Working memory development in monolingual and bilingual children

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ABSTRACT

Two studies are reported comparing the performance of monolingual and bilingual children on tasks requiring different levels of working memory. In the first study, 56 5-year-olds performed a Simon-type task that manipulated working memory demands by comparing conditions based on two rules and four rules and manipulated conflict resolution demands by comparing conditions that included conflict with those that did not. Bilingual children responded faster than monolinguals on all conditions and bilinguals were more accurate than monolinguals in responding to incongruent trials, confirming an advantage in aspects of executive functioning. In the second study, 125 children 5- or 7-year-olds performed a visuospatial span task that manipulated other executive function components through simultaneous or sequential presentation of items. Bilinguals outperformed monolinguals overall, but again there were larger language group effects in conditions that included more demanding executive function requirements. Together, the studies show an advantage for bilingual children in working memory that is especially evident when the task contains additional executive function demands.

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Introduction

It is now recognized that a variety of cognitively demanding experiences modulate brain development and, by extension, modify cognitive functioning (e.g., Green & Bavelier, 2003; Maguire et al., 2000; Polk & Farah, 1998; Salthouse & Mitchell, 1990). The modification to cognitive functioning

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typically follows from intensive practice in a particular process entailed by the experience. For example, video game players have superior spatial resolution of visual processing, presumably because of the practice obtained during gaming (Green & Bavelier, 2003). The exercise of speaking two or more languages on a daily basis is another experience that has been shown to produce changes in cognitive performance (see review in Bialystok, 2009). The mechanism by which bilingualism leads to this experience-induced cognitive change is likely based on the need to monitor attention to the target language in the context of joint activation of the other language. Substantial evidence from a variety of sources has supported the view that both languages are active in mind to some extent during both comprehension and production (Blumenfeld & Marian, 2007; Francis, 1999; Grainger, 1993; Kroll & de Groot, 1997; Marian & Spivey, 2003; Rodriguez-Fornells, Rotte, Heinze, Nosselt, & Munte, 2002; Thierry & Wu, 2007). The procedures for monitoring attention to the target language have been shown to be handled at least in part by the executive control system (see Luk, Green, Abutalebi, & Grady, in press, for a meta-analysis of functional magnetic resonance imaging evidence), and the recruitment of that system for language use improves its efficiency for a broad range of tasks. The process by which the executive control system interacts with language selection and the subsequent effect on specific aspects of that system, however, are not well understood. Such precision is necessary in order to understand the unique structure of bilingual minds and how experience can affect cognitive outcomes.

One area of uncertainty is the identification of the specific executive control function components that are involved in bilingual language processing and, subsequently, are boosted for bilinguals. A widely accepted interpretation of executive control proposed by Miyake and colleagues (2000) consists of three core components roughly corresponding to inhibition, shifting, and working memory. Early studies showing bilingual differences in performance focused primarily on inhibition (see Bialystok, 2001, for a review), tracing the bilingual advantage in executive control to the need to inhibit the irrelevant but jointly activated language (cf. Green, 1998). Subsequent research, however, has challenged that interpretation; bilingual advantages have been found in preverbal infants long before any inhibition could be relevant (Kovács & Mehler, 2009), some types of inhibition have been implicated in these effects and others have not (Colzato et al., 2008), and conditions that involved no inhibition appear to be equally affected (Hilchey & Klein, 2011). Therefore, the precise nature of how executive control is involved in bilingual performance is not clear.

Recently, Miyake and Friedman (2012) took a broader view and proposed that the executive function is characterized by "unity and diversity," that is, a set of correlated but separable abilities. This view captures a trend in recent research that emphasizes a reliance of executive function components on a common underlying mechanism (Best & Miller, 2010; Garon, Bryson, & Smith, 2008; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). On this view, working memory is automatically affected by any experience that affects the executive function system more broadly. Evidence for bilingual advantages in aspects of two of the three components, inhibition and shifting, is already documented, so from the concept of "unity" it follows that bilinguals should demonstrate enhanced working memory.

Understanding both the status of working memory in the constellation of the executive function and the effect of bilingualism on its development is important because working memory is arguably the most important component of the executive function. Working memory is central to a wide variety of cognitive abilities, especially those that involve dealing with interference, conflict, or distraction (see Kane, Conway, Hambrick, & Engle, 2007, for a review) and predicts essential cognitive and academic outcomes in children. For example, reading comprehension requires holding the previous text in mind so it can be related to the current material, and mental arithmetic requires holding numbers in mind while the operation is applied to update the result. Not surprisingly, therefore, the early acquisition of literacy and numeracy skills (Adams & Gathercole, 1995; Blair & Razza, 2007; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Gathercole, Pickering, Knight, & Stegmann, 2004; Savage, Cornish, Manly, & Hollis, 2006) and later language and math achievement (Barrouillet & Lepine, 2005; Blair & Razza, 2007; Bull & Scerif, 2001; Espy et al., 2004; Gathercole et al., 2004; Passolunghi, Vercelloni, & Schadee, 2007; Swanson & Kim, 2007) depend heavily on working memory.

Previous research investigating the effect of bilingualism on executive control has focused largely on the role of inhibition and shifting. Thus, the tasks typically require participants to switch between rules (Bialystok, 1999; Bialystok & Viswanathan, 2009; Costa, Hernández, Costa-Faidella, &

Sebastián-Gallés, 2009; Prior & MacWhinney, 2010) or to ignore interference from irrelevant stimuli, as in the Simon task (Bialystok, Craik, Klein, & Viswanathan, 2004; Martin-Rhee & Bialystok, 2008), flanker task (Carlson & Meltzoff, 2008; Costa, Hernández, & Sebastián-Gallés, 2008; Yang, Yang, & Lust, 2011), or Stroop task (Bialystok, Craik, & Luk, 2008). The typical finding is that bilingual participants perform faster on both congruent and incongruent trials in conflict tasks and switch between rules more efficiently, invoking both inhibition and switching into the account. For this reason, recent accounts of bilingual advantages in executive functioning have taken a more holistic view and attributed the advantage to broader processes such as conflict monitoring (Costa et al., 2009; Hilchey & Klein, 2011) and coordination (Bialystok, 2011). However, few studies have addressed the possibility that working memory is also involved in these tasks and is modified by bilingualism.

Some fragmentary evidence suggests that working memory might be affected by bilingualism in the same way as found for inhibition and shifting. Bialystok and colleagues (2004) presented younger and older adults who were monolingual or bilingual with a Simon task in which they were asked to indicate the color of a square by pressing the appropriate response key. In the experimental conditions, the squares were presented on either the left or right side of the display and either corresponded or not to the position of the relevant response key, creating congruent and incongruent trials. In a control condition, the stimuli were presented in the center of the display, so there was no interference from position. There was also a working memory manipulation consisting of 2-stimulus and 4-stimulus conditions in which the latter required holding more stimulus–response pairings in mind. The expectation was that the two language groups would perform equivalently in the control condition and that the increase in difficulty from the 2-stimulus presentation to the 4-stimulus presentation in the control condition would be equivalent for participants in the two language groups. As expected, there were no response time (RT) differences between language groups for the 2-stimulus condition, but the surprising result was that the additional time needed to hold in mind 4 stimulus pairings was significantly longer for the monolingual participants than for the bilinguals. This difference was larger for the older adults than for the younger adults, suggesting that bilingualism also slows the decline of these abilities with age. Thus, it appeared that even at this basic level of working memory, the bilingual participants were more efficient than the monolinguals. However, studies comparing simple working memory performance in monolingual and bilingual children have found no evidence of difference (Bialystok & Feng, 2010; Bonifacci, Giombini, Bellocchi, & Contento, 2011; Engel de Abreu, 2011). Therefore, the few studies on this topic are inconclusive, so there is no clear evidence regarding whether working memory, like inhibition and shifting, is also enhanced for bilinguals.

The characterization of the executive function as consisting of unity and diversity makes it challenging to investigate the components individually, but it is nonetheless crucial to determine whether differences in working memory can be identified and how they might interact with the other components. Working memory is the missing piece in the explanation of cognitive effects of bilingualism and requires independent study not only to understand cognitive processing in bilinguals but also to understand the integrity of executive control in development.

The hypothesis in the current research is that working memory is enhanced in bilingual children, particularly in conditions for which the other core components of executive control are also required. There are two reasons for this hypothesis. First, from the perspective of unity, the established effect of bilingualism on some components of the executive function will necessarily involve all of the components, including working memory, through their common foundation. Second, from the perspective of diversity, the joint activation of both languages for bilinguals in language processing requires not only inhibition and selection but also maintenance of representations of context, interlocutors, and discourse—all functions of working memory. Therefore, as with the other two components, the relations should be observed through interactions with other executive function processes. Just as inhibition of irrelevant information in an incongruent trial is observed primarily in the context of shifting between congruent and incongruent trials, so too we expect that working memory effects will be observed in situations where working memory demands are integrated with demands for inhibition and shifting. On this view, the core components of the executive function system are all involved in bilingual processing and are all modified as a consequence. It is empirically difficult to isolate the core components of the executive function, an issue that is central to the study of executive function. Bilingualism provides a unique window to test unity and diversity account. To the extent that working memory

is uniquely modified by bilingualism—the diversity view—there should be a main effect of working memory across manipulations in other components of the executive function. To the extent that working memory is integrated with the other components—the unity view—the strength of the working memory effect will be modulated by other task demands.

Study 1

Manipulation of the executive function demands in a Simon task paradigm was adapted from Bialystok and colleagues (2004) to create a task appropriate for children. Working memory demands were operationalized as the difference between performing the task while holding in mind either two response rules or four response rules in conditions that either had minimal additional executive control demands or included conflict and so required inhibition and shifting. Thus, manipulations in working memory could be examined across levels of executive control.

Method

Participants

Participants in the first study were 64 5-year olds (mean age = 5 years 5 months, *SD* = 5.4) who were attending kindergarten. All of the children lived in the same homogeneous middle-class community and attended the same neighborhood schools in a large city. Questions regarding parents' level of education revealed that all parents had at least college-level diplomas. Of this total sample, 7 children had mixed language experiences and could not be clearly classified as bilingual or monolingual and so were excluded from the analyses, and 1 monolingual child was excluded because his score on one task used to assess nonverbal intelligence was more than 2 standard deviations below the group mean. Thus, the final sample was composed of 56 children and included 29 monolinguals (17 boys and 12 girls) and 27 bilinguals (11 boys and 16 girls). All of the bilingual children spoke English at school and in the community and spoke a different language at home; they had been exposed to both languages since birth and used them daily. The non-English languages included Arabic (2), Bulgarian (1), Cantonese (2), Chinese (2, dialect unspecified), French (1), Hebrew (1), Igbo (1), Mandarin (4), Portuguese (1), Russian (7), Serbian (1), Spanish (3), and Urdu (1). All parents completed a questionnaire about the language environment at home, the language used for specific activities, and the languages used for interactions between family members. The responses were indicated on a 5-point scale where 1 = *entirely in English* and 5 = *entirely in the non-English language,* with 3 indicating balanced usage. The score for monolinguals was consistently 1. For bilinguals, the language spoken by the children obtained an average score of 2.5 (*SD* = 1.1), indicating a slight bias for English, and the language spoken by parents to children obtained an average score of 3.5 (*SD* = 1.0), indicating a slight bias for the non-English language.

Materials and procedure

Children were tested individually on three tasks in a quiet room at their school. Two background measures were administered: the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997) to assess receptive vocabulary in English and the Matrices subtest of the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 2004) to evaluate the equivalency of both groups on fluid intelligence. The third task was the pictures task, which is a Simon-type task that included a manipulation of working memory demands. The order of the tasks was as follows: Part 1 of the pictures task, K-BIT, Part 2 of the pictures task, and PPVT-III. The session lasted approximately 40 min, and children were given stickers on completion to thank them for their participation.

The measures for English receptive vocabulary (PPVT-III) and fluid intelligence (K-BIT) were administered and scored according to standard procedures.

Pictures task

The pictures task was programmed in E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) and presented on a Dell Latitude C840 laptop computer with a 15-inch monitor. All participants completed four conditions consisting of two blocks of 24 trials per condition, producing a total of

48 trials for each of the four conditions. The four conditions were created by combining two working memory levels (2 stimuli vs. 4 stimuli) with two conflict levels (central presentation vs. side presentation).

Center-2. An illustration of this task is presented in Fig. 1. Two stimuli, a purple flower and a red heart, were presented one at a time in the center of the screen. Participants were instructed to press a designated key to indicate which stimulus was shown. The keys were located on the right and left sides of the keyboard, and each was marked with a sticker indicating the color of the designated figure. The assignment of the key to the left or right position was counterbalanced across participants.

　　Each trial began with a 500-ms blank screen followed by a centered fixation cross for another 500 ms. After this, the stimulus appeared and children were asked to respond by pressing the correct key as quickly as possible without making mistakes. Timing began with the onset of the stimulus and terminated with the response. Children were not able to respond during the blank or fixation screens. The stimulus remained on the screen for a maximum of 3000 ms or until a response was made.

Conflict-2. The parameters were the same as in the previous condition, but the stimulus appeared on either the right or left side of the screen (see Fig. 1). The relationship between the presentation position and the position of the correct response key created congruent trials (the two positions were the same) and incongruent trials (the two positions were different).

Center-4. This condition was similar to the center-2 condition except that there were 4 stimuli: a blue cloud, a green tree, a yellow smiley, and a pink star. Children were instructed to press one key for 2 of the stimuli (blue cloud and yellow smiley) and to press the other key for the other 2 stimuli (green tree and pink star). The instructions were presented as four individual rules, one per stimulus (e.g., "press the right key for the green tree," "press the right key for the pink star"). All stimuli appeared in the center of the screen.
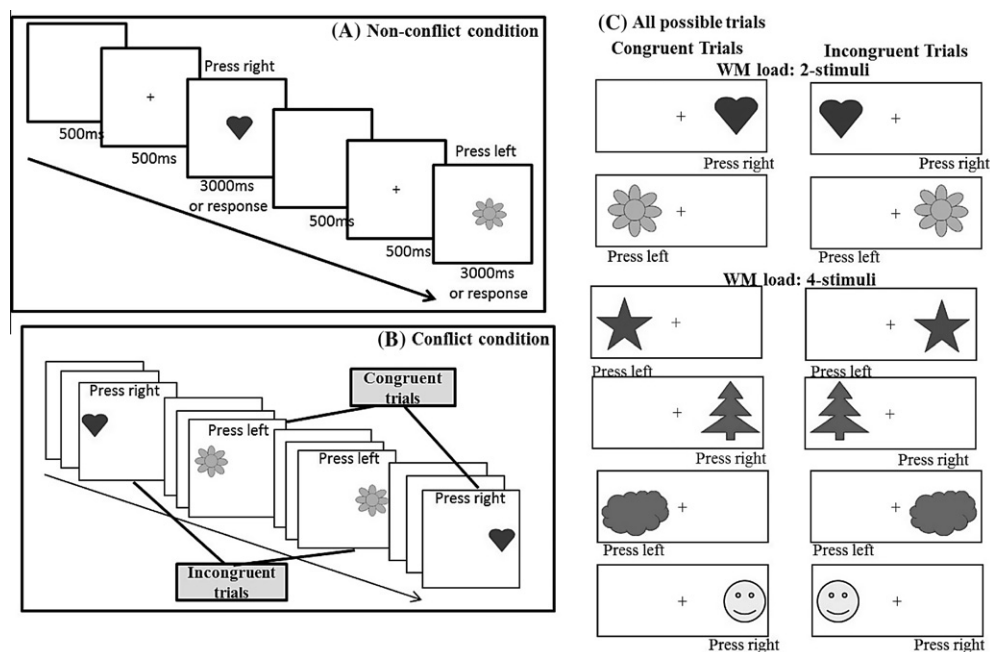

Fig. 1. Pictures task. (A) Procedure employed in the pictures task, center conditions. (B) Trial types in the conflict conditions. (C) Stimuli and trial types in the conflict conditions by memory load. WM, working memory.

Conflict-4. As in conflict-2, the stimuli were presented in the left or right position of the screen, creating congruent and incongruent trials.

All conditions began with instructions and a practice block consisting of 4 trials for the center blocks and 8 trials for the conflict blocks. The practice was repeated as needed until the child understood the instructions and could perform without error, but nearly all children learned the task after one practice block. The four conditions were presented in two sets beginning with the two conditions based on 2 stimuli and then, after a break to complete the K-BIT, the two conditions based on 4 stimuli. The center conditions always preceded the conflict conditions. This fixed order was used to ensure that children understood the task and could perform it properly in the simpler condition before introducing the conflict condition. Trials within blocks were randomly presented and equally distributed.

The four conditions manipulate the involvement of working memory (2 stimuli vs. 4 stimuli) and other executive control demands (center presentation vs. side presentation). For the center conditions, participants needed to hold arbitrary rules in mind to execute the task, with greater demands on the 4-stimulus conditions than on the corresponding 2-stimulus conditions. Therefore, the difference between performances on the 2-center and 4-center conditions indicates the ability to maintain arbitrary rules. The conflict conditions introduce the requirements for inhibition to focus on the rule-defined target and resist the response key primed by the position of the stimulus and shifting to monitor congruent and incongruent trials and stimulus changes. Thus, working memory can be examined in conditions that vary in executive control demands.

Results

Mean scores and standard deviations for the vocabulary and reasoning measures are reported in Table 1. Two-way analyses of variance (ANOVAs) for each background measure with gender and language group as between-participants factors showed no differences in age ($Fs < 1$) or K-BIT scores ($Fs < 1$). Regarding vocabulary skills in English, monolingual children obtained higher scores ($M = 111.6$, $SD = 9.3$) than bilinguals ($M = 102.1$, $SD = 12.2$) on the PPVT-III, $F(1, 52) = 10.44$, $p = .002$, $d = 0.88$, consistent with previous research (Bialystok, Luk, Peets, & Yang, 2010). There were no correlations between PPVT-III and any of the other measures, indicating that language differences between the groups did not influence performance on other tasks. Because there were no effects of gender on any group variables, subsequent analyses were collapsed across gender.

For the pictures task, 3 participants were excluded (2 bilinguals and 1 monolingual) because they did not complete all of the blocks. Accuracy data are reported in Table 2. Nonconflict and conflict blocks were analyzed separately because the conflict block contained a factor for congruence that was not present in the centrally presented nonconflict block. A two-way ANOVA for language group and working memory level (2 vs. 4) on accuracy in the nonconflict block showed a main effect of memory load, with children recalling fewer items in the 2-stimuli condition than in the 4-stimuli condition, $F(1, 51) = 11.41$, $p = .001$, $d = 0.49$, and no difference between language groups and no interaction effect ($Fs < 1$).

Table 1
Mean scores (and standard deviations) on background measures by language group in Study 1 and Study 2.

| | 5-year-olds: Studies 1 and 2 | | | | 7-year-olds: Study 2 | | | |
| | Monolingual | | Bilingual | | Monolingual | | Bilingual | |
Gender	Female	Male	Female	Male	Female	Male	Female	Male
n	12	17	16	11	18	16	17	18
Age (in months)	66	65	66	67	82	82	83	83
	(2.9)	(5.6)	(6.9)	(5.9)	(2.4)	(2.8)	(2.2)	(3.5)
K-BIT standard score	101.7	105.2	105.8	103.6	102.5	100.9	109.0	99.9
	(11.6)	(10.0)	(14.6)	(8.8)	(11.5)	(14.5)	(14.8)	(13.6)
PPVT-III standard score	112.1	111.2	104.6	98.5	103.6	103.9	95.5	96.8
	(8.1)	(10.3)	(9.7)	(14.9)	(7.6)	(6.7)	(11.6)	(9.2)

Table 2
Mean percentages of correct responses (and standard deviations) for the pictures task by language group in Study 1.

Block	Working memory	Trial	Monolingual	Bilingual	Overall
Nonconflict	2 Stimuli	Center	92.8 (6.9)	91.7 (5.7)	92.3 (6.4)
	4 Stimuli	Center	94.8 (5.1)	96.0 (6.8)	95.3 (5.9)
Conflict	2 Stimuli	Congruent	94.5 (5.9)	94.3 (5.7)	94.4 (5.8)
		Incongruent	85.8 (13.9)	90.9 (7.4)	88.2 (11.5)
	4 Stimuli	Congruent	95.1 (6.3)	94.2 (7.2)	94.7 (6.6)
		Incongruent	93.1 (7.2)	95.3 (5.0)	94.1 (6.3)

For the conflict block, a three-way ANOVA for language, working memory level, and congruence revealed a main effect of working memory load ($M = 91.4$, $SD = 9.1$, and $M = 94.4$, $SD = 6.5$, for 2 stimuli and 4 stimuli, respectively), $F_{(1,51)} = 12.63$, $p < .001$, $d = 0.38$, a main effect of congruence, $F_{(1,51)} = 11.11$, $p = .001$, $d = 0.43$, with higher scores for congruent trials ($M = 94.5$, $SD = 6.3$) than for incongruent trials ($M = 91.3$, $SD = 8.4$), and significant interactions of congruence by language, $F_{(1,51)} = 4.56$, $p = .04$, $\eta_p^2 = .082$, and congruence by working memory load, $F_{(1,51)} = 11.09$, $p = .001$, $\eta_p^2 = .18$. For the congruence by language interaction, there was no effect of congruence for bilinguals ($F < 1$, congruent $CI_{.95} = 92–96\%$, incongruent $CI_{.95} = 90–96\%$), but there was a significant effect for monolinguals, $F_{(1,27)} = 13.00$, $p = .001$, $d = 0.39$, with higher accuracy in congruent trials ($CI_{.95} = 93–97\%$) than in incongruent trials ($CI_{.95} = 86–92\%$). Thus, the accuracy of bilinguals was not reduced in incongruent trials as it was for monolinguals. The congruence by working memory load interaction showed that the effect of congruence was found only for the 2-stimulus condition, $F_{(1,51)} = 14.85$, $p < .001$, $d = 0.51$ (congruent $CI_{.95} = 93–96\%$, incongruent $CI_{.95} = 85–91\%$) and not for the 4-stimulus condition ($F < 1$, congruent $CI_{.95} = 93–97\%$, incongruent $CI_{.95} = 92–96\%$).

RT data for correct responses are shown in Fig. 2. Trials with RTs less than 200 ms and more than 2500 ms were excluded (2.8% of trials). For the nonconflict block, a two-way ANOVA for language group and working memory level showed a main effect of memory load, $F_{(1,51)} = 209.93$, $p < .001$, $d = 2.19$, with faster responses in the 2-stimulus condition ($M = 830$ ms, $SD = 140$) than in the 4-stimulus condition ($M = 1198$ ms, $SD = 192$), $F_{(1,51)} = 209.93$, $p < .001$, $d = 2.19$, and a main effect of language group, $F_{(1,51)} = 7.18$, $p = .010$, $d = 0.62$, with faster responses from bilinguals ($M = 962$ ms, $SD = 155$) than from monolinguals ($M = 1060$ ms, $SD = 162$) and no interaction.

For the conflict condition, a three-way ANOVA revealed main effects of working memory load, $F_{(1,51)} = 90.37$, $p < .001$, $d = 1.56$, with faster responding to 2-stimulus trials, language group, $F_{(1,51)} = 4.48$, $p = .039$, $d = 0.44$, with bilinguals responding faster than monolinguals, $F_{(1,51)} = 4.48$, $p = .039$, $d = 0.44$, and congruence, $F_{(1,51)} = 36.17$, $p < .001$, $d = 0.28$, with faster responses to congruent trials. There were no significant interactions. Thus, RTs for bilinguals, 2-stimulus conditions, and congruent trials were faster than their counterparts. To evaluate the presence of speed accuracy trade-offs, Pearson correlations were calculated between RTs and accuracy. No significant correlations were found for any of the conditions.

Discussion

Monolingual and bilingual children performed equivalently on a test of fluid intelligence, but monolinguals obtained higher scores than bilinguals on a test of English receptive vocabulary. This pattern is consistent with previous research in which monolinguals typically demonstrate a higher vocabulary in the language of testing (Bialystok et al., 2010; Oller, Pearson, & Cobo-Lewis, 2007). It is important that there were no significant correlations between PPVT-III scores and any of the dependent variables, so this difference did not affect experimental outcomes.

In the nonconflict condition, all children showed a high level of accuracy, with correct responses provided on more than 90% of the trials. Executive function demands were low, with the primary demand being the need to hold arbitrary rules in mind to respond appropriately. The conflict condition produced different results for the two language groups. Whereas incongruent trials were more
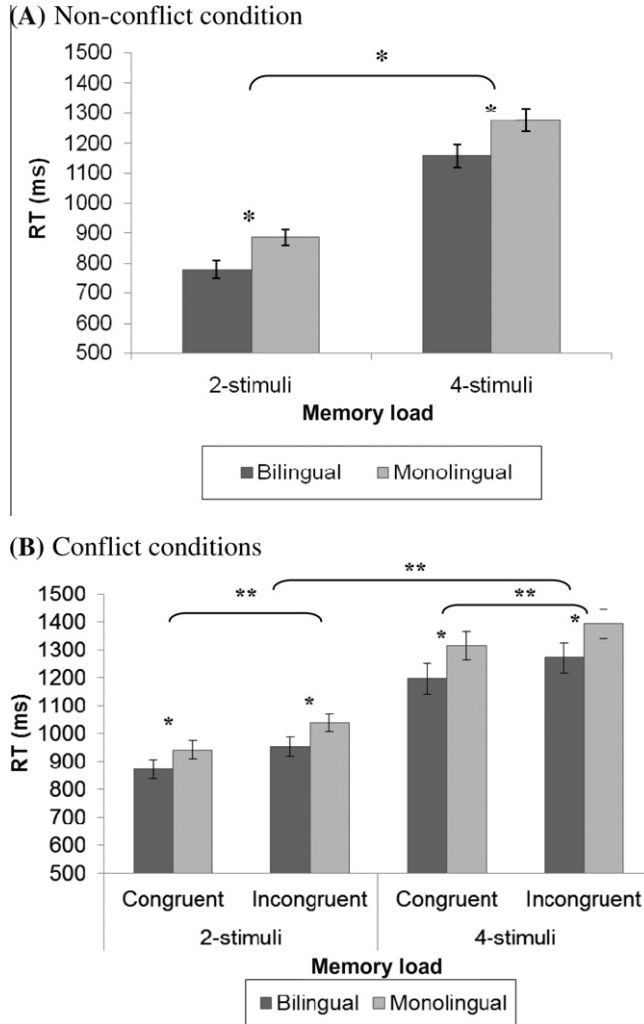
(A) Non-conflict condition

(B) Conflict conditions

Fig. 2. Mean response times (and standard errors) by language group for the pictures task (in milliseconds) in Study 1 for the nonconflict block based on central presentation (A) and the conflict block based on side presentation of stimuli (B). Note: $*p<$ .05; $**p<$ .01.

difficult than congruent trials for monolinguals, the misleading cues did not increase task difficulty for bilinguals. These findings are consistent with evidence from studies using a Simon task (Martin-Rhee & Bialystok, 2008) or flanker task (Carlson & Meltzoff, 2008; Yang et al., 2011) showing an advantage in conflict resolution for bilingual children.

RT data showed that bilingual children were faster than monolinguals even in the simpler nonconflict condition. Because there was no interaction of conflict and working memory load and no evidence of speed–accuracy trade-offs, bilinguals appear to be more efficient in performing the task and in coordinating the demands across the manipulations of executive control and working memory.

Children in both language groups produced more accurate but slower responses to the 4-stimulus condition than to the 2-stimulus condition. This pattern may indicate that children were attending more carefully in the more difficult condition. It is also possible that even the 2-stimulus condition was demanding for this age group (Gerstadt, Hong, & Diamond, 1994) and that bilingual children

are more advanced than monolinguals in their progress in developing these skills. For children in this age range, working memory tasks that involve holding in mind two or more items require children to engage extra attentional processes to solve the tasks (Gathercole, Pickering, Ambridge, & Wearing, 2004; Miles, Morgan, Milne, & Morris, 1996; Wilson, Scott, & Power, 1987). The fact that bilingual children were able to maintain their speed advantage in the presence of conflict from incongruent trials or increases in memory load may be evidence of enhancement of working memory. Note, too, that the bilingual advantage on the centrally presented stimuli is similar to the results found by Bialystok and colleagues (2004) for adults, where bilinguals outperformed monolinguals in a condition requiring them to hold four rules in mind and respond correctly to a stimulus presented in the center of the screen. It is also possible that faster RTs in bilinguals indicate faster processing of stimuli, and this may have been elicited by better management of information in working memory.

In sum, bilingual children performed the task more efficiently than monolinguals, responding more rapidly throughout and achieving higher accuracy on the difficult incongruent trials. This pattern was found for both conditions that included low executive control demands and those for which executive control demands were higher. The second study pursued these results by presenting children with a visuospatial span task that manipulated working memory demands in a different way.

Study 2

Study 2 used a visuospatial working memory task to minimize the role of linguistic demands because of expected vocabulary differences between monolingual and bilingual children. The task was a span task, so working memory was assessed by evaluating the number of items children could correctly recall. As in Study 1, stimulus presentation was manipulated to create conditions that varied in their demands for executive control. Different results have been observed when comparing visuospatial working memory in which the information is presented simultaneously or sequentially. Rudkin, Pearson, and Logie (2007) administered the Visual Pattern Test (VPT; Della Sala, Gray, Baddeley, & Wilson, 1997) and a version of the Corsi blocks task (Corsi, 1972; Milner, 1971) and explored the involvement of executive function in each task. Although both visuospatial working memory tasks require participants to recall the positions of the presented stimuli, the VPT presents all of the stimuli at the same time, requiring only recall of positions, whereas the Corsi blocks task presents the stimuli sequentially, increasing memory demands to maintain and possibly manipulate the order of presentation. Rudkin and colleagues (2007) found that Corsi performance was affected by the inclusion of a dual task, whereas performance on the VPT was not disrupted. This difference was interpreted as evidence that sequential presentation recruits more resources than simultaneous presentation and, therefore, signals the involvement of greater executive functioning for sequential presentation. Not surprisingly, the ability to perform the simpler simultaneous task develops earlier than the ability to perform the more complex sequential task; that is, 5-year-olds are not yet capable of carrying out complex working memory tasks that involve manipulation of information, whereas 7-year-olds have developed this skill (Gathercole et al., 2004; Miles et al., 1996).

In Study 1 using a simple task, we showed that monolingual and bilingual children of the same chronological age were at different stages in developing their ability to perform this working memory task. The task in Study 2 is more complex and captures the development of the ability to mentally manipulate visuospatial information. This skill has been shown in previous research to develop over 5 to 7 years of age (Gathercole et al., 2004; Miles et al., 1996). Therefore, we included a group of older children to provide a more complete picture of the emerging ability to perform this task by monolingual and bilingual children. In the current study, children were asked to recall the positions of items in a matrix following simultaneous or sequential presentation. In addition to imposing a greater memory burden in that both position and order information are required, the sequential task also requires executive control to monitor two sources of information and update both position and order information (Rudkin et al., 2007). Thus, as in Study 1, the children's ability to perform a working memory task can be compared for a condition in which only simple recall is required and a more difficult condition in which memory and executive control demands are higher. If the working memory advantage for bilinguals is independent of other task demands, then the prediction is that bilinguals will outperform

monolinguals on both conditions in that working memory is involved in both. If the bilingual advantage in working memory is constrained by other task demands, then bilinguals will demonstrate an advantage only when other executive control demands are high.

Method

Participants

The same 56 5-year-olds from Study 1 and a new sample of 69 7-year-olds (mean age = 6 years 11 months, SD = 2.76 months) participated in the second study (see Table 1). The new sample was composed of 34 monolinguals (16 boys and 18 girls) and 35 bilinguals (18 boys and 17 girls). All children lived in the same middle-class neighborhoods, and all parents reported having at least some postsecondary education. As in Study 1, the bilingual children spoke English at school and in the community and spoke a different language at home. All bilingual children had been exposed to both languages since birth and used them daily. The non-English languages included Arabic (3), Bengali (1), Cantonese (4), Chinese (3), Farsi (1), Hindi (1), Italian (1), Japanese (2), Persian (2), Mandarin (2), Portuguese (1), Punjabi (2), Russian (2), Spanish (1), Tamil (4), Urdu (4), and Vietnamese (1). The language history questionnaire completed by parents indicated that for bilinguals the language spoken by the children at home obtained an average score of 3.0 (SD = 0.95), and the language spoken by parents to the children obtained an average score of 4.0 (SD = 1.07), indicating a tendency to use the non-English language. The score for monolinguals was consistently 1.

Materials and procedure

The same background measures for receptive vocabulary and nonverbal fluid intelligence from Study 1 were used.

Frogs matrices task

The frogs matrices task (FMT) is a computerized variant of the Corsi blocks task (Berch, Krikorian, & Huha, 1998; Milner, Corsi, & Leonard, 1991) that measures visuospatial working memory. The task was programmed in E-Prime software (Schneider et al., 2002) and included two conditions. In both conditions, children were shown a 3 × 3 matrix on a 15-inch KEYTEC Magic Touch computer and were told that each of the nine cells represented a pond in which frogs had been resting. Frogs were presented either as a group (simultaneous condition) or one at a time (sequential condition), and children needed to remember which ponds had frogs in them. In the sequential presentation condition, the ponds needed to be recalled in the correct order. In the simultaneous presentation condition (Fig. 3A), all of the frogs were shown for 2000 ms, followed by a 2000-ms delay with a blank matrix on the screen. At the end of the delay, a "ding" sound was heard, indicating that the child could respond by touching the screen to show the positions that had contained a frog. In the sequential presentation condition (Fig. 3B), each frog occupied the pond for 1 s. After the last frog disappeared, a "ding" sound indicated that the child could respond by touching each pond in which there had been a frog in the order they had been shown. Testing began with two frogs and increased by one frog after every second trial, producing two trials at each sequence length, to a maximum string length of 6. There was a total of 10 trials per condition.

Memory span was calculated as the longest string length in which the child remembered all of the frogs on at least one of the two trials. Total scores were calculated as the sum of all frogs correctly recalled up to the child's span and then were converted to proportion scores based on the maximum possible for that condition. For the simultaneous condition, the maximum score was 40. If a child was correct on both trials containing two frogs (2 + 2), was correct on one of the trials containing three frogs (3) but missed one of the frogs in the second trial with three frogs (2), and failed on both trials containing four frogs, remembering three frogs in the first trial (3) and two frogs in the second trial (2), then the child's span would be 3 and the total score would be 2 + 2 + 3 + 2 + 3 + 2 = 14 or 0.35. For the sequential condition, the total possible was 80 because 1 point was awarded for each correct location and 1 point was awarded for recalling that location in the correct order. Thus, children received separate scores for accuracy (i.e., whether the selected frog was one shown in the trial) and order (i.e., whether the frog was given in the correct sequence).
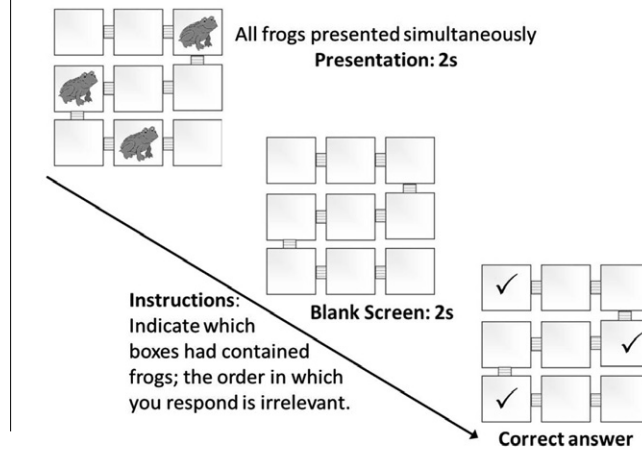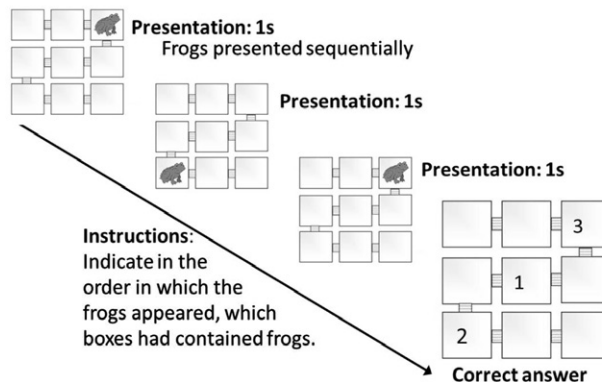
(A) Simultaneous presentation

All frogs presented simultaneously
Presentation: 2s

Instructions:
Indicate which
boxes had contained
frogs; the order in which
you respond is irrelevant.

Blank Screen: 2s

✓

✓

✓

Correct answer

(B) Sequential presentation

Presentation: 1s
Frogs presented sequentially

Presentation: 1s

Presentation: 1s

Instructions:
Indicate in the
order in which the
frogs appeared, which
boxes had contained frogs.

3

1

2

Correct answer

Fig. 3. Sample items for the simultaneous presentation (A) and sequential presentation (B) of the FMT in Study 2.

Children were tested individually in a quiet room. At the end of each session, children were given stickers and thanked for their participation.

Results

Background scores are reported in Table 1. Within each age group, there was no difference between language groups in age ($Fs < 1$). Three-way ANOVAs for gender, language, and age group showed no differences in K–BIT for any factor ($Fs < 1$). However, for the PPVT-III standard scores, there were main effects of language, $F(1, 117) = 24.66$, $p < .001$, $d = 0.78$, and age group, $F(1, 117) = 13.80$, $p < .001$, $d = 0.66$, with no differences by gender and no significant interactions. Scores were higher for monolinguals and 5-year-olds. Because PPVT-III scores are standardized by age, we assume that the difference between 5- and 7-year-olds' scores reflects sampling differences. As in Study 1, there were no correlations between PPVT-III and the dependent measures, ruling out language group vocabulary

differences as a confound in the results. There were no gender effects, so data were collapsed across gender in subsequent analyses.

For the FMT, one 7-year-old monolingual was excluded because his data from the sequential condition were missing due to technical failure. Two measures were calculated for each condition as described above: span and proportion of total correct answers. The data are presented in Table 3. Three-way ANOVAs for condition, age group, and language group were conducted for each measure. The analysis of span indicated main effects of condition, $F(1, 120) = 187.17$, $p < .001$, $d = 1.56$, with higher scores for the simultaneous presentation ($M = 5.3$, $SD = 1.1$) than for the sequential presentation ($M = 3.5$, $SD = 1.2$), and age group, $F(1, 120) = 14.81$, $p = .001$, $d = 0.45$, with the older children reaching a higher span ($M = 4.6$, $SD = 1.0$) than the younger children ($M = 4.1$, $SD = 1.2$). No other main effects or interactions were found.

The analysis of proportion correct indicated main effects of condition, $F(1, 120) = 172.59$, $p < .001$, $d = 1.22$, with higher scores for the simultaneous presentation ($M = .78$, $SD = .26$) than for the sequential presentation ($M = .50$, $SD = .21$), age group, $F(1, 120) = 6.31$, $p = .01$, $d = 0.34$, with higher scores for the older children ($M = .68$, $SD = .22$) than for the younger children ($M = .60$, $SD = .24$), and language group, $F(1, 120) = 4.17$, $p = .04$, $d = 0.35$, with higher scores for the bilinguals ($M = .68$, $SD = .27$) than for the monolinguals ($M = .60$, $SD = .27$). There was a significant two-way interaction of condition by language group, $F(1, 120) = 3.73$, $p = .05$, $\eta_p^2 = .03$. Pairwise comparisons revealed that language group differences were significant in the difficult sequential condition, $F(1, 120) = 9.97$, $p = .002$, $d = 0.61$ (monolinguals: $CI_{.95} = .39–.49\%$; bilinguals: $CI_{.95} = .50–.60\%$), but not in the easier simultaneous condition ($F < 1$; monolinguals: $CI_{.95} = .71–.84\%$; bilinguals: $CI_{.95} = .74–.86\%$). The three-way interaction of language group by age group by condition was also significant, $F(1, 120) = 4.53$, $p = .03$, $\eta_p^2 = .035$. For bilinguals, there were no differences in age for the simultaneous condition ($F < 1$; 5-year-olds: $CI_{.95} = .70–.87\%$; 7-year-olds: $CI_{.95} = .72–.89\%$), but there was an advantage for older children in the sequential condition, $F(1, 120) = 5.05$, $p = .02$, $d = 0.50$ (5-year-olds: $CI_{.95} = .42–.57\%$; for 7-year-olds: $CI_{.95} = .54–.67\%$). For monolinguals, older children performed better in the simultaneous condition, $F(1, 120) = 5.73$, $p = .01$, $d = 0.41$ (5-year-olds: $CI_{.95} = .60–.79\%$; 7-year-olds: $CI_{.95} = .76–.93\%$), but not in the sequential condition, $F(1, 120) = 1.40$, $p = .20$, $d = 0.29$ (5-year-olds: $CI_{.95} = .34–.48\%$; 7-year-olds: $CI_{.95} = .40–.53\%$). Therefore, 5-year-old bilinguals performed at the same level as 7-year-old monolinguals in the simpler simultaneous condition.

Discussion

As in previous research, children performed better in the simultaneous condition than in the sequential condition (cf. Lecerf & de Ribaupierre, 2005; Mammarella, Pazzaglia, & Cornoldi, 2008; Tucker, Novelly, Isaac, & Spencer, 1986). Moreover, children's ability to perform these tasks improved over the ages studied (cf. Gathercole et al., 2004; Miles et al., 1996). Although there were no language group differences in span, bilingual children obtained higher scores than monolinguals in both conditions on the more sensitive proportion correct score. The two-way interaction showed that bilingual children obtained higher scores than monolinguals on the more difficult sequential condition, and the

Table 3
Mean scores (and standard deviations) of span and proportion correct scores for FMT in simultaneous and sequential presentation conditions by age and language group in Study 2.

Measure	Task	5-year-olds		7-year-olds	
		Monolingual	Bilingual	Monolingual	Bilingual
Span	Simultaneous	4.9 (1.3)	5.1 (1.3)	5.5 (0.8)	5.5 (0.9)
	Sequential	3.2 (0.9)	3.3 (1.4)	3.7 (1.0)	3.8 (1.4)
Proportion correct	Simultaneous	.70 (.28)	.79 (.25)	.83 (.23)	.81 (.26)
	Sequential	.41 (.17)	.50 (.26)	.46 (.17)	.61 (.18)

three-way interaction revealed that the younger bilingual children performed better than their monolingual counterparts on the simpler simultaneous condition.

General discussion

These two studies addressed the question of whether bilingual advantages could be found in working memory and, if so, whether those advantages were tied to other components of executive control such as inhibition and shifting. In both studies, bilingual children outperformed monolinguals on the working memory tasks, and evidence for this advantage was found across manipulations in the level of other executive control components. In Study 1, the difference was found for both a simple condition in which children needed to hold two or four rules in mind to press a response key and a difficult condition in which the response also required executive control to ignore distraction from a misleading position and shift between trials. In Study 2, the difference was found in a simple condition in which young bilingual children performed at the level of older monolingual and bilingual children and in a difficult condition in which children needed to recall both position and order information and ignore interference from competing positions in the wrong sequence. Notably, however, the advantage for the bilingual children was larger in the more difficult conditions, and the other executive function components, such as performing the incongruent trials in Study 1, were also handled better by the bilingual children. Thus, bilingual children do perform better than monolinguals on working memory tasks, an advantage that is nonetheless related to the other executive function demands of the task. This pattern of results is consistent with the view of unity and diversity described by Miyake and Friedman (2012) and contributes to our understanding of the development of working memory in monolingual and bilingual children and to the relation between working memory and the other executive control components.

Consider first the implications for understanding the development of bilingual children. The results clearly indicate that explanations of developmental or executive function differences between monolingual and bilingual children need to include differences in working memory. Earlier accounts focused on specific components such as inhibition (e.g., Bialystok, 1999), but more recent studies have looked beyond inhibition or a single component explanation (e.g., Bialystok, 2010). The presence of both main effects of working memory advantages for bilingual children and an enhancement of those effects when other executive function demands are present is consistent with the importance of working memory over and above other aspects of executive functioning.

Previous studies examining the working memory ability of monolingual and bilingual children have failed to find clear evidence for a bilingual advantage. One reason for this may be found in the differences in the tasks used in the current studies and those used in previous research. For example, Bialystok and Feng (2010) asked children to recall lists of words, and Engel de Abreu (2011) presented several tasks, all of which involved words or digits. In both cases, performance on the working memory tasks was equivalent for monolingual and bilingual children, but bilingual children generally experience more difficulty than monolinguals in verbal processing. In both of those studies, bilingual children obtained lower scores than monolinguals on tests of receptive and productive vocabulary. This difference in vocabulary may have created a handicap for bilingual children performing verbal tasks, and the equivalent performance may in fact be masking a latent bilingual advantage. In the current studies, the tasks were visual and visuospatial, with very low verbal requirements, minimizing the possibility of a confound with linguistic processing. In this case, bilingual children outperformed monolinguals on the working memory measures.

The second implication of the current results is for conceptions of the relation among components of the executive function. The bilingual advantage in the working memory tasks in the current studies was independent of other task demands, as shown by the main effect of language group in both studies. In Study 1 bilingual advantages were found for both conflict and nonconflict blocks, and in Study 2 bilingual children outperformed monolinguals in total score for both the simpler and more difficult memory conditions. These results point to an effect of bilingualism on working memory that is separate from previously reported advantages in executive functioning. However, the executive control demands of the task in both studies had a significant role in determining the outcomes for working

memory. In Study 1 a bilingual advantage in accuracy was found for the difficult incongruent trials, and in Study 2 the young bilingual children showed a better performance than monolinguals in the simple condition, whereas in the more difficult condition the bilingual advantage was equivalent for children at the two age levels. These results suggest that the bilingual advantage might not be attributable to a single component of executive functioning and that working memory alone is not modified by bilingualism; instead, the experience of bilingualism affects an integrated set of abilities in which efficiency is enhanced on cognitively demanding tasks.

This view of a more integrated set of abilities for the executive function is consistent with the position offered by Miyake and Friedman (2012), arguing for both unity and diversity of the traditional components of executive control. Working memory can be manipulated and assessed somewhat independent of other executive control components, but the results from the current studies show that the outcomes depend on the other task demands. It is also consistent with an interpretation offered by Hilchey and Klein (2011), who attribute the bilingual advantage not to a specific component such as inhibition but rather to an overall ability to monitor attention (see also Costa et al., 2009). Thus, the current results endorse a view that attributes an advantage to bilingual children on working memory tasks and also defines a role for other task demands in controlling those outcomes.

The current studies fill an important gap in our understanding of the bilingual mind. Working memory is crucial to cognitive development, and its precocious development by bilingual children is important evidence for developmental effects of experience. The results also contribute to the growing literature on the effect of experience on cognitive outcomes. In this regard, bilingualism is particularly important because, unlike experiences such as musical training and video game playing, bilingual children are not typically preselected for talent or interest. The children in the current studies were bilingual because of a family history of immigration and not because of a talent for learning languages. This is powerful evidence for the role of experience in shaping the mind and directing the course of development.

Acknowledgments

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