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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 children who were 5-years old performed a Simon-type task that manipulated working memory demands by comparing conditions based on 2-rules and 4-rules and manipulated conflict resolution demands by comparing conditions that included conflict with those that did not. Bilingual children outperformed monolinguals at both levels of conflict resolution 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 who were 5-years old or 7-years old 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.

It is now recognized that a variety of cognitively demanding experiences can 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 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 (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

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the target language have been shown to be handled at least in part by the executive control system (Luk, Green, Abutalebi, & Grady, in press, for meta-analysis of fMRI 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 boosted for bilinguals. A widely-accepted interpretation of executive control proposed by Miyake et al. (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 (Bialystok, 2001 for 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 (Kovacs & Mehler, 2009), some types of inhibition have been implicated in these effects and others 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) have taken 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 impacts 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, et al., 1998; Gathercole, Pickering, Knight, & Stegmann, 2004, 2005; 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., 2004a; Passolunghi, Vercelloni, & Schadee, 2007; Swanson & Kim, 2007) depend heavily on working memory.

Previous research investigating the effect of bilingualism on executive control has largely focused on the role of inhibition and shifting. Thus, the tasks typically require the participant to switch between rules (Bialystok, 1999; Bialystok & Viswanathan, 2009; Costa, Hernández, Costa-Faidella, & Sebastian-Galles, 2009; Prior & MacWhinney, 2010) or 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) or 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 et al. (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- to 4-stimulus presentation in the control condition would be equivalent for participants in the two language groups. As expected, there were no 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 monolingual than bilingual participants. This difference was larger for the older adults than 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). The few studies on this topic, therefore, 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 present 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 the components including working memory through their common foundation; and second, from the perspective of diversity, the joint activation of both languages for bilinguals in language processing not only requires 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 primarily observed 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 all modified as a consequence. It is empirically difficult to isolate the core components of the executive function, an issue that is central in 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 were adapted from Bialystok et al. (2004) to create a task appropriate for children. Working memory demands were operationalized as the difference between performing the task while holding in mind two response rules or four response rules in conditions that either had minimal additional executive control demands or included conflict and thus required inhibition and shifting. Thus, manipulations in working memory could be examined across levels of executive control.

Method

Participants—Sixty-four 5-year olds (mean age = 5 years, 5 months, $SD = 5.4$) who were attending kindergarten participated in this study. All 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. Seven children had mixed language experiences and could not be clearly classified as bilingual or monolingual so were excluded from the analyses. One monolingual child was excluded because his score in the K-BIT 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, including 29 monolingual (17 boys) and 27 bilingual (11 boys) children. All the bilingual children spoke English at school and in the community and 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 in which 1 meant "entirely in English" and 5 meant "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 in a quiet room in their school on three tasks. 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 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 minutes and children were given stickers upon 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—This 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 vs. 4 stimuli) with two conflict levels (central presentations vs. side presentations).

Center-2: An illustration of this task is presented in Figure 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 side of the keyboard and were marked with a sticker indicating the color of the designated figure. The assignment of the key to 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 response.

Conflict-2: The parameters were the same as in the previous condition but the stimulus appeared either on the right or the left side of the screen (see Figure 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 condition center-2 except that there were four stimuli: blue cloud, green tree, yellow smiley, and pink star. Children were instructed to press one key for two of the stimuli (blue cloud and yellow smiley) and the other key for the other two stimuli (green tree and pink star). The instructions were presented as four individual rules, one per stimulus (i.e., “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.

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 almost all children learned the task after one practice block. The four conditions were presented in two sets beginning with the two conditions based on two stimuli and then, after a break to complete the K-BIT, the two conditions based on four 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 vs. 4 stimuli) and other executive control demands (center 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 performance on 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 (ANOVA) for each background measure with gender and language group as between-subjects factors showed no differences in age, $F_s < 1$, and K-BIT scores, $F_s < 1$. 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, $F(1,52) = 10.44$, $d = 0.88$, $p = .002$, 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, three participants were excluded (2 bilinguals, 1 monolingual) because they did not complete all the blocks. Accuracy data are reported in Table 2. Non-conflict and conflict blocks were analyzed separately because the conflict block contained a factor for congruence that was not present in the centrally-presented non-conflict block. A two-way ANOVA for language group and working memory level (2 vs. 4) on accuracy in the non-conflict block showed a main effect of memory load, with children recalling fewer items in the 2-stimuli than in the 4-stimuli condition, $F(1,51) = 11.41$, $d = 0.49$, $p = .001$, and no difference between language groups and no interaction effect, $F_s < 1$.

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), $F(1,51) = 12.63$, $d = 0.38$, $p < .001$, a main effect of congruence, $F(1,51) = 11.11$, $d = 0.43$, $p = .001$, with higher scores for congruent trials ($M = 94.5$, $SD = 6.3$) than incongruent trials ($M = 91.3$, $SD = 8.4$), and significant interactions of congruence by language, $F(1,51) = 4.56$, $\eta^2_p = .082$, $p = .04$, and congruence by working memory load, $F(1,51) = 11.09$, $\eta^2_p = .18$, $p = .001$. For the congruence by language interaction, there was no effect of congruence for bilinguals, $F < 1$ (for congruent $CI_{.95} = 92\text{--}96\%$, and for incongruent $CI_{.95} = 90\text{--}96\%$), but a significant effect for monolinguals, $F(1,27) = 13.00$, $d = .39$, $p = .001$, with higher accuracy in congruent ($CI_{.95} = 93\text{--}97\%$) than in incongruent trials ($CI_{.95} = 86\text{--}92\%$). 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 only found for the 2-stimulus condition, $F(1,51) = 14.85$, $d = .51$, $p < .001$, (for congruent $CI_{.95} = 93\text{--}96\%$ and for incongruent $CI_{.95} = 85\text{--}91\%$) but not for the 4-stimulus condition, $F < 1$, (for congruent $CI_{.95} = 93\text{--}97\%$ and for incongruent $CI_{.95} = 92\text{--}96\%$).

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

For the conflict condition, a three-way ANOVA revealed main effects of working memory load $F(1,51) = 90.37$, $d = 1.56$, $p < .001$, with faster responding to 2-stimulus trials, language group, $F(1,51) = 4.48$, $d = 0.44$, $p = .039$, with bilinguals responding faster than monolinguals, $F(1,51) = 4.48$, $d = 0.44$, $p = .039$, and congruence, $F(1,51) = 36.17$, $d = 0.28$, $p < .001$, 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 monolingual children 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). Importantly, there were no significant correlations between PPVT scores and any of the dependent variables, so this difference did not affect experimental outcomes.

In the non-conflict condition, all children showed a high level of accuracy, with correct responses provided to over 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 difficult than congruent trials for monolinguals, the misleading cues did not increase task difficulty for the bilinguals. These findings are consistent with evidence from studies using a Simon task (Martin-Rhee & Bialystok, 2008) or flanker task (Carlson & Meltzoff, 2008; Yang, Yang & Lust, 2011) showing an advantage in conflict resolution for bilingual children.

RT data showed that bilingual children were faster than monolinguals, even in the simpler non-conflict 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 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 the 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 task (Gathercole, Pickering, Ambridge, & Wearing, 2004b; 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 et al. (2004) for adults, in which the bilinguals outperformed monolinguals on a condition requiring them to hold 4 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 a better management of information in working memory.

In sum, bilingual children performed the task more efficiently than monolingual children, 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 required participants to recall the positions of the presented stimuli, the VPT presents all the stimuli at the same time, requiring only recall of positions, but the Corsi blocks task presents the stimuli sequentially, increasing memory demands to maintain and possibly manipulate the order of presentation. They found that Corsi performance was affected by the inclusion of a dual task whereas performance on 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 one: 5-years old are not yet capable of carrying out complex working memory tasks that involve manipulation of information, but 7-year old children have developed this skill (Gathercole et al., 2004a; Miles et al., 1996).

In Study 1 using a simple task, we showed that monolingual and bilingual children at 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 the ages 5- to 7-years old (Gathercole et al., 2004a; 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 present 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-old children from Study 1 and a new sample of 69 7-year-old children (mean age = 6 years, 11 months, $SD = 2.76$ months) participated in the study (see Table 1). The new sample was composed of 33 monolingual children (16 males) and 35 bilinguals (18 males). All children lived in the same middle-class neighborhoods and all parents reported having at least some post-secondary education. As in Study 1, the bilingual children spoke English at school and in the community and 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 ($SD = .95$), 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 (FMT): The 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 had to remember which ponds had frogs in them. For sequential presentation, the ponds needed to be recalled in the correct order. In the simultaneous presentation condition (Figure 3a), all the frogs were shown for 2000 ms and 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 (Figure 3b), each frog occupied the pond for one second. After the last frog disappeared, a “ding” sound indicated that the child could by touching each pond in which there had been a frog in the order in which they had been shown. Testing began with 2 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 were a total of 10 trials per condition.

Memory span was calculated as the longest string length in which the child remembered all 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 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 2 frogs (2+2) and on one of the trials containing 3 frogs (3), but missed one of the frogs in the second trial with three frogs (2),

and failed in both trials containing 4 frogs, remembering 3 frogs in the first trial and 2 in the second, then child's span would be 3 and total score would be $2+2+3+2+3+2=12$ or 0.3. For the sequential condition, the total possible was 80 because one point was awarded for each correct location and one 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).

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, $F_s < 1$. Three-way ANOVAs for gender, language and age group showed no differences in K-BIT for any factor, $F_s < 1$. However, for the PPVT standard scores there were main effects of language, $F(1,117) = 24.66$, $d = 0.78$, $p < .001$, and age group, $F(1,117) = 13.80$, $d = .66$, $p < .001$, with no differences by gender and no significant interactions. Scores were higher for monolinguals and 5-years old children. Since PPVT scores are standardized by age, we assume that the difference between 5-year-old and 7-year-old 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-years old monolingual was excluded as 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, $F(1,120) = 187.17$, $d = 1.56$, $p < .001$, with higher scores for the simultaneous presentation ($M = 5.3$, $SD = 1.1$) than sequential presentation ($M = 3.5$, $SD = 1.2$), and age group, $F(1,120) = 14.81$, $d = 0.45$, $p = .001$, with the older children reaching 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, $F(1,120) = 172.59$, $d = 1.22$, $p < .001$, with higher scores for the sequential presentation ($M = 0.78$, $SD = 0.26$) than simultaneous presentation ($M = 0.50$, $SD = 0.21$), age group, $F(1,120) = 6.31$, $d = 0.34$, $p = .01$, with higher scores for older children ($M = 0.68$, $SD = 0.22$) than younger children ($M = 0.60$, $SD = 0.24$), and language group, $F(1,120) = 4.17$, $d = 0.35$, $p = .04$, with higher scores for bilinguals ($M = 0.68$, $SD = 0.27$) than monolinguals ($M = 0.60$, $SD = 0.27$). There was a significant two-way interaction of condition by language group, $F(1,120) = 3.73$, $\eta^2_p = .03$, $p = .05$. Pairwise comparisons revealed that language group differences were significant in the difficult sequential condition, $F(1,120) = 9.97$, $d = .61$, $p = .002$ (for monolinguals $CI_{.95} = .39-.49\%$, and for bilinguals $CI_{.95} = .50-.60\%$), but not in the easier simultaneous condition, $F < 1$, (for monolinguals $CI_{.95} = .71-.84\%$, and for bilinguals $CI_{.95} = .74-.86\%$). The three-way interaction of language group by age group by condition was also significant, $F(1,120) = 4.53$, $\eta^2_p = .035$, $p = .03$. For bilinguals there were no differences in age for the simultaneous condition $F < 1$ (for 5-year-olds $CI_{.95} = .70-.87\%$, and for 7-year-olds $CI_{.95} = .72-.89\%$), but there was an advantage for older in the sequential condition $F(1,120) = 5.05$; $d = .50$, $p = .02$ (for 5-year-olds $CI_{.95} = .42-.57\%$, and for 7-year-olds $CI_{.95} = .54-.67\%$). For monolinguals, older children performed better in the simultaneous condition, $F(1,120) = 5.73$; $d = .41$, $p = .01$ (for 5-years old $CI_{.95} = .60-.79\%$, and for 7-years old $CI_{.95} = .76-.93\%$), but not in the sequential condition $F(1,120) = 1.4$; d

$= .29$ $p = .2$ (for 5-years old $CI_{.95} = .34-.48\%$, and for 7-years old children ($CI_{.95} = .40-.53\%$). Therefore, 5-year-old bilingual children performed at the same level as 7-year-old monolingual children in the simpler simultaneous condition.

Discussion

As in previous research, children performed better in the simultaneous condition than they did 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., 2004b; 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 three-way interaction revealed that the younger bilingual children performed better than their monolingual counterparts on the simpler simultaneous condition.

General Discussion

The two studies addressed the question of whether bilingual advantages could be found in working memory and if so, if 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 had to hold 2 or 4 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 had 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 monolingual children 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 are 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 present study 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 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 present 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 present results is for conceptions of the relation among components of the executive function. The bilingual advantage in the working memory tasks in the present 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 non-conflict blocks, and in Study 2, bilingual children outperformed monolinguals in total score for both the simpler and more difficult memory condition. 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 may 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 independently of other executive control components, but the results from the present studies show that the outcomes depend on the other task demands. It is also consistent with an interpretation offered by Hilchey and Klein (2011) in which they attribute the bilingual advantage, not to a specific component such as inhibition, but to an overall ability to monitor attention (see also Costa et al., 2009). Thus, the present results endorse a view which attributes an advantage to bilingual children on working memory tasks as well as defining a role for other task demands in controlling those outcomes.

The present 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 such experiences as musical training and video game playing, bilingual children are not typically pre-selected for talent or interest. The children in the present 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.

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Figure 1. Pictures Task. (a) Procedure employed in the pictures task, center conditions. (b) Type of trials in the conflict conditions. (c) Stimuli and type of trials in the conflict conditions by memory load.

(a) Non-conflict condition

(b) Conflict conditions

Figure 2.

Mean response times (and standard error) by language group for the Pictures Task (in milliseconds) in Study 1 for (a) the non conflict block based on central presentation and (b) the conflict block based on side presentation of stimuli.

(a) Simultaneous presentation

(b) Sequential presentation

Figure 3. Sample items for the (a) simultaneous and (b) sequential presentation of the Frogs Matrices Task in Study 2.

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

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

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Table 2
Mean percentage of correct responses (and standard deviations) for the Pictures Task by language group in Study 1.

Block	WM	Trial	Monolingual		Bilingual		Overall	
			Mean	(sd)	Mean	(sd)	Mean	(sd)
Non-Conflict	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)

Table 3

Mean scores (and standard deviations) of span and proportion correct scores for FMT Tasks 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	0.70 (.28)	0.79 (.25)	0.83 (.23)	0.81 (.26)
	Sequential	0.41 (.17)	0.50 (.26)	0.46 (.17)	0.61 (.18)