and neck. The skin is rubbed slightly and the electrodes are attached with a sticky paste. The electrodes on the scalp are kept in place by an elastic hat that fits over the head. When the electrodes are taken off, the electrode paste is removed with water. We will remove as much of it as possible. Should any remain, it will come out with the next shampoo. The skin under the electrode may occasionally be slightly reddened for a little while after the recording but this soon returns to normal.

We will provide the child with clear instructions and examples at the beginning of each task so that the child will know what to do. When using the computer, the child will answer by using the mouse. If the child does not know how to use a mouse, we will show him/ her how to use one. We will provide the child with breaks throughout the testing time if he/ she wishes to take them, and we will answer any questions that they may have. The study will take about 2 hours. The child will be given small gifts and stickers for their participation.

Risks and Discomforts. We do not foresee any risks or discomfort from the participation in the research. However, if the child feels uncomfortable or becomes tired, he/ she can take a break whenever they want.

Benefits of the Research and Benefits to You. The child will not receive direct benefit from being in this study. However, your child's participation will facilitate our understanding of the role of bilingualism in cognitive development. The results can be applied to assist educators and healthcare professionals to work with adults from various age groups.

Voluntary Participation. Your child's participation in the study is completely voluntary and you/ your child may choose to stop participating at any time. Your decision not to volunteer will not influence the treatment you may be receiving, the nature of the ongoing relationship you may have with the researchers or study staff, or the nature of your relationship with York University either now, or in the future.

Withdrawal from Study. You can stop participating in the study at any time, for any reason, if you or your child so decide. If you or your child decide to stop participating, you will still be eligible to receive the promised compensation for agreeing to be in the project. Your decision to stop participating, or to refuse to answer particular questions, will not affect your relationship with the researchers, York University, or any other group associated with this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible.

Confidentiality. The information (data) we get from your child will not be associated with any identifying information. All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your child's name will not appear in any report or publication of the research. Your child's data collected through paper-and-pencil and mouse-press will be stored on the computer and in a paper format. Your child's data will be safely stored in a locked file cabinet for seven years, after which it will be destroyed. Only research staff will have access to this information. Confidentiality will be provided to the fullest extent possible by law. Only group averages, and not information about individual performance, will be reported in the results included in future publications.

Questions About the Research? If you have any questions about the research in general or about your role in the study, please feel free to contact the principal investigator, Raluca Barac, at (416) 736-2100 ext. 66217 or Dr. Ellen Bialystok, either by phone at (416) 736-2100 x 66109 or by e-mail (ellenb@yorku.ca). This research has been reviewed and approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, York Research Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).

Legal Rights and Signatures:

I, ____________________, give consent for my child ________________________ to participate in *"Inhibition of responses in young monolingual and bilingual children: Evidence from ERP"* conducted by _______________________. I have understood the nature of this project and give permission for my child to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature ______________________ **Date** __________________
Participant (Parent/ Guardian)

Signature ______________________ **Date** __________________
Principal Investigator