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Changes in Executive Function over time in bilingual and monolingual school-aged children

Ji Sook Park,
University of Toronto

Susan Ellis Weismer, and
University of Wisconsin-Madison

Margarita Kaushanskaya
University of Wisconsin-Madison

Abstract

We examined the development of three EF components – inhibition, updating, and task shifting – over time in monolingual and bilingual school-aged children. We tested 41 monolingual and 41 simultaneous bilingual typically developing children (ages 8–12) on non-verbal tasks measuring inhibition (the Flanker task), updating (the Corsi blocks task), and task shifting (the Dimensional Change Card Sort task; DCCS) at two time points, one year apart. Three indexes of task shifting (shifting, switching, and mixing costs) were derived from the DCCS task. The two groups did not differ in their development of updating, but did demonstrate distinct patterns of development for inhibition. Specifically, while the bilingual group demonstrated a steep improvement in inhibition from Year 1 to Year 2, the monolingual group was characterized by stable inhibition performance over this time period. The two groups did not differ in their developmental patterns for shifting and switching costs, but for mixing costs, the bilingual children outperformed the monolingual children in both years. Together, the findings indicate that bilingual experience may modulate the developmental rates of some components of EF but not others, resulting in specific EF performance differences between bilinguals and monolinguals only at certain developmental time points.

Keywords

bilingualism; inhibition; updating; task shifting; longitudinal approach

In the current study, we examined the developmental growth rates of executive function (EF) in two groups of school-aged children: monolingual and bilingual. Such a longitudinal and multi-faceted approach to studying EF contributes to the current state of the literature in two ways. First, it steps beyond the cross-sectional comparisons between bilingual and monolingual children, and considers the possibility that developmental patterns of EF may interact with experience thus informing the highly contentious literature on bilingualism and

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Address correspondence to Margarita Kaushanskaya, Waisman Center, University of Wisconsin-Madison, 1500 Highland Avenue, Madison, WI 53705. Phone: (608) 263-5764. kaushanskaya@wisc.edu.

EF. Second, it considers multiple components of EF within the same sample of participants thus generating important information regarding the specificity of the effects that bilingual experience may (or may not) have on EF.

Bilingual Influences on EF

Executive Function (EF) refers to a set of top-down cognitive processes that regulate thoughts and behavior (Diamond, 2013). Although the structure of EF continues to be debated, one common approach is to construe EF as interrelated but separable components (e.g., see Diamond, 2013 for a review). The common components of EF are: *inhibition* (the ability to focus on target information while ignoring irrelevant information), *updating* (the ability to maintain and incorporate new information in working memory), and *task shifting* (the ability to flexibly switch between different mental rules or tasks). This particular structure of EF has been identified in adults and confirmed in school-aged children (see Bardikoff & Sabbagh, 2017 for review).

The theoretical framework that formalizes the relationship between bilingual experience and EF is the Inhibitory Control (IC) model (Green, 1998). The foundational aspect of the IC model is the assumption that both languages are active when bilinguals comprehend and produce words in a target language (for review, see Kroll, Dussias, Bogulski, & Valdes-Kroff, 2012). As a result, bilinguals are required to continuously control their cross-language co-activation in order to select and maintain the target language. Control is also necessary for bilinguals to purposefully switch between languages according to a given context, without interference from the unintended language. The Inhibitory Control (IC) model (Green, 1998) posits that a top-down domain-general cognitive system monitors and regulates two languages whenever bilinguals engage in language tasks. The IC model is supported by neuroimaging studies which show that bilingual language processing can be localized to neural regions associated with monitoring and inhibiting interference (see Luk, Green, Abutalebi, & Grady, 2012 for a reviews). One prediction of the IC model is that bilinguals’ need to exercise a greater degree of control over their linguistic system than monolinguals leads bilinguals to develop more efficient EF mechanisms.

Inhibition has been the central focus of the work linking bilingual experience to EF because it has been hypothesized to be at the root of bilinguals’ ability to select and maintain the activation of the target language and resolve conflicts between two linguistic systems (see Kroll et al., 2012; Luk et al., 2012). Consistent with this hypothesis, bilinguals’ performance on many nonverbal inhibition tasks has been reported to be superior to monolinguals’, including the Simon task (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Poarch & Van Hell, 2012) and flanker-type tasks (e.g., Poarch & Van Hell, 2012; Yang, Yang, & Lust, 2011). However, these positive findings are currently being re-evaluated because a number of recent studies have presented evidence indicating the absence of bilingual advantages for inhibition, with monolinguals and bilinguals performing similarly on the Simon task (e.g., Gathercole et al., 2014; Morton & Harper, 2007) and flanker-type tasks (Antón et al., 2014; Paap & Greenberg, 2013).

In addition to inhibition, updating and task shifting have been scrutinized for bilingual effects, although to a much lesser extent. The link to updating has been rooted in the logic that bilinguals may employ updating skills to maintain representations of interlocutors, discourse, and context in working memory (Morales, Calvo, & Bialystok, 2013). Consistent with this hypothesis, bilinguals have been reported to outperform monolinguals on nonverbal updating tasks such as Corsi blocks tasks (Luo, Craik, Moreno, & Bialystok, 2013) and the Dot Matrix task (e.g., Blom et al., 2014). However, in a number of studies, monolinguals and bilinguals were found to perform similarly on nonverbal updating tasks such as Corsi blocks tasks (Bialystok et al., 2008) and the Dot Matrix task (Engel de Abreu, Cruz-Santos, Tourinho, Martin, & Bialystok, 2012).

Task shifting has also been hypothesized to be influenced by bilingual experience because bilinguals must continuously monitor their communication contexts to select the appropriate language for their interlocutors (Hernández, Martin, Barceló, & Costa, 2013) and switch back and forth between two languages (Prior & MacWhinney, 2010). The study of task shifting is complicated by the fact that task shifting measures tend to be more complex than inhibition and updating measures, and yield multiple indexes of performance that may capture somewhat distinct EF skills. A typical shifting task such as the Dimensional Change Card Sorting task (DCCS), for example, requires a participant to sort cards based on one of two rules (e.g., color vs. shape) in three different conditions: pre-shift (the condition that requires participants to abide by only one rule), post-shift (the condition that requires participants to apply the other rule), and mixed (the condition that requires participants to sort cards based on either of the two rules according to a given cue for each trial).

The DCCS task yields three distinct indices of performance – shifting costs, switching costs, and mixing costs. Shifting costs are defined as the difference between the pre-shift and the post-shift condition and index the ability to overcome perseveration (e.g., Frye, Zelazo, & Palfai, 1995). Switching costs are defined as the difference between non-switch and switch trials in the mixed condition and index the recurring flexibility or the ability to flexibly shift back and forth between dimensions or rules (e.g., Prior & MacWhinney, 2010). Finally, mixing costs are defined as the difference between the trials in the pre-shift condition and non-switch trials in the mixed condition, and index monitoring ability (e.g., Prior & MacWhinney, 2010). A number of studies have shown that bilinguals outperform monolinguals on task-shifting measures (shifting costs - Okanda, Moriguchi, & Itakura, 2010; mixing costs - Barac & Bialystok, 2012; switching costs - Prior & MacWhinney, 2010). However, while some studies have reported bilingual advantages in mixing costs but not in switching costs (Barac & Bialystok, 2012), at least one study has observed the opposite pattern of results (Prior & MacWhinney, 2010). Furthermore, a number of studies have failed to observe performance differences between bilinguals and monolinguals on any of the task-shifting measures (Paap & Greenberg, 2013).

Prominent explanations for the lack of consistency in the bilingual EF literature focus on variability across studies in task parameters (e.g., task complexity: Costa et al., 2009; task impurity and lack of convergent validity: Paap & Sawi, 2014; nonverbal vs. verbal tasks: Calvo et al., 2016), group differences in demographic characteristics (e.g., SES: Morton & Harper, 2007; culture: Tran, Arredondo, & Yoshida, 2015), and language profiles in bilinguals (e.g., language proficiency/balance: Yow & Li, 2015; age of acquisition: Pelham & Abrams, 2014; language switching experience: Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016). The fluctuations in particular languages spoken by the bilinguals and the degree of overlap between them (e.g., languages that overlap orthographically vs. languages that do not; Coderre & van Heuven, 2014), as well as in the socio-cultural and political context within which bilinguals function (e.g., countries where bilingualism is the norm vs. countries where it is an exception, Blom, Boerma, Bosma, Cornips, & Everaert, 2017) also likely lead to distinct findings in the bilingual EF literature. The goal of the present study was to consider one alternative possibility: That the course of EF development may interact with bilingual experience, such that group differences on EF measures may be observable only at certain developmental time points.

Development of EF

The developmental timeline of the three EF components is linked to the development of the prefrontal cortex and the formation of the connections between the prefrontal and the parietal cortex (Collette et al., 2005). EF develops on a protracted timeline, consistent with the prolonged maturation rates of the neural substrates that are associated with EF (Bardikoff & Sabbagh, 2017). Developmental studies indicate somewhat distinct maturation rates for inhibition, updating, and task-shifting, such that updating and shifting manifest a more protracted developmental trajectory than inhibition (e.g., Best & Miller, 2010; Diamond, 2013). Inhibition abilities improve throughout early childhood (see Best & Miller, 2010 for a review) and begin to approach maturity before or at 12 years of age (Ridderinkhof & Van der Molen, 1995; Rueda et al., 2004). Conversely, task shifting (e.g., Davidson et al., 2006; Huizinga et al., 2006) and updating (e.g., Brocki & Bohlin, 2004; De Luca et al., 2003) continue to mature through adolescence or even young adulthood (Huizinga et al., 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004). We take the somewhat distinct developmental trajectories of EF components as a starting point of our inquiry and ask: Is it possible that different EF components are differentially sensitive to the effects of bilingual experience at different developmental time points?

The hypothesis that different EF components will be differentially affected by bilingualism is rooted in the Inhibitory Control model (Green, 1998), which explicitly links inhibition and task-shifting skills to bilingualism. That is, inhibition and task-shifting (but not updating) are hypothesized to be specifically engaged by bilinguals’ need to manage cross-linguistic competition (see Marian, Bartolotti, Rochanavibhata, Bradley, & Hernandez, 2017 for a review). However, the IC is not a developmental model, and does not account for changes in the EF that occur with maturation and with increased experience and expertise. Yet, empirical work strongly suggests that the EF system undergoes significant changes over the course of development (Best & Miller, 2010; Diamond, 2013 for reviews). The functionality of the EF system may dictate the degree to which it becomes involved in managing cross-linguistic competition in bilinguals. For instance, as inhibition becomes more efficient, its involvement in the management of linguistic competition may strengthen, especially in childhood, when linguistic skills continue to develop as well. As the result, the likelihood of finding a positive effect of bilingualism upon inhibition may increase as children become older.

The Current Study

In the current study, we aimed to contribute to the current bilingual EF literature in two ways. First, we suggest that a consideration of multiple EF components within the same sample of participants can yield important information regarding the specificity of the effects that bilingual experience may (or may not) have on EF. Second, we suggest that in studies of EF in children, it is important to consider the rates of EF development because developmental patterns may interact with experience differently for specific EF components. The vast majority of prior studies have targeted the question of bilingual effects on EF through cross-sectional designs (e.g., Antón et al., 2014; Bialystok, Craik, & Luk, 2008), and only a few studies have employed a longitudinal design (Blom et al., 2014; Tran et al., 2015). In one longitudinal study focusing on inhibition, Tran et al. (2015) found that when monolingual and bilingual children were tested every six months over a period of two years (3 – 5 years old), bilingual advantages on the Attention Network Task were observed only at two out of the six time points dispersed throughout this period. In another longitudinal study examining updating, Blom et al. (2014) found that bilingual children outperformed their monolingual peers at six years of age, but not at five years of age on a nonverbal updating task, but only when controlling for age, SES, and Dutch receptive vocabulary.

These longitudinal studies indicate that bilingual and monolingual children may show different levels of EF performance at different ages for different EF components. However, these studies focused on a single EF component, and on young children (3–6 years old). Since EF development spans the school-aged years, examining EF development within an older age group may yield more revealing data with respect to how the development of different EF components may interact with language experience. This is especially crucial for any study attempting to examine multiple EF components, since in younger children (3–6 years old) the EF system is characterized by greater integration, forming one factor in factor studies; conversely, in school-age children, separation of EF into individual (but related) components such as inhibition, updating, and task shifting can be observed (see Bardikoff & Sabbagh, 2017 for review). We chose to study children over a one-year period because extending the study into older ages would take us into the adolescent period. Given that adolescents go through cognitive regression due to neural reorganization (Taylor, Barker, Heavey, & McHale, 2015), and given the lack of empirical work examining the effect of bilingualism on EF in adolescence, we decided to only study the children over a single year.

In summary, in the present study, we examined the developmental rates of three EF components – inhibition, updating, and task shifting – in bilingual and monolingual school-aged children. The children were tested twice, a year apart. Based on the IC model (Green, 1998), we hypothesized that bilingualism would be more likely to affect performance on the inhibition and task-shifting measures than the updating measure. Based on the empirical literature strongly indicating that EF components undergo significant improvements in childhood (Best & Miller, 2010; Diamond, 2013), we hypothesized that their involvement in the management of linguistic competition may also change with development. Such fluctuations in the degree to which EF components would be involved in bilingual language processing may give rise to bilingual effects upon EF at some developmental points, but not others. This second hypothesis is necessarily exploratory due to the fact that there are no existing theories regarding the interaction between language experience and developmental trajectories of EF in bilinguals.

Method

Participants

Eighty-two typically-developing school-age children - 41 English-speaking monolinguals (20 males) and 41 English-Spanish speaking bilinguals (23 males) participated. A power analysis using the Power ANalysis for GEneral Anova designs program (PANGEA v. 02; Westfall, 2016) indicated that a sample of 41 participants per group with a minimum of 2 trials per condition and a small-to-medium effect size (d =.35) would yield at least 99.9% power to detect the significant interactions between language experience and time in the Flanker and DCCS tasks using the linear mixed effects model analysis. For the Corsi-block task, this analysis indicated that a sample of 41 participants per group with a small-to-medium effect size (d=.35) would yield 82.6% power to detect the critical interaction between language experience and time.

The children were drawn from a larger longitudinal study of language and Executive Function development in children. All children attended English-speaking elementary schools. In the first year of testing (Year 1), the children were between 8 and 10 years of age ($M_{monolingual}$ = 9.39, SD = 0.98; $M_{bilingual}$ = 9.42; SD = 1.03). The same children were re-tested a year later (Year 2; $M_{monolingual}$ = 10.40, SD = 0.97; $M_{bilingual}$ = 10.45, SD = 1.04). The bilingual children experienced exposure to both English and Spanish before 3 years old (mean age of acquisition of English = 10.24 months, SD = 14.51; mean age of acquisition of Spanish = 1.93 months, SD = 7.87). A parent questionnaire revealed that for the bilingual children, in the first year of testing, the mean ratio of language exposure was 56% (English) to 44% (Spanish), indicating that the sample as a whole was English-dominant. Monolingual children were selected from the larger sample (N = 64) to match the bilingual children. Children's chronological age was the first matching variable. Once children's ages were matched, we then selected monolingual participants to match the bilingual participants in non-verbal IQ. All monolingual children were native speakers of English with no exposure to a language other than English, either at home or in school. All children had normal hearing and vision, and no history of language impairment or developmental disabilities, per parent report.

Procedure

All procedures for this study were approved by the University of Wisconsin-Madison Institutional Review Board (Protocol Number SE-2011-0818, "Executive Function in Children with Typical and Atypical Language Abilities"). Children were tested in two sessions, with each session lasting 1.5–2 hours. During the first session, children were administered standardized tests assessing nonverbal intelligence and a broad range of language skills. During the second session, children completed all the EF tasks in randomized order. The caregivers completed questionnaires to obtain information on the children's demographic information such as years of maternal education (which is often used as a proxy measure of socioeconomic status; Hoff, 2006), background information regarding general development, as well as speech and language, medical, and educational history. Primary caregivers of bilingual children were interviewed in their preferred language (English or Spanish) to obtain detailed information on their children's school history, language development, language immersion, language dominance, and language exposure in each language.

Standardized tests

All children were administered a battery of standardized language and cognitive tests at Time 1. The Perceptual Reasoning Index of the Wechsler Intelligence Scale for Children - Fourth Edition (WISC-IV; Wechsler, 2003) was used to measure children's nonverbal intelligence. Children's receptive and expressive English language abilities were measured using the Clinical Evaluation of Language Fundamentals - Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003). The bilingual children's Spanish language abilities were measured using the Spanish Clinical Evaluation of Language Fundamentals – 4th edition (Wiig, Semel, & Secord, 2006). See Table 1 for children's demographic information and performance on the standardized tests. The group comparisons indicate that there were no group differences in chronological age, sex, and nonverbal intelligence; however, there were significant differences in maternal education and English language abilities between the two groups, such that monolingual children were characterized by higher levels of maternal education and English language abilities than bilingual children.

Non-verbal EF measures

Detailed information and figures representing each of the EF tasks is included in Online Supplementary Materials.

Inhibition—A child-appropriate, non-verbal version of the Flanker task was used to measure inhibition skills. The Flanker task has been used widely by prior studies to index inhibition skills in children (e.g., Weintraub et al., 2013; Yang et al., 2011). Children were asked to press a left or right button corresponding to the direction of the middle target while disregarding surrounding stimuli. Children were directed to respond as accurately and quickly as possible, and both accuracy and RTs were collected.

Updating—A nonverbal Corsi blocks task was used to assess children's updating ability. The Corsi Blocks task is a broadly used measure of nonverbal updating (e.g., Diamond, 2013; Morales et al., 2013). Nine identical boxes were randomly positioned on the computer screen; on each trial, these boxes lit up in a particular sequence. Children were asked to remember and click on the boxes in the same order that they lit up, using a computer mouse. The Corsi blocks task only yields accuracy data; the highest level at which the child correctly responded on 2 out of 3 trials was used for the analyses.

Task Shifting—The DCCS task was used to measure children's task-shifting ability. The DCCS task is a commonly used task-shifting measure (e.g., Frye, Zelazo & Palfai, 1995; Morton, Bosma, & Ansair, 2009). Both accuracy and RTs were collected for the DCCS task. Three different variables indexing different aspects of shifting performance were derived from the DCCS task: *shifting costs* (pre-shift minus post-shift trials); *switching* costs (non-switch minus switch trials in the mixed condition); and *mixing costs* (pre-shift minus non-switch trials in the mixed condition).

The performance measure for the Corsi-blocks task was an accuracy measure indexing the maximum capacity level. For the flanker and DCCS tasks, the primary performance measures were RT-based, because in line with adult studies (e.g., Prior & MacWhinney, 2010), our versions of the two tasks yielded very high levels of accuracy. Only RT trials for correct responses were analyzed. Trials that were under 150 ms from the onset of the stimuli presentation and trials that were more than 2.5 SDs above or below the individual participant's mean were excluded. Following these data-cleaning procedures, an average of 2.82% (min: 2.50% – max: 3.08%) of trials were removed for the RT analyses across tasks.

Results

We conducted linear mixed effects models to analyze the data in R, version 3.2.2 (R Core Team, 2015) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015). In each model, as fixed effects, we entered group (monolinguals vs. bilinguals), time (Year 1 and Year2), and condition as well as the two-way interactions (group x time, group x condition, time x condition), and the three-way interactions (group x time x condition). For the Corsi blocks task, only group (monolinguals vs. bilinguals), time (Year 1 and Year2), and their interaction (group x time) were included because condition was not relevant to the Corsi Blocks task. We included the random intercepts for subjects as well as by-subjects random slopes for the effects of time, condition, and the interaction between time and condition. Given that there was a group difference in SES which may influence EF performance (e.g., Hackman, Gallop, Evans, & Farah, 2015), maternal education was entered as a control variable in all the models. Across all the EF tasks, maternal education was not a significant predictor.

Inhibition (Flanker task)

See Figure 1 for the graphical representation of monolingual and bilingual children's changes in flanker performance over time. There was a significant main effect of time, $t = -3.59$, $p < .001$, indicating that children became more efficient from Year 1 ($M = 614.08$, $SD = 123.31$) to Year 2 ($M = 572.56$, $SD = 112.75$). There was also a significant main effect of condition, $t = 10.86$, $p < .001$, indicating that children were faster in the neutral condition ($M = 569.84$, $SD = 111.13$) than in the incongruent condition ($M = 616.79$, $SD = 123.81$). No other coefficients in the model were significant. However, a significant three-way interaction was revealed among time, condition, and group, $t = -3.00$, $p = .003$ (See Table 3).

To identify the locus of the interaction, follow-up analyses were conducted within each group. When the reference group was changed to the monolingual group, the results revealed that there was a significant main effect of condition, $t = 7.50$, $p < .001$, indicating that the monolingual children were faster in the neutral condition than the incongruent condition. However, there was no significant main effect of time, $t = -1.63$, $p = 0.108$, and the two-way interaction between time and condition was also not significant, $t = 1.74$, $p = 0.083$. These results indicate that for the monolingual group, there were no significant developmental changes in RTs for the neutral condition or the incongruent condition.

When the reference group was changed to the bilingual group, there was a significant main effect of condition, similar to the monolingual group, $t = 7.86$, $p < .001$. However, unlike for the monolingual group, for the bilingual group, there were a significant main effect of time, $t = -3.46$, $p < .001$, such that bilinguals demonstrated more efficient flanker performance in Year 2 than in Year 1. There was also a significant two-way interaction between time and condition for the bilinguals, $t = -2.51$, $p = .013$. Over time, bilingual children became more efficient in the incongruent condition ($t = -2.47$, $p = .016$ but remained stable in the neutral condition ($t = -4.07$, $p < .001$).

When the mean difference scores between the incongruent and neutral conditions were compared between the groups in each year, the results revealed that in Year 1, the two groups exhibited comparable inhibition skills, $t = -1.77$, $p = .081$. However, in Year 2, the bilingual children demonstrated significantly better inhibition (i.e., less negative RT difference scores) than the monolingual children, $t = 2.11$, $p = .038$. Note that one bilingual participant whose difference score RT (z scored) exceeded −3.29 was considered an outlier and was omitted from the difference-score analysis.

Updating (Corsi blocks task)

See Figure 2 for the graphical representation of monolingual and bilingual children's changes in Corsi blocks performance over time. There was a significant main effect of time, $t = 2.86$, $p = .005$, with children showing improvement in their updating skills from Year 1 (M = 4.67, SD = 0.95) to Year 2 (M = 4.99, SD = 1.18). However, neither the main effect of group, $t = 1.24$, $p = .217$, nor the interaction between time and group was significant, $t = 0.51$, $p = .610$ (See Table 4).

Shifting (DCCS task)

Given that the three outcomes were drawn from the same task, the Bonferroni correction for multiple comparisons was applied. The adjusted critical p value was .008 for the two interaction terms of particular interest: the two-way interaction (Condition x Group) and the three-way interaction (Time x Condition x Group).

Shifting Costs (Pre-shift vs. Post-shift)—See Figure 3 for the graphical representation of monolingual and bilingual children's changes in shifting costs over time. There was a significant main effect of time, $t = -5.00$, $p < .001$, where all children showed improvement in their shifting skills from Year 1 (M = 687.73, SD = 256.60) to Year 2 (M = 604.45, SD = 176.98). There was also a significant main effect of condition, $t = 11.13$, $p < .001$, indicating that children were faster in the pre-shift condition (M = 543.98, SD = 114.14) than in the post-shift condition (M = 748.19, SD = 258.37). In addition, a significant two-way interaction was revealed between time and condition, $t = -2.50$, $p = .015$. The results indicate that over time, children showed more improvement in the post-shift condition, $t = -4.66$, $p < .001$ (Year 1: M = 816.03, SD = 288.99; Year 2: M = 680.36, SD = 201.97) than in the pre-shift condition, $t = -1.96$, $p = .053$ (Year 1: $M = 559.43$, $SD = 123.50$; Year 2: $M = 528.54$, $SD = 101.61$). No other coefficients in the model were significant (See Table 5).

Switching costs (MixedNonSwitch vs. MixedSwitch)—See Figure 4 for the graphical representation of monolingual and bilingual children's changes in switching costs over time. There was a significant main effect of time, $t = -5.80$, $p < .001$, where all children showed improvement in their switching skills from Year 1 ($M = 1175.00$, $SD = 339.06$) to Year 2 ($M = 1016.81$, $SD = 307.38$). There was also a significant main effect of condition, $t = 12.86$, $p < .001$, indicating that children were faster in the mixed non-switch condition ($M = 1004.76$, $SD = 281.83$) than in the mixed switch condition ($M = 1187.06$, $SD = 354.83$). No other coefficients in the model were significant (See Table 6).

Mixing costs (Pre-shift vs. MixedNonSwitch)—See Figure 5 for the graphical representation of monolingual and bilingual children's changes in mixing costs over time. There was a significant main effect of time, $t = -4.92$, $p < .001$, where all children showed improvement from Year 1 ($M = 818.25$, $SD = 338.65$) to Year 2 ($M = 730.49$, $SD = 282.98$). There was also a significant main effect of condition, $t = 25.54$, $p < .001$, indicating that children were faster on the trials in the pre-shift condition ($M = 543.98$, $SD = 114.14$) than on the non-switch trials in the mixed condition ($M = 1004.76$, $SD = 281.83$). In addition, a significant two-way interaction was revealed between time and condition, $t = -2.79$, $p = .006$. Over time, children showed more improvement for the non-switch trials in the mixed condition, $t = -5.37$, $p < .001$ (Year 1: $M = 1077.06$, $SD = 283.11$; Year 2: $M = 932.45$, $SD = 261.25$) than for the trials in the pre-shift condition, $t = -1.93$, $p = .055$ (Year 1: $M = 559.43$, $SD = 123.50$; Year 2: $M = 528.54$, $SD = 101.61$).

Notably, there was a significant two-way interaction between condition and group, $t = -3.25$, $p = .002$. The critical p value after the Bonferroni correction was .008, indicating that the interaction was significant after adjusting for multiple comparisons. Follow-up analyses revealed that there was no difference between bilinguals and monolinguals in the pre-shift condition (collapsed across time), $t = 0.99$, $p = .325$ (Monolinguals: $M = 532.44$, $SD = 100.30$; Bilinguals: $M = 555.53$, $SD = 125.41$). In contrast, there was a significant group difference for the non-switch trials in the mixed condition (collapsed across time), $t = -2.10$, $p = .039$, such that bilinguals ($M = 941.80$, $SD = 237.61$) were faster than monolinguals (Monolinguals: $M = 1067.71$, $SD = 307.36$). No other coefficients in the model were significant (See Table 7).

When the mean difference scores between the trials in the pre-shift condition and the non-switch trials in the mixed condition were compared between the two groups, the results revealed that the bilingual children exhibited smaller mixing costs (i.e., less negative RT difference scores) than the monolingual children in Year 1, $t = 2.70$, $p = .009$ and in Year 2, $t = 2.59$, $p = .011$. The results indicate that the bilingual children demonstrated significantly better monitoring skills than the monolingual children across both time points.

Discussion

Our findings highlight the usefulness of a longitudinal and multifaceted approach when investigating bilingual influences on EF. Consistent with prior findings, we found that the monolingual children demonstrated different developmental patterns for the three EF components. That is, in monolingual children, inhibition skills were stable (i.e., mature) in late childhood (Ridderinkhof & Van der Molen, 1995; Rueda et al., 2004), while updating and task-shifting continued to develop during this time period (Davidson et al., 2006; Scherf et al., 2006). Unlike the monolingual group, the bilingual group exhibited maturation of skills across the three components of EF during the targeted age-range, including inhibition. The outcome of such different developmental rates for inhibition across the two groups was that the two groups of children were comparable in inhibition skills in Year 1, but the bilingual children outperformed the monolingual children in inhibition skills in Year 2. The two groups did not differ in their development of updating skills or of shifting and switching sub-domains of task-shifting ability. However, the bilingual children demonstrated more efficient monitoring skills (indexed by the mixing costs on the DCCS) than the monolingual children, and this effect was stable over time.

Examining inhibition, updating, and task-shifting over time

Our findings for *inhibition*, with comparable inhibition skills between monolingual children and bilingual children in Year 1 but not Year 2, is significant, in that that both sets of findings have precedents in the literature. That is, the Year 1 results are consistent with studies that have reported *no* bilingual advantages in inhibition in childhood (e.g., Antón et al., 2014; Duñabeitia et al., 2014). At the same time, the Year 2 results are entirely consistent with a number of studies that have yielded bilingual advantages in inhibition in childhood (e.g., Poarch & Van Hell, 2012; Yang et al., 2011). Had we examined inhibition during only one of these time points, we would have arrived at an erroneous conclusion about how bilingualism influences inhibition. The current study enabled us to observe that bilingual children experienced a greater improvement in inhibition than monolingual children over time, and it was this difference between groups in the growth rates of inhibition that yielded bilingual advantages in Year 2. In the bilingual EF literature, it is inhibition that has received the greatest amount of attention as the cognitive skill that is most likely to benefit from bilingual experience (Kroll et al., 2012). In the IC model, inhibition has been hypothesized to play a key role in bilinguals' ability to successfully resolve competition between their two languages (Green, 1998). Consistent with this hypothesis, the development of inhibition skills in bilingual children may extend over a longer developmental period to support the challenge of using the two languages. This continued recruitment of inhibitory control by bilingual children may yield a steeper improvement in inhibition in this group, yielding superior bilingual performance over time.

Our findings for *updating* indicate that the two groups of children performed very similarly to each other at both time points, suggesting a null effect of bilingualism on nonverbal updating abilities within our targeted age range. This finding is consistent with the IC Model (Green, 1998), which does not draw a connection between updating and the management of linguistic competition in bilinguals. It is also consistent with prior studies that have noted a minimal impact of bilingualism upon nonverbal updating skills (e.g., Engel de Abreu, 2011; Namazi & Thordardottir, 2010). However, the results are inconsistent with other prior studies that suggested bilingual advantages in updating skills for children (e.g., Blom et al., 2014; Morales et al., 2013). Just like previous researchers who have attempted to explain the lack of consistency in the general bilingual EF literature, we consider the possibility that SES influences and task parameters may have contributed to our not finding effects of bilingualism on updating skills. For instance, in the Morales et al (2013) study, both monolingual and bilingual children were from the middle class whereas in our study, the bilingual children were characterized by lower levels of maternal education than the monolingual children. However, while the two groups did differ significantly in levels of maternal education, on average, the primary caregivers' levels of education in both groups placed them squarely within the middle-SES range. It is also important to point out that we did consider maternal education in our models, and for updating (as well as other EF measures) we found no effects of maternal education on performance. Furthermore, we found group differences in inhibition despite the maternal education discrepancy. Therefore, we believe that it is more likely that the particular parameters of the updating task may drive the likelihood of finding the effects of bilingualism. For instance, more demanding updating tasks that also load onto inhibition may be more likely to yield bilingual effects than the more "pure" updating tasks like the one used here. It is also possible that bilingual experience may modulate updating skills within a timeframe different from the one targeted in the present study.

For *task shifting*, our findings suggest that bilingual experience may modulate the development of the three indexes of task shifting in distinct ways. The bilingual children outperformed their monolingual peers only for one index of shifting abilities (i.e., mixing costs), and this effect held steady over time. In contrast, they performed very similarly to their monolingual peers on the two other shifting indexes (shifting and switching costs) at both time points. Previous studies have also observed distinct influences of bilingualism upon mixing costs and switching costs, with the majority of findings indicating bilingual advantages in mixing costs, but not switching costs (e.g., Barac & Bialystok, 2012). Our findings, together with these prior studies, lend support to the idea that the three performance measures derived from shifting tasks index somewhat distinct mechanisms, and that bilingualism is more likely to exert a positive influence on the mixing-cost measures than the shifting-cost or the switching-cost measures.

A number of prior investigations into task shifting performance have separated mixing costs from shifting and switching costs (e.g., Davidson et al., 2006; Goffaux, Phillips, Sinai, & Pushkar, 2006). This is because the three indexes of task shifting have been hypothesized to rely on somewhat distinct cognitive processes. Thus, shifting costs and switching costs have been linked with the ability to inhibit previously-relevant stimulus-response associations (Meiran, 1996) or with the ability to re-configure the relevant task sets (Rubin & Meiran, 2005). In contrast, mixing costs have been linked with the ability to recruit the monitoring system – a cognitive system whose function is to manage or resolve the interference between competing task sets (Rogers & Monsell, 1995). A number of authors have argued that the cognitive process behind the mixing costs is most closely aligned with the cognitive process that underpins bilingual language use. For example, Costa et al. (2009) suggested that bilinguals must continuously monitor their languages in bilingual settings so that they can decide which language is appropriate to use for communication. Consistent with this hypothesis, our findings suggest that the continuous use of the monitoring system by bilingual children may result in very specific enhancements to their monitoring skills, in comparison with monolingual children.

Caveats and conclusions

We observed differences in the timeline of the development for inhibition, but not for updating and task shifting, between bilingual and monolingual school-aged children. It is possible that these differences in developmental rates of EF may yield bilingual-monolingual differences at some time points in development but not others, thus contributing to the contentious bilingual EF literature. Future studies will need to examine EF development at a younger and an older age than the age targeted by the present study. Although our findings are consistent with prior studies, they may be specific to the particular time period we examined. It is also possible that our findings are specific to the particular tasks we have chosen to index the three EF components and to the particular population of bilinguals and monolinguals we have chosen to study.

Significant challenges are associated with accurately measuring a particular EF, because EF tasks are multifaceted, often tapping into multiple cognitive skills (see Diamond, 2013; Kaushanskaya et al., 2017 for reviews). For instance, although the card sorting task is considered to be a classic task-shifting measure, it also likely indexes updating of working memory (which is involved in maintaining the sorting rules in an active state) and inhibition (which is involved in suppressing prepotent responses) (Diamond, 2013). Similarly, the Corsi blocks task can be used to measure short-term memory (e.g., Ang & Lee, 2008) and working memory (e.g., Van Asselen et al., 2006), consistent with a theoretical view that short-term and working memory are aspects of the same construct (e.g., Unsworth & Engle, 2007). Because of their multifaceted nature, EF tasks are often used by different research groups to index different aspects of EF (see Kaushanskaya et al, 2017). In order to determine whether our findings are specific to the particular EF tasks we have chosen, or to the broad EF constructs they were meant to index, future studies may wish to incorporate multiple measures of the same EF construct. However, this strategy may not bring much clarity since different EF tasks purportedly measuring the same construct often fail to correlate with each other (Paap & Greenburg, 2013; Paap & Sawi, 2014).

Another issue to consider is whether our findings can generalize to other populations of bilingual and monolingual speakers. The variability in the construct “bilingualism” (related to proficiency, exposure, degree of overlap between bilinguals’ linguistic systems, etc.) as well as in factors that can shape the development of EF and that are often confounded with bilingualism (e.g., SES, birth country and/or ethnicity; social, cultural, and political contexts; etc.) likely contribute significantly to the conflicting findings regarding the bilingual effects on cognition. Systematic examination of these factors and the degree to which they influence the relationship between bilingualism and EF is an important direction for this line of research. One especially important future direction for this line of research is a focus on the dual-language context that bilinguals occupy, and an examination of whether changes in language environment contribute to changes in bilingual children's EF performance over time. Such future studies would be well-framed by the Adaptive Control Hypothesis (ACH; Green & Abutalebi, 2013), which predicts that cognitive demands of language control differ by different interactional contexts.

Finally, because there does not currently exist a developmental model of EF that would take bilingualism into account, our hypothesis regarding the possibility that bilingualism may influence EF components at different points on the developmental continuum was admittedly exploratory. The IC model (Green, 1998) is helpful in predicting a positive, and specific, effect that bilingualism may have on inhibition and task-shifting, but it is not a developmental account. It therefore does not factor in the gains in EF and language skills that take place in childhood, and makes no predictions regarding the fluctuations in bilingualism-EF relationships that may characterize the period of childhood. In cases where the existing theoretical framework fails to account for a crucial piece of empirical data (i.e., the gains in EF that take place in childhood, Best & Miller, 2010), experimental exploration can be crucial to the development of an alternative theoretical framework, or to the extension of the existing framework. Our finding that bilingual and monolingual children appear to develop inhibition skills on distinct timelines, with monolingual children plateauing in their development at 8–10 years of age, and bilingual children continuing to make gains until 9–11 years of age, was critical to understanding why group differences in inhibition were not observed in Year 1 of the study, but were observed in Year 2. The challenge for the IC model (or for an alternative theoretical account) is to explain why bilingualism would change the course of EF development, and what precise stages of cognitive development are sensitive to the effects of language experience.

Generally, the findings of the present study indicate that the patterns of group differences in EF performance may depend on ages or time points when individuals are tested. We believe that there is significant potential for a longitudinal approach in studying the effects of language experience on EF. Considering developmental trajectories of EF and measuring multiple EF components within the same sample of children may help resolve at least some of the conflicting findings regarding the effects of bilingualism on EF in childhood. In the midst of the heated debates on bilingual advantages, this study indicates the need for longitudinal work examining the influence of bilingual experience on EF at various stages of cognitive development, and for theoretical frameworks that take into account the developmental trajectories of EF and language skills.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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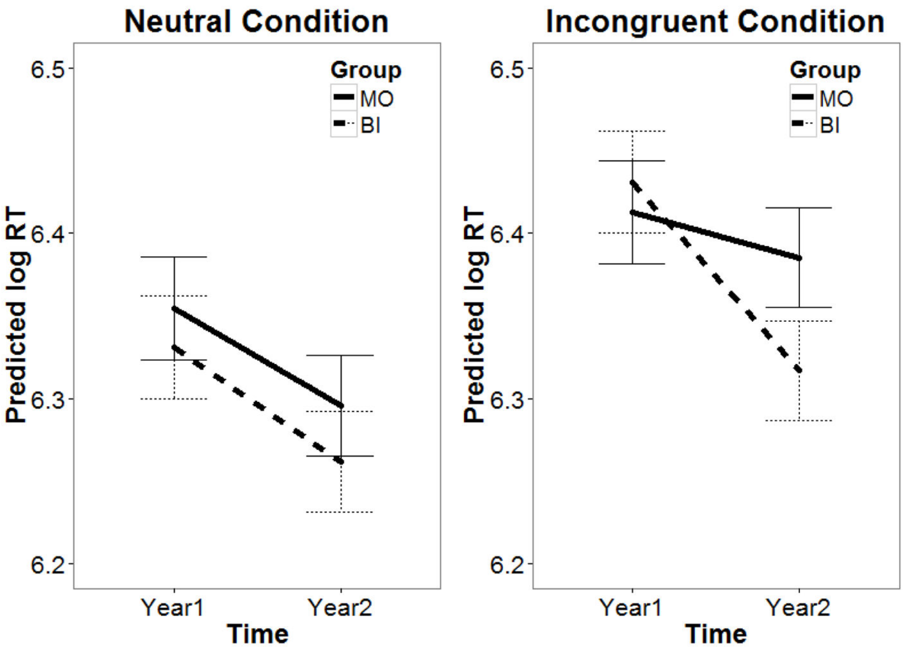

Figure 1.

Children’s inhibition performance (the Flanker task) over time.

Note: Smaller values indicate faster RT. Error bars represent ±1 standard errors.

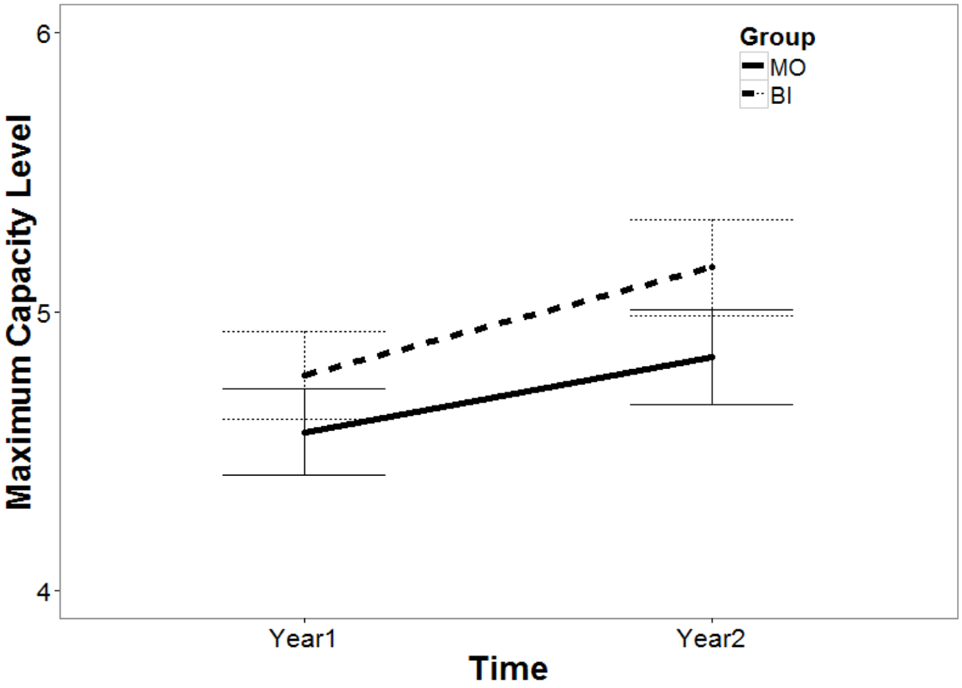

Figure 2.

Children’s updating performance (the Corsi blocks task) over time.

Note: Maximum Capacity Level indicates the highest level of difficulty at which children successfully completed at least 2 of 3 items. Larger values indicate better updating skills. Error bars represent ±1 standard errors.

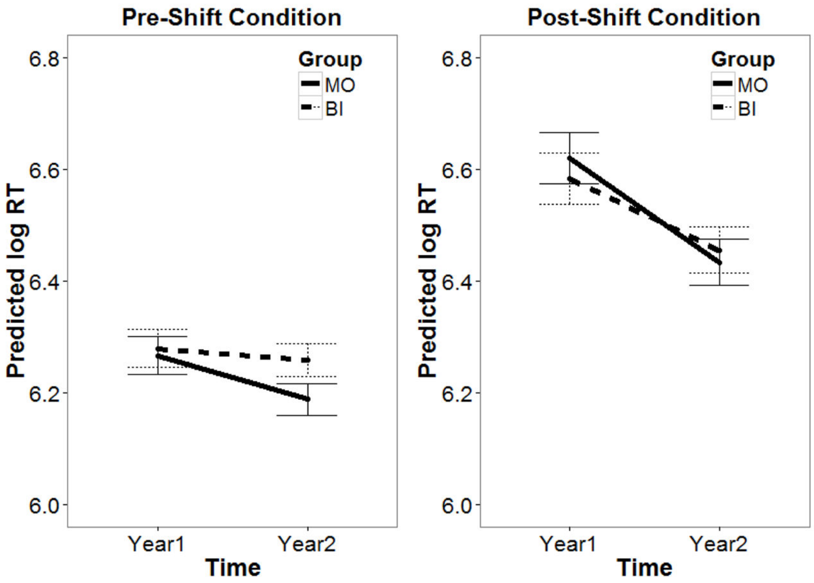

Figure 3.

Children’s shifting costs (DCCS task) over time.

Note: Smaller values indicate faster RT. Error bars represent ±1 standard error.

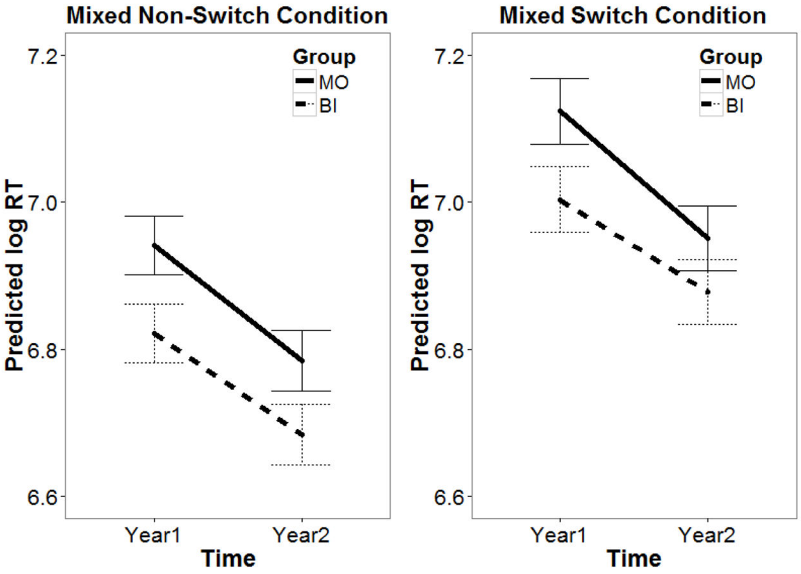

Figure 4.

Children’s switching costs (the DCCS task) over time.

Note: Smaller values indicate faster RT. Error bars represent ±1 standard errors.

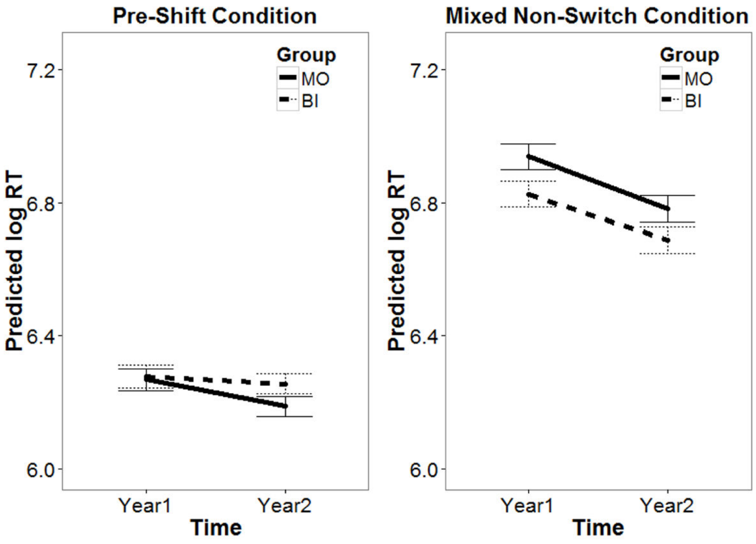

Figure 5.

Children’s mixing costs (the DCCS task) over time.

Note: Smaller values indicate faster RT. Error bars represent ±1 standard errors.

Table 1

Demographic information and performance on standardized tests for monolingual and bilingual children

		Monolinguals		Bilinguals		
		Mean	**SD**	**Mean**	**SD**	***t*-tests**
N			41 (20 males)		41 (23 males)	
Year 1 Age		9.39	0.98	9.42	1.03	$t = -0.13$
Year 2 Age		10.40	0.97	10.45	1.04	$t = -0.22$
Maternal Education[1]		17.49	2.80	14.12	4.23	$t = 4.25^{*}$
Nonverbal IQ[2]		112.23	11.73	108.67	14.04	$t = 1.22$
Year1 English CELF-4[3]		111.29	11.39	98.07	16.44	$t = 4.23^{*}$
Age of Acquisition (months)[4]	Spanish		1.93 7.87			
	English		10.24 14.51			
Year1 Spanish CELF-4[5]				87.15	13.43	
Weekly Exposure to English/Spanish (percentage)[6]				55.90/44.07	17.28/17.27	

Note.

[1] Years of maternal education: Used as proxy for SES

[2] Nonverbal IQ: Perceptual Reasoning subscale on Wechsler Intelligence Scale for Children – 4th edition (Wechsler, 2003)

[3] English CELF-4: Core Language Standard Score on Clinical Evaluation of Language Fundamentals – 4th edition (Semel et al., 2003)

[4] Age of Acquisition: Parental report of when child began hearing each language

[5] Spanish CELF-4: Core Language Standard Score on Spanish Clinical Evaluation of Language Fundamentals – 4th edition (Wiig, Semel, & Secord, 2006)

[6] Weekly Exposure: Parental report of exposure to each language during a typical week

[*] $p < .01$.

Table 2

Children’s performance on nonverbal EF measures in Year 1 and 2

		Monolinguals		**Bilinguals**		**Monolinguals**		**Bilinguals**	
		Year 1				**Year 2**			
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Inhibition (Flanker)									
	Neutral ACC	0.95	0.06	0.96	0.08	0.97	0.05	0.97	0.06
	Neutral RT	584.39	91.34	591.54	129.62	553.08	99.67	550.33	113.91
	Incongruent ACC	0.93	0.10	0.93	0.11	0.94	0.09	0.95	0.07
	Incongruent RT	621.16	99.50	659.24	149.35	605.66	109.58	581.14	117.87
Updating (Corsi Blocks)									
	Maximum Capacity	4.63	0.88	4.71	1.02	4.90	0.93	5.08	1.38
Task-Shifting (DCCS)									
Shifting costs	PreShift ACC	0.97	0.09	0.94	0.13	0.98	0.08	0.97	0.08
	PreShift RT	553.83	105.98	565.03	138.60	511.05	89.29	546.02	109.84
	PostShift RT	0.90	0.17	0.89	0.15	0.91	0.13	0.94	0.11
	PostShift RT	840.49	328.15	791.56	241.15	677.94	200.31	682.77	203.59
Switching costs	MixedNonSwitch ACC	0.89	0.11	0.89	0.12	0.94	0.07	0.92	0.07
	MixedNonSwitch RT	1150.94	313.94	1003.18	225.45	984.49	276.64	880.41	233.57
	MixedSwitch ACC	0.74	0.14	0.70	0.18	0.80	0.14	0.74	0.16
	MixedSwitch RT	1366.32	371.73	1179.57	324.88	1151.17	367.89	1051.17	269.46
Mixing costs	PreShift ACC	0.97	0.09	0.94	0.13	0.98	0.08	0.97	0.08
	PreShift RT	553.83	105.98	565.03	138.60	511.05	89.29	546.02	109.84
	MixedNonSwitch ACC	0.89	0.11	0.89	0.12	0.94	0.07	0.92	0.07
	MixedNonSwitch RT	1150.94	313.94	1003.18	225.45	984.49	276.64	880.41	233.57

Table 3

Linear Mixed-Effects Model for inhibition

	Estimate	SE	t
Intercept	6.349	0.018	351.28**
Maternal Education	−0.026	0.020	−1.30
Time (Year 1 vs. Year 2)	−0.067	0.019	−3.59**
Condition (Neutral vs. Incongruent)	0.076	0.007	10.86**
Group (Monolingual vs. Bilingual)	−0.027	0.040	−0.67
Time x Condition	−0.007	0.013	−0.54
Time x Group	−0.048	0.038	−1.29
Condition x Group	0.003	0.014	0.25
Time x Condition x Group	−0.076	0.025	−3.00*

* $p < .01$,

** $p < .001$.

Table 4

Linear Mixed-Effects Model for updating

	Estimate	SE	t
Intercept	4.834	0.096	50.59**
Maternal Education	0.154	0.105	1.46
Time (Year 1 vs. Year 2)	0.327	0.114	2.86*
Group (Monolingual vs. Bilingual)	0.263	0.211	1.24
Time x Group	0.117	0.229	0.51

* $p < .01$,

** $p < .001$.

Table 5

Linear Mixed-Effects Model for shifting costs

	Estimate	SE	t
Intercept	6.386	0.018	352.63 ***
Maternal Education	0.015	0.018	0.82
Time (Year 1 vs. Year 2)	−0.103	0.021	−5.00 ***
Condition (Pre-shift vs. Post-shift)	0.275	0.025	11.13 ***
Group (Monolinguals vs. Bilinguals)	0.017	0.039	0.44
Time x Condition	−0.107	0.043	−2.50 *
Time x Group	0.058	0.041	1.40
Condition x Group	−0.049	0.049	−1.00
Time x Condition x Group	0.001	0.086	0.01

* $p < .05$,

** $p < .01$,

*** $p < .001$.

Table 6

Linear Mixed-Effects Model for switching costs

	Estimate	SE	t
Intercept	6.898	0.024	282.78 *
Maternal Education	0.006	0.026	0.23
Time (Year 1 vs. Year 2)	−0.148	0.026	−5.80 *
Condition (Mixed non-switch vs. Mixed switch)	0.181	0.014	12.86 *
Group (Monolinguals vs. Bilinguals)	−0.103	0.054	−1.92
Time x Condition	−0.002	0.024	−0.09
Time x Group	0.033	0.051	0.64
Condition x Group	0.013	0.028	0.48
Time x Condition x Group	0.029	0.048	0.59

* $p < .001$.

Table 7

Linear Mixed-Effects Model for mixing costs

	Estimate	SE	t
Intercept	6.528	0.018	368.73[**]
Maternal Education	0.011	0.018	0.58
Time (Year 1 vs. Year 2)	−0.099	0.020	−49.19[**]
Condition (Pre-shift vs. Mixed non-switch)	0.561	0.022	25.54[**]
Group (Monolinguals vs. Bilinguals)	−0.033	0.039	−0.86
Time x Condition	−0.099	0.035	−2.79[*]
Time x Group	0.039	0.040	0.96
Condition x Group	−0.143	0.044	−3.25[*]
Time x Condition x Group	−0.039	0.071	−0.56

[*] $p < .01$,

[**] $p < .001$.