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Brief Report

Coordination of executive functions in monolingual and bilingual children

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ABSTRACT

Two groups of 8-year-old children who were monolingual or bilingual completed a complex classification task in which they made semantic judgments on stimuli that were presented either visually or auditorily. The task requires coordinating a variety of executive control components, specifically working memory, inhibition, and shifting. When each of the visual and auditory tasks was presented alone, performance was comparable for children in the two groups. Combining the two modalities into a dual-task paradigm made the task more difficult, and on this combined task bilingual children maintained better accuracy than monolingual children, especially on the visual task. The results are interpreted in terms of the enhanced ability of bilingual children to coordinate the executive control components required in performing this complex task.

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Introduction

The development of executive control is one of the most significant cognitive achievements during childhood (Carlson, 2005; Jones, Rothbart, & Posner, 2003; Zelazo, Carlson, & Kesek, 2008), a process that continues into adolescence (Best, Miller, & Jones, 2009). The majority of the research investigating this issue examines development of the component processes that together make up the executive function. One framework commonly used for this purpose is that proposed by Miyake and colleagues (2000) consisting of three core components: selective attention and inhibition, shifting, and working memory. Although there continues to be debate about the precise core components, the approach has led to productive research showing the gradual emergence of executive control during the early years and the expanding repertoire of the cognitive behaviors it supports.

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There are two limitations to this approach. The first is that the contributions of individual core components are difficult to isolate empirically and relate to complex performance that is characteristic of real-life tasks. Experimental tasks rarely produce pure measures of these components (Best & Miller, 2010), and in studies that attempt to isolate them performance is typically best described by interactions among multiple components (Garon, Bryson, & Smith, 2008). Because real-life tasks rarely recruit a single core component, the components need to be managed and coordinated for effective performance and the ability to manage them might be different from their individual development. Thus, some higher order management function might be another aspect of the development of executive control. Multitasking is an example of an everyday performance in which a variety of executive control components are required and is difficult to understand in terms of individual components.

The second limitation is that experience may modify the development of executive control, requiring more complex descriptions of development. Bilingualism has been shown to be one such experience (for a review, see Bialystok, Craik, Green, & Gollan, 2009). Executive control develops earlier in bilingual children than in comparable monolinguals (Adi-Japha, Berberich-Artzi, & Libnawi, 2010; Bialystok, 2010; Carlson & Meltzoff, 2008; Yang, Yang, & Lust, *in press*), and bilingual adults continue to outperform monolinguals on such tasks (Bialystok, Craik, Klein, & Viswanathan, 2004; Colzato et al., 2008; Costa, Hernández, & Sebastián-Gallés, 2008; Prior & MacWhinney, 2010; Treccani, Argyri, Sorace, & Della Sala, 2009). The studies used different tasks, but all involved some subset of the component processes normally considered to be part of executive control. However, it is not known whether bilingualism affects individual core components or is a coordinating function that allows the components to function together. For example, in tasks such as the Simon task (Simon & Wolf, 1963) and the flanker task (Eriksen & Eriksen, 1974) that include congruent and incongruent trials, all participants perform equivalently on single blocks of congruent trials but bilinguals outperform monolinguals on both congruent and incongruent trials when presented in mixed blocks (Bialystok et al., 2004; Costa et al., 2008). At a minimum, these results indicate that the bilingual performance cannot be attributed to a single component such as inhibition, even though inhibition is clearly affected by bilingualism (Blumenfeld & Marian, 2011). Thus, a more complete understanding of the development of executive control is obtained by examining groups with different relevant experiences.

Why would bilingualism modify executive control? There is now overwhelming evidence that both languages are always active to some degree, even in contexts that clearly support only one of the languages (e.g., Francis, 1999; Grainger, 1993; Kroll & de Groot, 1997; Rodríguez-Fornells, Rotte, Heinze, Nosselt, & Munte, 2002; Thierry & Wu, 2007). For example, Marian, Spivey, and Hirsch (2003) conducted an eye movement study with Russian–English bilinguals using the visual world paradigm and showed that eye movements to pictures of words named in English were disrupted by pictures in the stimulus array whose Russian translation had overlapping phonology with the English target item. There was no reason to process the Russian name for the object, but participants did this automatically and that Russian name affected performance on the English task. Therefore, bilingualism places individuals in a “dual-task” situation for which executive control is constantly required. Speakers must construct speech plans according to the current context (i.e., working memory), selectively attend to linguistic structures in the target language while ignoring competition from the other language (i.e., inhibition), and monitor progress of the interaction (i.e., shifting). Thus, the impact of bilingualism may be found less in the individual core components of executive control than in their coordination and management to enable bilingual language use.

The possibility that bilingualism enhances performance in a dual-task situation was tested by Bialystok, Craik, and Ruocco (2006). Younger and older participants who were monolingual or bilingual classified stimuli into two semantic categories. The stimuli were presented either visually and required a manual key press or auditorily and required a spoken response. Tasks were performed separately and then combined into a dual-task presentation. The semantic categories were letters or numbers and animals or musical instruments. For the visual task, the letter–number stimuli were strings of digits or letters and the animal–music stimuli were colored photos presented in the center of the computer monitor. For the auditory task, the letter–number stimuli were the names of letters or numbers spoken by a female voice and the animal–music stimuli were WAV files of those sounds

played through headphones. The dependent variable was the number of correctly classified items in each condition. Bilinguals of both age groups were able to correctly classify more items than monolinguals in the dual-task condition when the visual task consisted of items from the letter–number category, but no language group differences were found in the animal–music task.

The current study adapted this paradigm to investigate how bilingualism influences children's performance in a complex task that requires coordination of several components of executive control. Multitasking is a common activity that involves all three core components and, therefore, requires their coordination. Thus, rather than focusing exclusively on individual processes, the task examines the ability to manage a complex set of executive control demands. Only stimuli from the animal–music classification were used. Unlike the previous study (Bialystok et al., 2006), the two stimuli in the dual-task conditions were presented simultaneously; participants could respond to either modality first and the next trial began after both responses had been registered. In contrast to previous research that focused on individual components of executive control, the current study investigated the coordination of these components in complex performance with less attention to their individual contribution. The components themselves may be at different levels as well in the two groups, but the assumption is that the need for coordination is above and beyond those individual levels. Therefore, a bilingual advantage in this task would contribute to understanding the differences previously reported and would have implications for understanding the role of executive control in a world where multitasking is increasingly common.

Method

Participants

The participants were 63 8-year-olds who lived in the same middle-class neighborhoods and attended the same local public schools. There were 32 monolingual children (21 girls and 11 boys) and 31 bilingual children (15 girls and 16 boys). Prior to the study, parents provided signed consent and completed the Language and Social Background Questionnaire (LSBQ) to describe the home language environment. Parents rated features of the environment on a series of 5-point scales in which 1 indicated *always in English* and 5 indicated *always in the non-English language*. The questions included language spoken to the child, language spoken by the parents to each other, language spoken by siblings to each other, language in which videos were watched, and so on. An average score of 3 indicates that home language use was divided evenly between the two languages. These scores, reported in Table 1, were different for the two groups, $F(1, 50) = 132.67$, $p < .0001$. The bilingual participants spoke English plus one of Cantonese (3), Farsi (1), Gujarati (1), Korean (2) Mandarin (4), Persian (1), Romanian (4), Spanish (3), Tamil (8), Turkish (1), Urdu (1), or Vietnamese (2). The questionnaire also recorded information about parents' education as a proxy for socioeconomic status (SES) and showed no significant difference between groups (see Table 1).

Table 1
Mean scores (and standard deviations) for background measures by group.

	Monolinguals	Bilinguals
<i>n</i>	32	31
Age (months)	103.6 (3.7)	103.4 (3.4)
Home language environment	1.0 (0.1)	2.4 (0.6)
Father's education ^a	3.1 (1.1)	2.8 (1.3)
Mother's education ^a	3.0 (1.0)	2.5 (1.3)
PPVT standard score	108.2 (13.1)	104.4 (12.3)
Kbit standard score	99.6 (14.9)	100.5 (12.5)

^a Education was quantified using a 5-point scale where 1 = *no high school diploma*, 2 = *high school graduate*, 3 = *some college or college diploma*, 4 = *bachelor's degree*, and 5 = *graduate degree*.

Tasks and procedures

Participants were tested individually in a quiet space in their school. Tasks were administered in a fixed order: The session began with the dual-modality classification task (DMCT) followed by the matrices subtest of the Kaufman Brief Intelligence Test (Kbit) (Kaufman & Kaufman, 1990) to measure general intelligence and the Peabody Picture Vocabulary Test III (PPVT-III) (Dunn & Dunn, 1997) to measure English receptive vocabulary. Both the Kbit matrices and the PPVT were administered according to standard instructions, and scores were converted to standard scores following the procedures described in the manuals. The session lasted approximately 30 min.

The DMCT was presented on a 10-in. ThinkPad X-series laptop. Children classified visual and auditory stimuli as animals or musical instruments. Testing began with single-task block for each modality and was followed by a dual-task block in which the visual and auditory stimuli were presented simultaneously. Reaction time (RT) and accuracy were recorded for all trials.

The stimuli in the visual task were pictures of 25 animals and 25 musical instruments, and the stimuli in the auditory task were WAV files capturing the sound of 25 animals and 25 musical instruments. Each trial began with a fixation “+” in the center of the screen that remained visible for 500 ms. Following this, the visual stimulus appeared in the location that the fixation had occupied and remained on the screen for 1000 ms, and the WAV file for the auditory stimulus was played through headphones. This was followed by a blank screen for 2000 ms or until a response was made. The RT clock began with the onset of the stimuli. For the visual task, the keyboard keys J and L were covered with stickers marked “A” (for animal) and “M” (for musical instrument). In the auditory task, responses were made verbally by saying the word “animal” or “music” into a microphone that triggered an RT response.

There were 25 trials in the single-modality block and 50 trials in the dual-modality condition, presented in randomized order. These trials were further designated as match or mismatch trials, indicating whether the visual and auditory stimuli were from the same category or different categories, respectively. Practice trials with feedback preceded each block. At the end of the testing session, children were given a small gift for their participation.

Results

Background data are reported in Table 1. There was no difference between groups in age, $F < 1$, Kbit score, $F < 1$, or PPVT, $F(1, 61) = 1.46$, *ns*. RTs and accuracy for the DMCT are shown in Table 2. RT data are for correct responses, excluding RTs less than 250 ms and greater than 2500 ms. All analyses were initially conducted with gender as a between-groups factor, but none of the main effects or interactions was significant, all F s < 1 , so analyses presented are collapsed across gender.

RT data were analyzed with a three-way analysis of variance (ANOVA) for language group, condition, and modality. There was a main effect of condition in which the single task was performed more rapidly than the dual task, $F(1, 60) = 152.48$, $p < .0001$, a main effect of modality, $F(1, 60) = 11.56$, $p < .001$, and an interaction of condition and modality, $F(1, 60) = 145.01$, $p < .0001$. The visual task was faster in the single-modality condition, $F(1, 60) = 59.57$, $p < .0001$, but the auditory task was faster in the dual-modality condition, $F(1, 60) = 35.30$, $p < .0001$, presumably because responses were typically made first to auditory stimuli. There was no effect for language group, $F < 1$. RT data in the dual task were categorized for congruence; in match trials both responses were from the same domain, and in mismatch trials they were from different domains. A three-way ANOVA for modality, congruence, and language group showed that match trials were faster than mismatch trials, $F(1, 60) = 35.30$, $p < .0001$, and auditory trials were faster than visual trials, $F(1, 60) = 4.51$, $p < .04$, with no effect of language group, $F < 1$, and no interactions.

A three-way ANOVA for language group, condition, and modality on accuracy scores revealed an effect of language group, $F(1, 61) = 4.26$, $p < .04$, condition, $F(1, 61) = 157.96$, $p < .0001$, interaction of modality and language, $F(1, 61) = 5.07$, $p < .02$, and interaction of condition and modality, $F(1, 61) = 9.18$, $p < .004$. To understand these results, separate two-way ANOVAs were conducted for each condition. For the single task, there were no effects for any factor: language group,

Table 2

Mean scores (and standard deviations) for accuracy (% correct) and RTs (ms) in dual-modality classification task by language group.

	Reaction time (ms)	
	Monolinguals	Bilinguals
<i>Single-task conditions</i>		
Visual	692 (93)	692 (77)
Auditory	1065 (440)	982 (217)
<i>Dual-task conditions</i>		
Visual	1412 (389)	1335 (362)
Match	1404 (408)	1295 (360)
Mismatch	1419 (392)	1376 (377)
Auditory	1257 (344)	1171 (317)
Match	1255 (355)	1121 (332)
Mismatch	1259 (374)	1221 (382)
	Accuracy (% correct)	
	Monolinguals	Bilinguals
<i>Single-task conditions</i>		
Visual	85.9 (9.5)	89.3 (8.9)
Auditory	89.6 (5.5)	89.4 (6.5)
<i>Dual-task conditions</i>		
Visual	65.3 (16.7)	75.2 (12.4)
Match	76.6 (15.7)	80.1 (13.9)
Mismatch	60.2 (22.5)	64.3 (17.0)
Auditory	64.7 (18.3)	68.2 (12.8)
Match	72.6 (16.5)	75.1 (13.5)
Mismatch	56.4 (23.1)	62.5 (17.8)

$F(1, 61) = 1.86$, *ns*, modality, $F(1, 61) = 1.44$, *ns*, or their interaction, $F(1, 61) = 3.39$, *ns*. In contrast, the dual-modality condition indicated a significant effect of language group, $F(1, 61) = 3.93$, $p = .05$, $d = 0.49$, with higher scores for bilinguals; modality, $F(1, 61) = 4.84$, $p < .03$, $d = 0.24$, with higher scores for the visual task; and a trend toward an interaction between the two, $F(1, 61) = 3.50$, $p = .06$, limiting the language group difference to the visual task. Considering only the visual task, the higher accuracy for bilinguals was substantial, $F(1, 61) = 7.04$, $p < .01$, $d = 0.67$.

The effect of congruence was examined by a three-way ANOVA for congruence, modality, and language group. The results indicated that match trials were more accurate than mismatch trials, $F(1, 61) = 78.65$, $p < .0001$, $d = 0.99$, and visual responses were more accurate than auditory responses, $F(1, 61) = 4.17$, $p < .05$, $d = 0.23$, with no difference between language groups, $F(1, 61) = 1.30$, *ns*, and no interactions.

Differences between language groups were further explored by comparing the number of children in each language group who passed or failed each condition. The criterion for passing was set at 60% correct because scores below this level were not different from chance, $t < 1$. All children achieved the pass criterion for the single-modality task. The distributions showing the

Table 3

Frequency distributions for pass/fail by language group for each response type in the dual-modality condition using a criterion of 60% correct for pass.

	Fail	Pass
<i>(A) Distribution for responses to visual stimuli</i>		
Monolinguals	15	17
Bilinguals	3	28
<i>(B) Distribution for responses to auditory stimuli</i>		
Monolinguals	14	18
Bilinguals	8	23

number of children passing in each language group for the dual-modality task are shown in Table 3. For the visual responses (Table 3A), more bilinguals passed than monolinguals, $\chi^2(1) = 10.68$, $p < .001$, but for the auditory responses (Table 3B), the distributions were not significantly different, $\chi^2(1) = 2.23$, $p = .13$.

Discussion

The monolingual and bilingual children were matched on a variety of background measures and performed the simple task, in which classifications were conducted in a single modality, with the same accuracy and the same speed. Not surprisingly, combining these tasks into a paradigm that required simultaneous judgments in both modalities made the task more difficult. Although accuracy decreased for all children, performance in these dual-modality conditions was significantly better for bilingual children than for monolinguals, at least on the visual task. Similarly, using a categorical pass/fail criterion, bilingual children met the threshold for the visual component in the dual-task presentation more frequently than did monolinguals. Although the language group differences in RT did not reach significance, the task effects showed the same patterns as the accuracy data. Importantly, therefore, the bilingual advantages in accuracy came with no cost to RT.

The dual-modality conditions recruited all three core executive control components: hold rules in mind for categorizing in the two modalities (i.e., working memory), attend to the classification for the target response while ignoring the other modality (i.e., inhibition), and shift attention across the stimuli so that both responses could be completed (i.e., shifting). There was no evidence that any one of these components was carried out more effectively by the bilingual children, but their coordination or joint recruitment in the dual-task situation was more efficient; the bilingual advantage was equivalent for match and mismatch trials in the same way that previous research has shown equivalent advantages for congruent and incongruent trials in mixed presentations. The interpretation is that bilingual language use requires coordination of these component processes in that speakers must attend to two representations, ignore interference from the nontarget language, and switch appropriately between representations. This experience in managing attention to two language systems improves performance broadly and extends to other systems based on the activation and attention to two representations.

Each of the response modalities required somewhat different processes, and the bilingual advantage was found only for the visual responses that were associated with a key press. The auditory stimuli required producing the name of the category, and lexical production is slower and more effortful for bilinguals than for monolinguals (Michael & Gollan, 2005). Thus, verbal production may have been a limitation on bilingual performance in the auditory task. This possibility could be confirmed in a design that included the opposite pairings, namely verbal response to visual stimuli and manual response to auditory stimuli. Nonetheless, the pattern in which the benefit is found in only (or especially) one of the tasks is consistent with previous research using dual-task paradigms (e.g., Morris, Gick, & Craik, 1988). Similarly, in the study by Bialystok and colleagues (2006), bilinguals outperformed monolinguals in the dual-task condition for the more automatic letter–number classification but not for the more effortful animal–music classification that required interpretation before stimuli could be classified.

These results contribute to understanding how bilingualism affects the development of executive control in children. The task required children to make complex judgments, recruiting all components of the executive function system, and bilingual children could do this more effectively than their monolingual counterparts. Because no one component was especially responsible and no interaction between language group and component was found, the results lend support to the interpretation that bilingualism enhances a general network of executive control, possibly in addition to targeting specific core components such as inhibition (cf. Bialystok & Martin, 2004) or shifting (cf. Meuter & Allport, 1999). Research based only on monolingual children has been unable to uncover this effect, which is an integral part of the executive function system. Thus, an important outcome of bilingualism may be in managing executive control components to address complex goals. Because most real-life tasks are integrative and based on networks of control, the effect of bilingualism on cognitive performance during childhood may be more powerful than previously believed.

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