

Bilingualism, Aging, and Cognitive Control: Evidence From the Simon Task

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Previous work has shown that bilingualism is associated with more effective controlled processing in children; the assumption is that the constant management of 2 competing languages enhances executive functions (E. Bialystok, 2001). The present research attempted to determine whether this bilingual advantage persists for adults and whether bilingualism attenuates the negative effects of aging on cognitive control in older adults. Three studies are reported that compared the performance of monolingual and bilingual middle-aged and older adults on the Simon task. Bilingualism was associated with smaller Simon effect costs for both age groups; bilingual participants also responded more rapidly to conditions that placed greater demands on working memory. In all cases the bilingual advantage was greater for older participants. It appears, therefore, that controlled processing is carried out more effectively by bilinguals and that bilingualism helps to offset age-related losses in certain executive processes.

Research in cognitive aging has advanced enormously in the past few decades, producing detailed studies and sophisticated models of age-related changes in cognitive functions (see chapters in Craik & Salthouse, 2000). Most of this research involves English-speaking participants, and conclusions have been drawn with little or no regard to the possibility that the participants might also speak another language. Yet the existing evidence strongly suggests that bilingualism has an effect on cognitive processing, at least for children and younger adults (see chapters in de Groot & Kroll, 1997, and Harris, 1992). What has not been examined is whether these effects persist over the life span and continue to influence changes in cognitive processing in bilingual older adults. One current reality is that bilingualism is increasingly common in many countries. As an example, the 1996 Canadian Census reported that approximately 11% of Canadians spoke English or French at home in addition to some other language; when only respondents over age 65 were considered, the figure was 13% (Canada Census 1996, n.d.). In the United States, 17.9% of Americans reported that they spoke a language other than English at home, and it is a reasonable assumption that most of them also speak English (U.S. Census Bureau, 2003). Given the prevalence of bilingualism in North American society (and the prevalence is certainly greater in most European countries), it is important to

establish the precise effects of bilingualism on cognitive processing and the way in which these effects are modulated by aging.

Studies involving adult bilinguals have focused largely on psycholinguistic aspects of language use, so most of these studies have investigated only bilingual participants to compare processing in the two languages. A few studies on lexical processing that have included between-groups comparisons have reported bilingual disadvantages on some tasks, such as lexical decision (Ransdell & Fischler, 1989) and semantic fluency (Gollan, Montoya & Werner, 2002). In a review of this literature, Michael and Gollan (in press) point out that these deficits are quite limited, but they attribute the observed reduction in fluency to the bilingual's need to maintain a vocabulary base approximately twice as large as that of a monolingual and to the reduced frequency with which bilinguals access any particular word. These conditions result in weaker links between words and concepts for bilinguals; semantic fluency tasks, these authors argue, are a measure of the strength of these word-concept associations. Although some research has examined the role of cognitive processes such as working memory in the acquisition of a second language (Harrington & Sawyer, 1992; Miyake, 1998), very little research has investigated whether those processes are modulated by bilingualism.

Research with children has addressed the cognitive impact of bilingualism more directly. Bilingual advantages have been reported across a variety of domains, for example, creativity (Kessler & Quinn, 1987), problem solving (Bain, 1975; Kessler & Quinn, 1980), and perceptual disembedding (Duncan & De Avila, 1979). Positive effects for bilinguals, however, have not always been found; some studies reported negative effects (Macnamara, 1966), and others found no group differences (Rosenblum & Pinker, 1983). The disparate findings can be resolved by considering the cognitive processes implicated in the various tasks used to assess the effects of bilingualism. In general, tasks showing a bilingual

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advantage are characterized by the presence of misleading (usually perceptual) information and the need to choose between competing response options; tasks based more heavily on analytic knowledge or detailed representations of knowledge presented without a misleading context are solved equally well by monolinguals and bilinguals. This difference corresponds to the difference between control and representational processes, respectively. The functions contributing to control include selective attention to relevant aspects of a problem, inhibition of attention to misleading information, and switching between competing alternatives. The functions involved with representation include encoding problems in sufficient detail, accessing relevant knowledge, and making logical inferences about relational information. Research by Bialystok has shown that bilingual children develop control processes more readily than do monolingual children but that the two groups progress at the same rate in the development of representational processes (for reviews, see Bialystok, 1993, 2001).

Why would bilingualism enhance the development of children's control processes? Evidence from psycholinguistic studies of adult language processing shows that the two languages of a bilingual remain constantly active while processing is carried out in one of them (Bryson, 1998; Francis, 1999; Gollan & Kroll, 2001; Kroll & Dijkstra, 2002; Smith, 1997). The joint activity of the two systems requires a mechanism for keeping the languages separate so that fluent performance can be achieved without intrusions from the unwanted language. Green (1998) proposed a model based on inhibitory control in which the nonrelevant language is suppressed by the same executive functions used generally to control attention and inhibition. If this model is correct, then bilinguals have had massive practice in exercising inhibitory control, an experience that may then generalize across cognitive domains. If the boost given by childhood bilingualism is sufficiently strong, bilingualism may continue to influence certain control processes throughout the life span. Two questions follow from this possibility. The first is whether the advantages found for young children in executive processes are also seen in adult bilinguals. The second is whether such advantages are maintained in older adulthood and protect bilingual adults from the normal decline of these processes that occurs with age.

With regard to aging, it is well established that the representational functions that depend on well-learned knowledge and habitual procedures ("crystallized intelligence") hold up well in the later adult years, whereas abilities that depend on executive control processes ("fluid intelligence") show a marked decline in efficiency. In the former category, vocabulary levels (Park, 2000; Salthouse, 1991), general world knowledge (Salthouse, 1982), and language use (Wingfield & Stine-Morrow, 2000) all show little age-related decline. In contrast, executive control functions undergo declining efficiency with aging. In perceptual processing, older adults are less able to ignore irrelevant stimuli (Rabbitt, 1965) and to attend selectively to important aspects of the environment. Less effective attentional processes result in less efficient detection, discrimination, and selection of wanted stimuli, reduced resistance to interference, and impaired inhibition of information that is unimportant or irrelevant (McDowd & Shaw, 2000). Hasher and Zacks (1988) argued that much of the observed decline in cognitive functioning is the result of a decline in the effectiveness of inhibitory processes, although that general conclusion has been called into question by the results of more recent studies (e.g., Kieley & Hartley, 1997; Kramer & Strayer, 2001) and modified

and refined by Hasher and Zacks themselves (Hasher, Zacks, & May, 1999; Zacks, Hasher, & Li, 2000). What does seem clear is that older adults show a decline in the effectiveness of executive control processes in many situations unless task performance depends on strongly ingrained habits (Hay & Jacoby, 1996, 1999) or is well supported by the environmental context (Craik, 1986). In summary, then, children's cognitive development is characterized by a growth in both control of attention and representational complexity, whereas aging leads to a decline in the effectiveness of attentional control but not in the ability to utilize habitual procedures and representational knowledge. Bilingual children, therefore, experience a boost in the development of the types of cognitive processing that typically decline with aging.

A formidable obstacle to conducting research that allows meaningful comparisons of young children and older adults is the identification of a task that is suitable for all ages. Most of the research with young children has been based on tasks that are trivially easy even for older children, and studies of adult performance typically require expertise and endurance beyond the ability of children. Therefore, a task is needed that is relatively content free but dependent on the cognitive processes proposed to characterize the performance advantage of bilingual individuals. A task that meets these criteria is the Simon task (see review in Lu & Proctor, 1995). The task is based on stimulus-response compatibility and assesses the extent to which the prepotent association to irrelevant spatial information affects participants' response to task-relevant nonspatial information. In our implementation of this task, colored stimuli were presented on either the left or the right side of a computer screen. Each of the two colors was associated with a response key that was also on one of the two sides of the keyboard, aligned with the two stimulus positions. On congruent trials, the key that was the correct response for that color was on the same side as the stimulus; on incongruent trials, the correct response key was on the opposite side. Numerous studies with this task have confirmed that the irrelevant location information results in reliably longer reaction times (RTs) for incongruent items.

The increased time needed to respond to the incongruent items is the Simon effect. Van der Lubbe and Verleger (2002) found a larger Simon effect in a group of older adults (mean age = 61 years) than in a comparable group of young adults (mean age = 25 years), even after correcting for the general slowing associated with aging. Therefore, the Simon task measures aspects of processing that decline with aging. The next question is whether the ability to attend to the stimulus and ignore the irrelevant location information reflects the same type of cognitive control that is enhanced in development by bilingualism. If this is the case, then the performance of young bilingual children should be less affected by the irrelevant spatial code of the target than the performance of comparable monolingual children; bilinguals, that is, should show a reduced Simon effect. Moreover, if the effects of bilingualism on cognitive processing persist through adulthood and into aging, then this advantage should be found as well for adult bilinguals. Finally, if lifelong bilingualism provides a defense against the normal decline of these control processes, then older bilinguals should show less decrement in control as measured by the Simon task than should comparable older monolinguals.

In two studies with 4-year-olds (Martin & Bialystok, 2003), bilinguals outperformed monolinguals on the Simon task, but contrary to prediction, the advantage was found for both the

congruent and incongruent trials. The advantage for bilinguals, therefore, may lie not in their enhanced ability to inhibit the misleading spatial cue but in their ability to manage attention to a complex set of rapidly changing task demands. The present studies extend this paradigm into adulthood and aging. In three studies, we had monolingual and bilingual younger and older adults perform versions of the Simon task to determine whether the processing differences shown by bilingual children would extend into adulthood and old age. If they did, the implication would be that the advantage in cognitive control goes beyond the management of language processing to cognitive processing in general and may ameliorate the age-related declines seen in many cognitive tasks.

Study 1

In the first study, we investigated possible effects of adult aging and language group on the Simon task by replicating the experiment conducted with monolingual and bilingual children (Martin & Bialystok, 2003). The parameters for this earlier experiment were designed to be appropriate for young children—there were long delays between events and very few trials. Although this design has many fewer trials than is typical in such studies, we decided that this preliminary experiment should replicate the design that had already produced language group differences in children. Nonetheless, it is worth noting that the original study by Simon and Wolf (1963) in which the effect was discovered included only 16 trials per condition.

Method

Participants

There were 40 participants who composed two language groups and two age groups. Twenty of the participants were younger adults ranging in age from 30 to 54 years (mean age = 43.0 years), and 20 were older adults ranging in age from 60 to 88 years (mean age = 71.9 years). In each age group, half the participants were monolingual English speakers living in Canada, and the other half were Tamil–English bilinguals living in India. Tamil is an alpha-syllabic language from the Southern Indian state of Tamil Nadu. The monolingual and bilingual participants in each group were matched on age so that a monolingual was included in the study if his or her age matched exactly that of one of the bilingual participants. There were equal numbers of men and women in each group. All participants were tested by the same experimenter (Mythili Viswanathan) using the same equipment and the same instructional protocols, although the actual testing was carried out in two different countries.

The bilingual participants learned Tamil as their first language and were educated in both languages beginning at the age of 6 years. Schooling was conducted primarily in English, but Tamil was both taught as a subject and used as the medium of instruction for some subjects. From the beginning of schooling, the participants had used both Tamil and English on a daily basis throughout their lives. Data from the language background questionnaire (described below) indicated that the average daily use of English was 56% and that of Tamil was 44%. Research with both bilingual adults (Kroll & Stewart, 1994) and bilingual children (Bialystok, 1988) has revealed that the cognitive and linguistic consequences of bilingualism are more salient for those bilinguals who are relatively balanced in their proficiency, so the criterion of balanced bilingualism was used for the selection of the sample in the present studies. The monolingual English participants lived in Canada and were not functionally fluent in any other language despite the inevitable language courses in school. All the participants in both groups had bachelor's degrees and shared similar middle-class socioeconomic backgrounds. The younger adults were recruited through e-mail postings,

and the older adults were recruited through flyers posted in community centers in both countries.

Tasks and Procedure

Language background questionnaire. This questionnaire was filled out by the experimenter while interviewing the participant on language use and fluency in his or her two languages. The language usage chart addressed the percentage usage of each language at home, at work, with friends, and overall. The responses indicate the extent to which each language is used daily and the degree to which the participant is functionally bilingual.

Peabody Picture Vocabulary Test—Revised (PPVT-R; Dunn & Dunn, 1981). This is a standardized test of receptive vocabulary. The test consists of a series of plates, each containing four pictures. The experimenter names one of the pictures, and the respondent indicates which picture illustrates that word. The items become increasingly difficult, and testing continues until the participant makes 6 errors in 8 consecutive items. The score is determined by tables that convert the raw score to a standard score in terms of the age of the respondent. The test was administered in English to all participants.

Raven's Standard Progressive Matrices (Raven, 1958). Raven's Matrices is an untimed test that measures abstract nonverbal reasoning ability. The test consists of 60 items arranged in five sets (A, B, C, D, and E) of 12 items each. Each item contains a picture with a missing piece. Below the picture, there are either six (Sets A and B) or eight (Sets C to E) possible pieces to complete the picture. Both the sets and the items within the sets are arranged in order of difficulty. Participants are given a score for each correct answer, and these raw scores are converted into standardized ranks through tables based on the participants' ages.

Simon task. The experiment was presented on a laptop Gateway Solo 2150 computer with a 12-in. monitor. The sequence of events and collection of data were controlled by a program running in DMDX (n.d.), which is a Win 32-based display system. Each trial began with a fixation cross (+) in the center of the screen, measuring $x = 0.48^\circ$, $y = 0.40^\circ$, that remained visible for 800 ms and was followed by a 250-ms blank interval. At the end of this interval, a red or blue square appeared on the left ($x = 0.02^\circ$, $y = 0.36^\circ$) or the right ($x = 0.82^\circ$, $y = 0.36^\circ$) side of the screen and remained on the screen for 1,000 ms if there was no response. Participants were instructed to press the left shift key (marked "X") when they saw a blue square and the right shift key (marked "O") when they saw a red square. The timing began with the onset of the stimulus, and the response terminated the stimulus; there was then a 500-ms blank interval before the onset of the next trial. The experiment began with eight practice trials, and participants had to complete all eight trials successfully to proceed to the experimental trials for that condition. If a mistake was made, participants were given additional practice trials until all eight trials were completed without an error, but only 1 participant needed to repeat the practice set to achieve error-free performance. The 28 experimental trials, half of which presented the square on the same side as the associated response key (congruent trials) and half of which presented the square on the opposite side (incongruent trials), were presented in a randomized order.

Results

The background measures of age, PPVT scores, and Ravens scores are shown in Table 1. A two-way analysis of variance (ANOVA) on the Ravens scores found no differences for either age or language group (both $F_s < 1$), and a similar analysis on the PPVT scores also found no differences for either age, $F(1, 36) = 1.51$, $p = .23$, or language group, $F(1, 36) = 2.76$, $p = .11$.

The mean accuracy scores and RTs for the congruent and incongruent trials in the Simon task as a function of age and language group are shown in Table 2. For the accuracy scores, a three-way ANOVA for age group (older, younger), language

Table 1
Mean Background Measures (and Standard Deviations) by Age and Language Group in Study 1

Measure	Younger		Older	
	Monolingual	Bilingual	Monolingual	Bilingual
Age (in years)	43.0 (7.3)	43.0 (7.3)	71.6 (7.5)	72.3 (8.7)
PPVT-R	91.0 (4.4)	91.8 (9.8)	85.8 (7.1)	91.9 (2.6)
Raven	1.4 (0.5)	1.3 (0.5)	1.5 (0.5)	1.3 (0.5)

Note. PPVT-R = Peabody Picture Vocabulary Test—Revised; Raven = Raven’s Standard Progressive Matrices.

group (monolingual, bilingual), and congruency (congruent, incongruent) showed that there were more errors on incongruent trials, $F(1, 38) = 42.21, p < .01$, and there were interactions of language and congruency, $F(1, 38) = 31.86, p < .01$, and of language, age, and congruency, $F(1, 36) = 7.34, p < .01$, that confined the difference to the older monolinguals in the incongruent condition. The high error rate in this condition (28%) suggests that the RT data should be treated with some caution. However, mean RTs were also very high in this condition, so the result is not due to a speed-accuracy trade-off.

The RTs were examined with a three-way ANOVA for age group, language group, and congruency. The younger adults were faster than the older adults, $F(1, 36) = 28.29, p < .01$; bilinguals were faster than monolinguals, $F(1, 36) = 16.12, p < .01$; and congruent items elicited faster responses than did incongruent items, $F(1, 36) = 55.88, p < .01$. There were two-way interactions between age and congruency, $F(1, 36) = 21.60, p < .01$, and between language and congruency, $F(1, 36) = 12.93, p < .01$, indicating that the magnitude of the difference between congruent and incongruent trials (the Simon effect, also shown in Table 2) was greater for the older adults and for the monolingual participants. The table shows that the age-related increase in the Simon effect was less for the bilingual groups (748 – 40 = 708 ms) than for the monolingual groups (1,713 – 535 = 1,178 ms), but the three-way interaction of age, language, and congruency was not significant, $F(1, 36) = 1.34, p = .25$, indicating that, statistically, the age-related increase in the Simon effect was as great for bilinguals as it was for monolinguals.

Discussion

The main purpose of Study 1 was to explore the feasibility of comparing the Simon task performance of older monolingual and

bilingual adults with that of children. All participants were comparable on measures of verbal and spatial intelligence and similar in educational and social background, but bilinguals were consistently faster in responding to the Simon task. The pattern of results replicated that obtained with children in that the bilinguals were faster overall; in addition, the bilinguals in the present study showed a smaller Simon effect in that the incongruent items were less disrupting. For the older participants, the bilinguals also avoided the increase in errors that characterized the performance of the older monolinguals.

For both age and language groups, incongruent items required longer response times than congruent items, and this difference (the Simon effect) was reliably smaller for the younger adults and for the bilinguals. The absence of a significant three-way interaction among age, language, and congruency means that the age-related increase in the Simon effect was as great for the bilinguals as for the monolinguals. Thus, the older adults and the monolingual participants in both age groups were less able to inhibit the negative influence of the incongruent spatial information, but bilingualism (against our prediction) did not attenuate the age-related decline in inhibitory effectiveness. Nevertheless, the age-related increase in the Simon effect was substantially less for the bilingual adults (708 ms) than for the monolingual adults (1,178 ms), but the analyses are based on relatively small sample sizes and involve high variance in the RTs. Therefore, we postpone a final conclusion concerning the effects of bilingualism on this inhibitory function until we consider the results of the next experiment, which involved more participants and more experimental trials.

The bilingual speed advantage was reliably larger for the incongruent items but still present for the congruent items. There are three possible reasons for this speed advantage: Bilinguals may

Table 2
Mean Accuracy and Reaction Time (RT; in Milliseconds) by Age and Language Group in Study 1

Age and language group	Congruent		Incongruent		Simon effect
	Accuracy (%)	RT (in ms)	Accuracy (%)	RT (in ms)	
Younger					
Monolingual	100	770 (132.8)	86.4	1,304 (273.0)	535 (231.2)
Bilingual	100	497 (252.5)	97.1	536 (273.0)	40 (32.2)
Older					
Monolingual	99.2	1,437 (560.6)	72.1	3,150 (1,309.6)	1,713 (971.7)
Bilingual	100	911 (374.2)	100	1,659 (1,151.0)	748 (806.6)

Note. Standard deviations are in parentheses.

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simply be faster, bilinguals may profit more from the facilitation on the congruent trials, which may disproportionately boost performance on these items, or bilinguals may be less disrupted by interference on the incongruent trials. We investigated these alternatives in the next study. In addition, the RTs in the present study were very long, even if one considers that the older adults had a mean age over 70 years. This may be due to the fact that the RTs were measured at very early stages of practice. In the next study, we investigated this possibility by using a more standard design that included more trials.

Study 2

In Study 1, bilinguals in both age groups performed the Simon task more quickly than comparable monolinguals and showed less interference from the position information in the incongruent trials. In all conditions, however, both the absolute RTs and the difference scores indicating the Simon effect were unusually large. The main reasons for this may be methodological: The small number of trials meant that participants were very unpracticed on the task, and the relatively slow presentation rate may have produced a slow overall rate of responding. The RTs obtained in Study 1 were similar to those produced by children using the same program—specifically, in the range of 1,000 to 2,000 ms. In addition, although the means of the Simon effect values in Table 2 show that the bilingual advantage was greater for older adults (965 ms) than for younger adults (495 ms), the interaction between age and language on the size of the Simon effect was not significant, $F(1, 36) = 1.34, p = .25$.

Study 2 was designed to build on the preliminary results of Study 1 in two ways. The first was by replicating the patterns of age and group differences using a more conventional design; participants in Study 2 completed 192 trials of the Simon task, in contrast to the 28 trials in Study 1. The second was by including conditions that would help to isolate the source of the bilingual advantage. The first condition was a control condition, called center-2, in which speed of responding could be measured independently of the Simon interference by placing the colored squares in the center of the screen, thus eliminating conflict between the position of the target and the position of the response. Another concern was that the bilingual advantage might not reflect superior skill in ignoring the irrelevant position information but rather a greater ability to remember the rules associating each color with the appropriate response key. If bilingualism conferred an advantage in this type of working memory ability, then bilinguals would be more able to make rapid judgments about the correct response. We addressed this possibility by including two conditions in which the working memory demands were increased to determine whether this manipulation also favored bilinguals. In these conditions, the stimuli were four colors, so participants had to keep four rules in mind associating each color with a response.

Method

Participants

There were 94 participants composing two age and two language groups. The first age group consisted of 64 younger adults, ranging in age from 30 to 58 years (mean age = 42.6 years), divided evenly between monolingual speakers of English living in Canada and bilingual speakers of English and Tamil living in India (20 participants) or of English and Cantonese living

in Hong Kong (12 participants). Each of these bilinguals was matched for age with one of the monolinguals, making the age ranges and the mean ages the same for the two groups. There were equal numbers of men and women in each group. The second age group consisted of 30 older adults ranging in age from 60 to 80 years (mean age = 70.3 years), divided between English-speaking monolinguals and bilingual speakers of English and Tamil living in India (9 participants) or of English and French living in Canada (6 participants). There were equal numbers of men and women in each group. Participants were recruited using the same procedures as in Study 1. The Tamil participants were tested in India, and the Cantonese participants were tested in Hong Kong, all by the same experimenter using the same equipment.

All of the bilinguals were educated in both languages from the age of 6 years and had continued to use both their languages daily. As in Study 1, the language background questionnaire was used to determine the daily use of each language by the bilinguals. The first language of the Tamil-English bilinguals was Tamil, and they used English 55% of the time. The Cantonese-English bilinguals' first language was Cantonese, and members of this group used English 48% of the time. The French-English bilinguals learned both French and English from childhood and used English 52% of the time. The monolingual participants lived in Canada and did not have functional command of any other language. All participants had bachelor's degrees and similar middle-class socioeconomic backgrounds.

Tasks and Instruments

Language background questionnaire and usage chart. The same questionnaire used in Study 1 was used in Study 2.

Peabody Picture Vocabulary Test—Third Edition (PPVT-III; Dunn & Dunn, 1997). The PPVT-III is a more recent version of the PPVT in which the norms are extended to standardize scores of individuals who are more than 70 years old. The task proceeds in the same manner as that in the PPVT-R, presenting participants with plates of four pictures and one word. The starting item is set according to the participant's chronological age. In this version, testing terminates when the participant commits 8 errors out of 12 items in a set. As in Study 1, this test was administered only in English to all participants.

Cattell Culture Fair Intelligence Test (Cattell & Cattell, 1960). The Cattell test is a nonverbal test of general intelligence. The raw scores are converted into IQ scores by a set of tables based on age.

Alpha span task (Craik, 1986). The alpha span task (AST) is a measure of verbal working memory. Lists ranging in length from two to eight words are presented auditorily at the rate of 1 word per second. Words are presented in random order, and participants are required to repeat the words back in alphabetical order. The task begins with a list of two words and proceeds by presenting two trials at each list length and increasing the length by one upon completion of the pair. After an error, testing continues for two more list lengths. In the scoring system, 1 point is awarded for each item recalled in a correctly ordered pair; the paired word can either precede or follow the scored word. For example, if a list of four items is recalled correctly, the score is 4 points; if the correct recall sequence for a list of five items is "apple, car, hotel, rabbit, toy," and the participant recalls "apple, hotel, rabbit, toy," he or she would receive 3 points—1 each for hotel, rabbit, and toy. "Apple" does not receive a point because "apple-hotel" is not a correct pair. The AST score is the total number of points awarded across all presented lists.

Sequencing span task. The sequencing span task (SST) is similar to the AST but uses strings of double-digit numbers ranging from 10 to 99 that are presented in random order; the participant's task is to repeat back increasingly long strings of numbers in the correct order. No number was repeated across any of the strings, and no pairs of numbers in the presentation strings appeared in their correct ascending order. The responses were scored using the procedure described above for the AST.

Simon tasks. All participants completed four conditions in one of four preset orders consisting of 24 trials per condition. The entire set of four

conditions was then repeated in the reverse order, producing 48 trials for each of the four conditions.

Condition A: Center-2 (control). A series of squares that were either brown or blue appeared in the middle of the screen. Participants were instructed to press the left shift key (marked "X") when they saw a blue square and the right shift key (marked "O") when they saw a brown square. The trial began with a sound (a computer "bing") and a fixation cross (+) that appeared in the center of the screen for 300 ms. Immediately after this cue, the stimulus appeared ($x = 0.43^\circ$, $y = 0.38^\circ$) and remained on the screen until a response was made. The response clock started at the onset of the stimulus. The fixation cross (plus the sound) reappeared 500 ms after the response to signal the next trial.

Condition B: Side-2. The parameters were the same as those in the control condition, but the blue and brown squares appeared on either the left or the right side of the screen. The order of trials was randomized and divided equally between congruent and incongruent items. The DMDX parameters from Study 1 were used.

Condition C: Center-4. This condition was similar to the control condition except that the stimulus was one of four colors: pink, yellow, red, or green. Participants were instructed to press the left shift key when they saw a green square, the right shift key when they saw a red square, the left shift key when they saw a pink square, and the right shift key when they saw a yellow square. The instructions were presented as four individual rules (i.e., "press the left shift key for green"; "press the left shift key for pink") and not as two paired rules (i.e., "press the left shift key for green or pink"). All stimuli appeared in the center of the screen. This condition placed greater demands on working memory for the assignment of colors to responses than did the Center-2 condition.

Condition D: Side-4. In this condition, the stimuli were the same four colors, but they appeared in one of two side positions. The order of trials was randomized and again divided equally between congruent and incongruent items.

A set of practice trials preceded each condition. The two-color conditions had four practice trials, and the four-color conditions had eight practice trials, demonstrating each unique stimulus configuration for the condition. The parameters of these trials were identical to those of the test trials. Participants had to complete all practice trials correctly to proceed with testing. If a mistake was made during a practice trial, the program recycled until all trials were completed without error. Two participants repeated the set of practice trials.

Procedure

Test sessions began with the language background questionnaire and chart, the PPVT-III, and the AST, all administered in English. The RT tasks were administered in one of four pseudorandom orders that presented one block from each of the four conditions. After this, participants were given a break in which they completed the Cattell Culture Fair Intelligence Test and the SST. These tasks were followed by the remaining blocks of the Simon task, administered in the reverse order from that used for the first

blocks. For example, if a participant completed conditions in the order B, D, A, C, then the second set of experimental trials would proceed in the order C, A, D, B.

Results

The results for the background variables are presented in Table 3. Two-way ANOVAs testing for age and language group differences were carried out on each of these measures. The PPVT scores were the same for both age, $F(1, 90) = 2.75$, $p = .10$, and language groups, $F(1, 90) = 0.03$, $p = .86$, with no interaction. Similarly, Cattell scores were the same for both age, $F(1, 90) = 1.69$, $p = .20$, and language groups, $F(1, 90) = 2.37$, $p = .13$, with no interaction. In contrast, younger participants scored higher than older participants on both the AST, $F(1, 90) = 34.90$, $p < .01$, and the SST, $F(1, 90) = 4.86$, $p < .03$, but there were no differences between the language groups and no interactions ($F_s < 1$). No norms are available for the AST and SST scores, but the values shown in Table 3 are typical for participants of these ages who have been tested in our laboratory.

The mean accuracy scores for the Simon task ranged from 97% to 99% and are reported in Table 4. The error rates were higher for the younger participants than the older participants, $F(1, 90) = 13.94$, $p < .01$. There was no difference between the language groups ($F < 1$), but there was an interaction of language and age, $F(1, 90) = 8.62$, $p < .01$, because the higher accuracy rate for the older participants was stronger in the bilinguals.

The mean RTs for the Simon task organized by position of the stimulus (center or side) and number of colors (2 or 4) are also reported in Table 4. Before examining the Simon effect for the different conditions, we conducted a preliminary four-way ANOVA involving age (2), language group (2), color (2), and position collapsed across congruency (2). This analysis explored the effect of position uncertainty (always in the center versus on one of two sides) on the different groups. The ANOVA revealed significant effects for all four factors (younger participants, bilinguals, central position, and two-color conditions were faster), and all interactions were also significant. Therefore, we analyzed each condition separately in a series of two-way ANOVAs to examine the effects of age and language group (the means are shown in Table 5). For all four analyses, younger adults were faster than older adults: center-2, $F(1, 90) = 687.58$, $p < .01$; side-2, $F(1, 90) = 338.91$, $p < .01$; center-4, $F(1, 90) = 477.32$, $p < .01$; side-4, $F(1, 90) = 230.15$, $p < .01$. The two language groups performed the same in the center-2 condition ($F < 1$), but bilinguals were faster than monolinguals in the other three conditions:

Table 3
Mean Background Measures (and Standard Deviations) by Age and Language Group in Study 2

Measure	Younger		Older	
	Monolingual	Bilingual	Monolingual	Bilingual
Age (in years)	42.6 (8.8)	42.6 (8.8)	70.4 (5.6)	70.2 (6.9)
PPVT-III	85.4 (5.6)	86.0 (4.7)	79.7 (6.9)	81.4 (5.0)
Cattell	109.1 (6.1)	109.5 (6.7)	108.5 (7.6)	109.7 (7.9)
AST	28.8 (4.6)	28.0 (4.5)	22.4 (1.9)	24.0 (2.9)
SST	25.1 (4.8)	24.0 (4.8)	21.6 (2.8)	23.0 (5.1)

Note. PPVT-III = Peabody Picture Vocabulary Test—Third Edition; Cattell = Cattell Culture Fair Intelligence Test; AST = alpha span task; SST = sequencing span task.

Table 4
Mean Reaction Time (in Milliseconds) and Accuracy for Simon Task by Age and Language Group in Study 2

Age and language group	No. of colors	Center	Accuracy (%)	Side		Simon effect	Accuracy (%)	
				Congruent	Incongruent			
Younger	Monolingual	2	337 (16.4)	96.9	544 (42.2)	667 (76.2)	123 (88.8)	99.5
		4	583 (61.8)	98.3	802 (69.5)	890 (33.9)	88 (80.1)	99.0
	Bilingual	2	343 (27.0)	97.7	375 (42.1)	382 (39.9)	8 (27.3)	97.5
		4	456 (66.4)	97.8	509 (84.6)	509 (90.4)	0 (29.9)	98.4
Older	Monolingual	2	1,012 (216.2)	99.3	1,012 (280.6)	1,595 (384.4)	583 (174.9)	99.2
		4	1,716 (320.6)	98.5	1,336 (334.2)	2,210 (547.9)	874 (280.9)	97.2
	Bilingual	2	1,046 (204.0)	99.6	889 (231.2)	1,101 (267.8)	212 (180.6)	98.8
		4	1,256 (368.9)	98.9	1,002 (212.5)	1,266 (284.2)	264 (249.0)	99.2

Note. Standard deviations are in parentheses.

side-2, $F(1, 90) = 57.58, p < .01$; center-4, $F(1, 90) = 32.09, p < .01$; side-4, $F(1, 90) = 111.88, p < .01$. There were interactions of language and age group for the conditions based on four colors: center-4, $F(1, 90) = 14.16, p < .01$; side-4, $F(1, 90) = 11.85, p < .01$. In both cases, the age variable was associated with a larger increase in RT for monolingual participants: 1,133 ms versus 800 ms for the center-4 condition; 927 ms versus 625 ms for the side-4 condition. Language and age did not interact in the center-2 and side-2 conditions.

The relative effects of increasing the number of possible stimuli from two to four—referred to here as working memory costs—were assessed by subtracting two-color RTs from four-color RTs in all conditions and groups. The resulting means are shown in Figure 1a. The corresponding ANOVA (Age Group \times Language Group \times Position) revealed main effects of age group, $F(1, 90) = 71.1, p < .01$; language, $F(1, 90) = 129.0, p < .01$; and position (center vs. side), $F(1, 90) = 17.6, p < .01$. In addition, all interactions were significant: Age \times Language, $F(1, 90) = 38.3, p < .01$; Age \times Position, $F(1, 90) = 20.9, p < .01$; Language \times Position, $F(1, 90) = 7.13, p < .01$; and the three-way interaction

among age, language, and position, $F(1, 90) = 4.05, p < .05$. Thus, larger working memory costs were associated with older adults, with monolingualism as opposed to bilingualism, and with central as opposed to peripheral (side) stimuli. As shown by Figure 1a, the age-related increase in working memory costs was much smaller for bilingual participants; that is, bilingualism attenuates the negative effect of aging on working memory costs.

In our view, the difference between RTs to congruent and incongruent stimuli (the Simon effect) reflects the efficiency of inhibitory processes. That is, the participants' task is to press the key associated with the stimulus color regardless of spatial position; therefore, smaller Simon effects reflect less inhibition cost and more efficient inhibitory processes. These costs are shown in Figure 1b. Larger costs are associated with older adults, with monolinguals, and with four-color conditions. A three-way ANOVA on the data shown in Figure 1b revealed significant effects of age, $F(1, 90) = 307.3, p < .01$; language, $F(1, 90) = 146.6, p < .01$; and number of stimuli (two or four), $F(1, 90) = 17.8, p < .01$. In addition, the following interactions were significant: Age \times Language, $F(1, 90) = 63.3, p < .01$; Age \times Number, $F(1, 90) = 29.4, p < .01$; Language \times Number, $F(1, 90) = 8.92, p < .01$; and the three-way interaction among age, language, and number, $F(1, 90) = 14.18, p < .01$. Figure 1b shows that the age-related increase in the Simon effect was less when only two colors were involved and was less for bilingual participants. Further analyses showed that the interaction between age and language group was reliable for both the two-color, $F(1, 90) = 26.08, p < .01$, and four-color, $F(1, 90) = 57.04, p < .01$, conditions even though the effect was smaller for the two-color conditions. That is, in both color conditions, the age-related increase in the Simon effect was smaller for the bilingual participants.

Finally, we divided participants into decades of age to obtain a more complete picture of the transition across this age span. The numbers of participants in each decade were as follows: 30s, $n = 24$; 40s, $n = 22$; 50s, $n = 18$; 60s, $n = 15$; 70s, $n = 15$. Figure 2a displays the RTs for both language groups in the control condition (center-2) and shows that the response times in the simplest

Table 5
Mean Reaction Time (in Milliseconds) by Age and Language Group for Each Experimental Condition

Condition and language group	Younger	Older	
Center-2	Monolingual	337	1,012
	Bilingual	343	1,046
Center-4	Monolingual	583	1,716
	Bilingual	456	1,256
Side-2	Monolingual	606	1,304
	Bilingual	379	995
Side-4	Monolingual	846	1,773
	Bilingual	509	1,134

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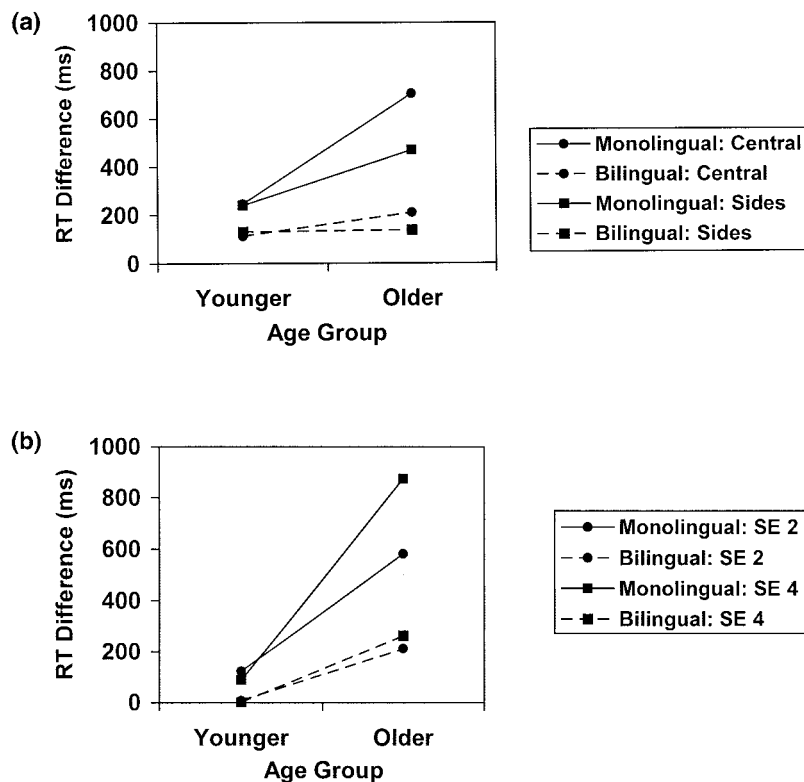


Figure 1. Mean reaction time (RT) cost for working memory and inhibition by age and language group in Study 2. (a): Working memory cost calculated as RT difference between four- and two-color conditions for central (Condition C – Condition A) and side (Condition D – Condition B) presentations. (b): Inhibition cost calculated as RT difference between incongruent and congruent trials for two-color (Condition B) and four-color (Condition D) presentations. SE 2 = Simon effect, 2 colors; SE 4 = Simon effect, 4 colors.

condition did not distinguish between the language groups at any age. Figure 2b shows the working memory costs, calculated as the RT difference between the two- and four-color presentations averaged across the central and peripheral display presentations. Figure 2c shows the inhibitory costs, calculated as the RT difference between congruent and incongruent trials (i.e., the Simon effect) for the two language groups averaged across the side-2 and side-4 conditions. Although no formal analyses were conducted on these data, it is clear from the figures that performance remained constant until age 60 and then RTs increased over the next 20 years. Figures 2b and 2c further show that the age-related increase in costs was greater for monolingual participants.

Discussion

As in Study 1, monolingual and bilingual adults who were either younger (approximately 40 years old) or older (approximately 70 years old) were equivalent on background measures of cognitive performance and working memory as well as on a number of social and educational factors, which made the lifelong bilingualism of one group the only notable difference between them. In addition, in both the younger and older groups, the monolinguals and bilinguals performed identically in the control condition, in which two colored squares were presented in the center of the screen (see Figure 2a). This important result underlines the fact that there were no inherent differences between the monolingual and bilingual

samples in the performance of a straightforward choice RT task. In all other conditions, bilinguals achieved faster response times than did monolinguals of the same age.

The striking finding, shown in Figure 1, is that the costs for both inhibition and working memory were greater for the monolinguals than the bilinguals in both age groups, and the increased RT associated with aging for each of these factors was greater for the monolinguals than the bilinguals. The age-related processing decline associated with these factors, in other words, was more severe for the monolinguals than for comparable bilinguals.

In the Simon conditions, the bilinguals were faster than the monolinguals on both the congruent and incongruent trials, but more important, as in Study 1 for which practice levels were much lower, the bilinguals showed a reliably smaller Simon effect than the monolinguals. For the younger bilinguals, up to the age of 60 years the Simon effect was very small (only 4 ms overall), replicating the results of Study 1. The older bilinguals in the present study (and in Study 1) did show a Simon effect, but its magnitude remained significantly smaller than that for monolinguals of the same age (see Figure 1b).

The four-color conditions added a surprising amount of difficulty to the task. For the younger participants in both language groups, the cost of remembering and processing four colors rather than two was greater than the cost of inhibiting the misleading position cues (compare Figures 2b and 2c). Also surprisingly, the

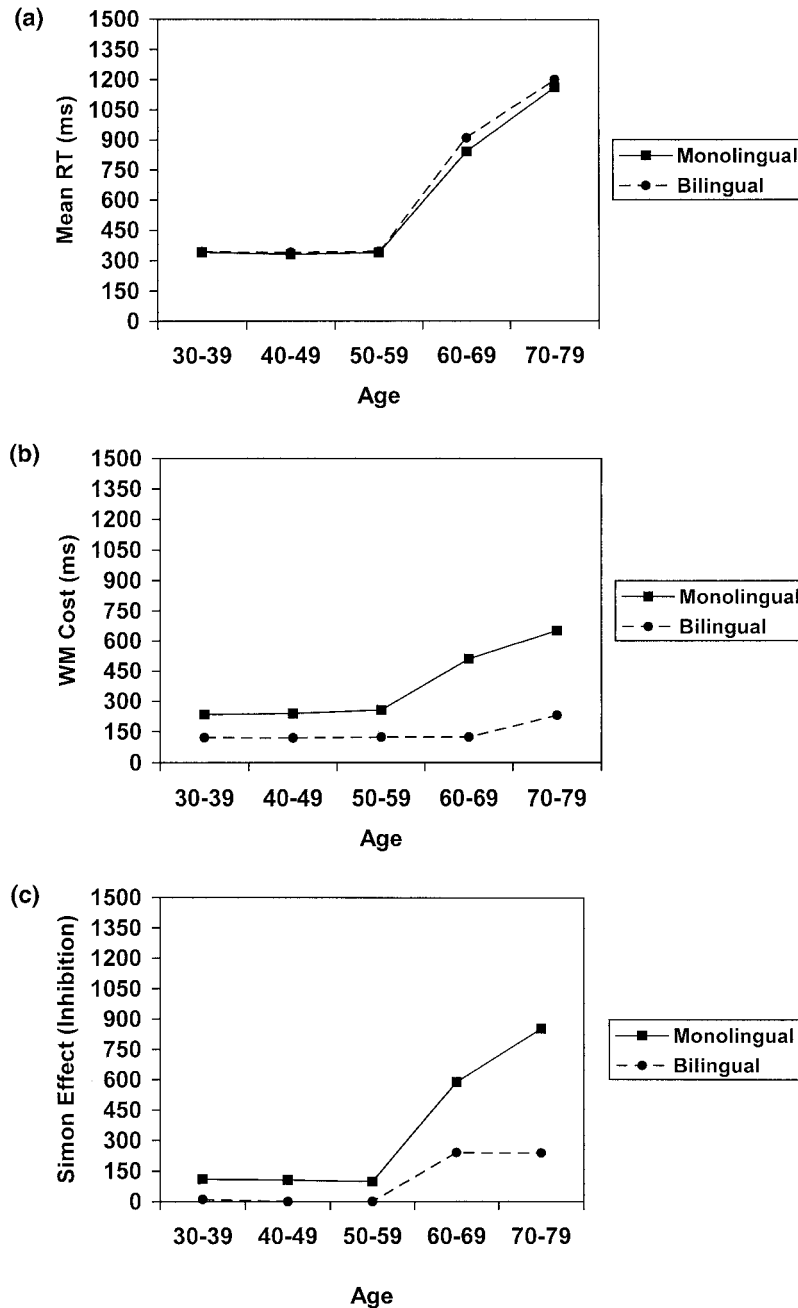


Figure 2. Mean reaction time (RT) by decade of age for monolinguals and bilinguals. (a): Mean RT for control condition (Condition A). (b): Mean RT cost for working memory (WM) as the average of the RT difference between the two-color (Condition C – Condition A) and four-color (Condition D – Condition B) conditions. (c): Mean RT cost for inhibition (Simon effect) as the average of the RT difference between congruent and incongruent trials for two-color (Condition B) and four-color (Condition D) conditions.

increase from two to four colors was handled better by the bilinguals than the monolinguals, for both the younger and older participants (see Figure 1a). It seems, then, that the bilingual advantage appears in situations with high processing demands (e.g., four colors vs. two colors) and is not restricted to conditions necessitating inhibition (e.g., incongruent vs. congruent), although the advantage is also found in such situations. We return to this important point in the General Discussion.

One result that should be noted is that the age-related decreases in alpha span and sequencing span were *not* modulated by bilingualism. Our purpose in including these two span measures was to establish the equivalence between the two language groups on a measure of cognitive processing capacity or working memory. Given that we found an unexpected bilingual advantage for working memory costs and concluded that bilingual participants perform more efficiently in tasks with high processing demands, it is

perhaps surprising that the bilingual advantage was not also found for these complex span tasks. It is known that performance on span tasks reflects (in part) the ability to inhibit interference from previous trials (Lustig, May, & Hasher, 2001; May, Hasher, Kane, 1999), and it might therefore be expected that bilinguals should show an advantage on such tasks. Speculatively, the bilingual advantage may be greater on tasks requiring speeded responses, or less on tasks involving the manipulation of words in one of their two languages, but a proper understanding of tasks showing the bilingual advantage must await the results of further exploratory studies.

The analysis by decades provides a more detailed description of the processing changes associated with this task for the two language groups. Although the groups maintained a constant difference in performance until 60 years of age, the pattern of RT increase beyond that age was different for the three effects. The control condition indicated a constant increase over the last two decades that was identical for both language groups. This presumably reflects the general slowing associated with normal aging. For working memory costs, the bilinguals maintained their performance levels until 70 years of age and then showed an increase in RT for the last decade tested. The monolinguals, in contrast, began to decline in their 60s and continued to decline in their 70s. For the Simon effect, both groups revealed a sharp increase in RTs between 60 and 70 years, after which the monolinguals continued to show increased RTs but the bilinguals remained constant. Therefore, in spite of significant slowing in response to both working memory and inhibition demands, bilinguals beyond 60 years of age continued to maintain an advantage over monolinguals in responding to both these factors.

In summary, three main results were found in Study 2. First, the bilinguals showed a reliably smaller Simon effect than the monolinguals—the difference between congruent and incongruent trials was not even significant for the younger bilingual participants. Second, bilingualism reduced the age-related increase in processing costs associated with four stimulus colors (working memory costs). Third, both the Simon effect, taken here to indicate the efficiency of inhibitory processing, and working memory costs, reflecting the ability to deal with increasing task complexity, increased reliably with age, but these age-related increases were also reliably attenuated by bilingualism.

Study 3

In Study 2, there were large differences in RT between the monolinguals and bilinguals for three of the conditions in spite of equivalent performance on the control, or center–2, condition. However, even that study included fewer trials than are usually used in this type of research. Therefore, in the final study, we verified the group effects by presenting two of the conditions from Study 2 to a new group of monolingual and bilingual adults but repeating the blocks of trials 10 times. The purpose was to determine whether the two language groups would eventually converge in their performance after sufficient practice.

The two conditions chosen were side–2 and center–4, the first representing the classic Simon task and the second representing a straightforward working memory task uncomplicated by congruity effects. That is, the side–2 condition requires inhibitory processes but no working memory load, whereas the center–4 condition involves working memory but not inhibition; these two conditions

thus represent the processes of major interest. As the experiment was exploratory, we tested a group of younger adults, comparable to the younger group in Study 2.

Method

Participants

The participants were 20 adults ranging in age from 30 to 55 years. Half were French–English bilinguals (mean age = 40.6 years), and half were English-speaking monolinguals (mean age = 38.8 years) living in the same Canadian community. Participants in the two groups were matched on age, with the exception of the oldest member of each group. There were equal numbers of men and women in each group. Participants were recruited through advertisement in a local community center. The bilinguals had been exposed to both languages at home from childhood and were educated in both languages. The language background questionnaire indicated that they used English 50% of the time in their daily lives. All participants had bachelor's degrees and were from similar socioeconomic backgrounds.

Tasks and Procedures

Five tasks from Study 2 were repeated in this study: the language background questionnaire, the PPVT–III, the Cattell Culture Fair Intelligence Test, the AST, and the SST. The procedures used to administer and score all these tests were the same as those described in Study 2.

Two conditions of the Simon task used in Study 2 were administered, the side–2 condition and the center–4 condition. Each of these was presented in 10 consecutive blocks of 24 trials with a short break between each repetition. The order of the two conditions was counterbalanced across participants. Testing began with the language background questionnaire, the PPVT–III, and the AST. These were followed by the first Simon task condition. Between the two Simon conditions, the Cattell Culture Fair Intelligence Test and the SST were administered.

Results

The results for the background variables are presented in Table 6. One-way ANOVAs testing for language group differences found no group difference for any of these measures.

The performance accuracy in the side–2 condition was 97.5% for the monolinguals and 95.4% for the bilinguals; in the center–4 condition, accuracy was 90% for the monolinguals and 91.7% for the bilinguals. The difference between conditions was significant, $F(1, 18) = 5.11, p < .04$, but there was no difference between the groups and no interaction ($F_s < 1$).

The mean RTs on the center–4 task for the two language groups are shown across blocks in Figure 3a. In a three-way ANOVA for

Table 6
Mean Background Measures (and Standard Deviations) by Language Group in Study 3

Measure	Monolingual	Bilingual
Age (in years)	38.8 (8.5)	40.6 (8.1)
PPVT–III	89.1 (6.1)	91.0 (5.8)
Cattell	110.0 (6.7)	111.5 (7.4)
AST	27.8 (3.8)	28.1 (3.4)
SST	25.4 (4.2)	28.0 (4.0)

Note. PPVT–III = Peabody Picture Vocabulary Test—Third Edition; Cattell = Cattell Culture Fair Intelligence Test; AST = alpha span task; SST = sequencing span task.

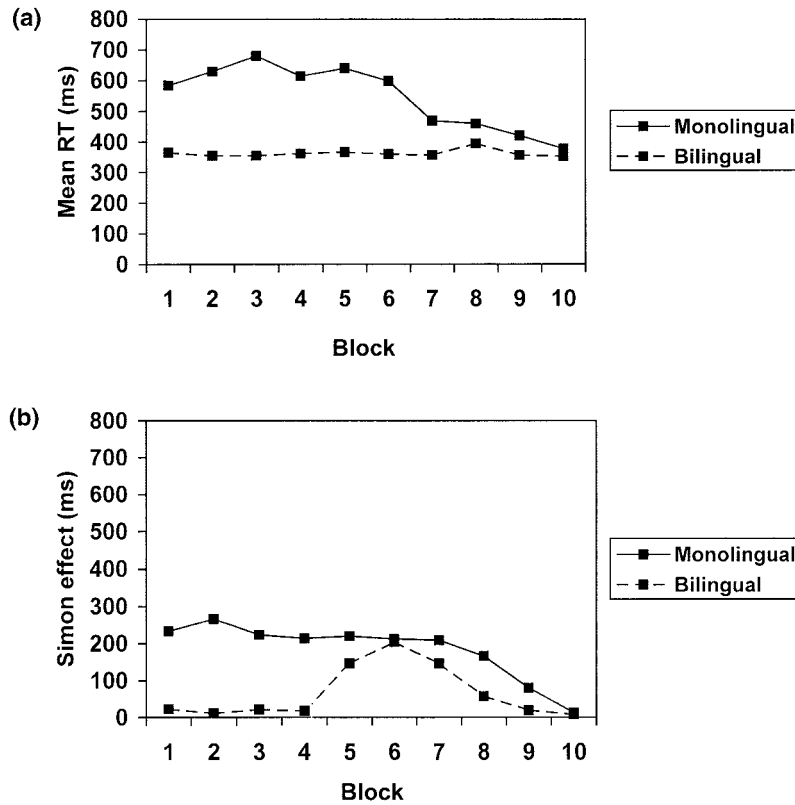


Figure 3. Mean reaction time (RT) by group over replication blocks in Study 3. (a): Mean RT for working memory task (Condition C). (b): Mean RT for Simon effect (Condition B).

language group, block, and presentation order, there were effects of block, $F(9, 162) = 10.15, p < .01$; language group, $F(1, 18) = 62.65, p < .01$; and their interaction, $F(9, 162) = 10.72, p < .01$. The interaction showed that the bilinguals maintained faster responding than the monolinguals for Blocks 1 to 7 and that the two groups converged for Blocks 8 to 10. There were no order effects or interactions.

The mean RT data for the congruent and incongruent trials in the side-2 condition are reported in Table 7. As in the previous studies, these data can also be shown as Simon effect scores by subtracting the RT for the congruent condition from that for the incongruent condition. These data are plotted across the 10 blocks by language group in Figure 3b. A three-way ANOVA for language, block, and order on the difference scores showed effects of block, $F(9, 162) = 17.44, p < .01$; language, $F(1, 18) = 27.05, p < .01$; and their interaction, $F(9, 162) = 9.94, p < .01$. The interaction indicates the pattern of convergence of the two language groups: The bilinguals showed less interference from the incongruent position on Blocks 1 to 4 and Block 8, but the advantage was lost in Blocks 5 to 7, where the bilinguals both slowed down and showed an increase in cost. There was a small but significant advantage again for the bilinguals in Block 9, but the two groups finally converged in Block 10, where the monolinguals were as fast and as efficient as the bilinguals. As with the center-4 condition, there were no order effects or interactions.

The RT peak between Blocks 5 and 7 for the bilinguals was puzzling. We examined the data for all 20 participants individually to determine the generality of this effect. For all monolinguals, the

performance across the 10 blocks was consistent, showing the steady pattern until about Block 7 and then a gradual decline in RT that is indicated in the group mean. In the bilingual group, 7 of the 10 participants showed the sharp increase in RT at Block 5 (especially for incongruent stimuli) that lasted for two or three blocks. The 3 participants who did not show this spike maintained constant times across all 10 blocks. We have no explanation for the increased time on those blocks by the majority of the bilingual participants. Anecdotally, it was the bilinguals who complained

Table 7
Mean Reaction Time (in Milliseconds) for Inhibition Condition by Language Group in Study 3

Block	Monolingual		Bilingual	
	Congruent	Incongruent	Congruent	Incongruent
1	532 (66.0)	766 (68.4)	335 (26.7)	358 (29.6)
2	516 (87.7)	782 (74.8)	347 (22.2)	359 (17.8)
3	522 (75.8)	747 (54.7)	349 (29.0)	370 (33.6)
4	547 (95.4)	762 (73.7)	343 (25.6)	360 (27.3)
5	505 (79.5)	727 (52.9)	392 (53.4)	538 (137.7)
6	493 (86.5)	705 (70.2)	393 (60.3)	597 (182.3)
7	456 (70.9)	666 (71.5)	362 (41.0)	508 (160.7)
8	456 (43.9)	623 (85.2)	344 (30.7)	401 (87.0)
9	405 (42.8)	486 (108.0)	349 (23.3)	368 (32.6)
10	386 (39.7)	398 (56.4)	346 (41.6)	354 (23.1)

Note. Standard deviations are in parentheses.

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more of boredom across the repetitions of the blocks than did the monolinguals and who needed more incentive to be reassured that the experiment was almost finished. When the end was closer, they seemed to regain some of their initial enthusiasm.

Finally, we investigated the generality of the practice effect by comparing the mean RTs on Blocks 1 and 2 for the subgroups who performed a particular task first and who performed that task second. The monolinguals performed at the same level as the bilinguals after 10 blocks of practice (see Figure 3), so if this practice effect carried over to the second task, the practiced monolinguals should have performed much better than the unpracticed monolinguals (i.e., those performing that condition as their first task). For the center-4 task (see Figure 3a), means for the practiced and unpracticed monolinguals (averaged over the first two blocks) were 617 ms and 594 ms, respectively; the corresponding means for bilinguals were 359 ms and 359 ms. A two-factor ANOVA involving language (monolinguals vs. bilinguals) and practice (task first vs. task second) revealed a main effect of language, $F(1, 16) = 81.1, p < .01$, but no effect of practice and no interaction (both F s < 1.0). The corresponding treatment of the Simon effect data in Figure 3b showed that means for the practiced and unpracticed monolinguals (again averaged over the first two blocks) were 223 ms and 276 ms, respectively, and that the means for the practiced and unpracticed bilinguals were 15 ms and 19 ms, respectively. A 2×2 ANOVA on these data confirmed the strong effect of language on the Simon effect, $F(1, 16) = 54.3, p < .01$, but again showed no reliable effects of order or of the Language \times Order interaction (both F s < 1.0). These data should be treated with some caution because the number of participants in each group was quite small. Nonetheless it appears that extensive practice on one task conferred a specific advantage to monolingual participants but that this practice effect did not transfer to the task performed second.

Discussion

As in the previous two studies, monolingual and bilingual adults who scored equivalently on a set of background measures examining working memory and cognitive level differed in their performance on the Simon task. In this case, however, the performances of the two groups eventually converged. Although the bilinguals maintained their level of performance across the 10 repeated blocks of the study, the monolinguals gradually improved. By the last blocks, the monolinguals achieved the level of efficiency that the bilinguals had demonstrated from the beginning. With practice, the groups performed equivalently. There was an anomalous slowing for the bilinguals in Blocks 5 to 7 in the inhibition condition, as though the distracting position suddenly became problematic. These participants did not slow generally, because there was no such change in their performance in the center-4 condition. Therefore, some kind of attention lapse or fatigue may have been responsible.

General Discussion

In all three studies, monolingual and bilingual adults who were comparable on background experiences and cognitive measures performed differently on the Simon task. Bilinguals responded faster to both congruent and incongruent trials but also produced a smaller Simon effect, indicating less disruption from the incon-

gruent items regardless of speed. Most important, bilingualism reduced the age-related increase in the Simon effect, implying that the lifelong experience of managing two languages attenuates the age-related decline in the efficiency of inhibitory processing. Moreover, a set of conditions that increased the number of different stimuli from two to four also yielded faster responses by the bilinguals, even when these stimuli were presented in the center of the screen and involved no interference from incongruent spatial position information. Again, the age-related increase in such working memory costs was reduced in the bilingual groups. A control condition that presented two stimuli in the center of the screen produced no difference in RT, however, ruling out an overall speed advantage as the explanation for performance differences between the groups.

The conclusion that the results cannot readily be attributed to general slowing in the older and monolingual groups is reinforced by the fact that proportional measures of the Simon effect yield the same pattern. The increases in RT from the congruent to the incongruent condition, expressed as proportional increases from the congruent values, were as follows in Study 1: younger monolinguals, .69; older monolinguals, 1.20; younger bilinguals, .08; older bilinguals, .82. For Study 2, the corresponding data were as follows: younger monolinguals, .17; older monolinguals, .61; younger bilinguals, .01; older bilinguals, .25. That is, in both studies the proportional increases from the congruent to the incongruent condition were larger for the older adults and for the monolingual groups, just as they were for the raw data shown in Tables 2 and 4.

The present studies were motivated by two questions. The first was whether the bilingual advantages in controlled processing observed for children would be sustained into adulthood. The results from these studies indicate that they are. In all three studies, adult bilinguals performed more efficiently than their monolingual counterparts. The second question was whether bilingualism would provide a defense against the decline of these executive processes that occurs with normal cognitive aging. Again, the present results suggest that it does. Although the crucial Age \times Language interaction for the Simon effect was not statistically reliable in Study 1, the pattern of results showed that the age-related increase in the Simon effect was substantially less for the bilingual participants. In Study 2, which involved more participants and more trials, the Age \times Language interaction was highly reliable for both two-color and four-color conditions. In addition, the Age \times Language interaction was also reliable for working memory costs in Study 2. Our initial hypothesis was that bilingualism boosts inhibitory control and that bilingualism would therefore be associated with a smaller Simon effect and with a smaller age-related increase in the Simon effect. The results support those expectations, but the additional unexpected finding of a positive effect of bilingualism on working memory costs leads us to speculate that the beneficial effects of bilingualism may be broader than its effect on inhibitory control. Rather, the effects may be on executive control functions generally and may act to reduce the negative impact of aging on such functions.

The performance of the older adults resembled results we obtained with children (Martin & Bialystok, 2003) that indicated a U-shaped function for the rise and fall of inhibitory processes (or executive control processes) across the life span. The conclusion that control processes first increase and then decrease from early childhood to old age is consistent with evidence from other studies

(Cepeda, Kramer, & Gonzalez de Sather, 2001; Christ, White, Mandernach, & Keys, 2001; Dempster, 1992; Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

The hypothesis was that bilinguals would outperform monolinguals only on the incongruent trials of the Simon task conditions, but the results indicated a broader effect. Bilinguals were faster as well on congruent trials and on conditions requiring greater working memory control even in the absence of competing position information. Why would bilinguals perform better than monolinguals on the congruent trials and working memory trials? One possibility is that the executive processes involved in attention and selection across these conditions are the same, and it is these central executive components, rather than just inhibition, for example, that are enhanced through the experience of lifelong bilingualism. Thus, the effect of bilingualism may be more general than hypothesized, influencing a variety of executive functions including both inhibition and at least some measures of working memory. The bilingual advantage, that is, resides in complex processing requiring executive control. A second possibility is that bilingualism does act to enhance inhibitory control, as originally hypothesized, and that this more effective inhibitory control is seen in some working memory tasks as well as in situations (such as the Simon task) in which the necessity to inhibit misleading information is more obvious. The role of inhibition in working memory tasks has been emphasized by Hasher, Zacks, and their colleagues (e.g., Hasher & Zacks, 1988; Zacks & Hasher, 1994). In Study 2, for example, participants performed eight blocks of trials under a variety of conditions; it seems reasonable to suppose that there is an advantage in being able to rapidly establish and maintain the appropriate set for each condition, having first deleted the obsolete set for the previous condition.

The gap between monolinguals and bilinguals diminished with practice in Study 3. This convergence of performance suggests that the bilingual advantage is most apparent when controlled processing is required and is less salient for more automated performance. Nonetheless, the practice effect on performance is still specific to individual problems. After extensive practice on the task they performed first, the monolingual group reached the level of performance shown by the bilinguals, but the monolinguals were again substantially poorer than the bilinguals on the first few trials of the task they performed second.

All the bilinguals in the present studies had used their two languages essentially every day of their lives, at least since the age of about 10 years, so we cannot be certain about the extension of our results to bilinguals with more limited bilingual experience. The balanced bilinguals included in our studies, however, demonstrated a surprising breadth of advantage over their monolingual peers in dealing with increased processing complexity in the Simon task. The bilinguals were more efficient at all ages tested and showed a slower rate of decline for some processes with aging. Our interpretation is that the executive processes required to manage their two language systems are invoked as well in the Simon task. These executive processes may not be neatly partitioned into parts that deal with inhibitory control and others that are concerned with working memory—it may be a more generalized set of control processes that manages these complex procedures. In that case, the simple experience of bilingualism that relies on some aspect of these processes to control the production of the relevant language appears to yield widespread benefits across a range of complex cognitive tasks.

References

- Bain, B. (1975). Toward an integration of Piaget and Vygotsky: Bilingual considerations. *Linguistics, 160*, 5–19.
- Bialystok, E. (1988). Levels of bilingualism and levels of linguistic awareness. *Developmental Psychology, 24*, 560–567.
- Bialystok, E. (1993). Metalinguistic awareness: The development of children's representations of language. In C. Pratt & A. Garton (Eds.), *Systems of representation in children: Development and use* (pp. 211–233). London: Wiley.
- Bialystok, E. (2001). *Bilingualism in development: Language, literacy, and cognition*. New York: Cambridge University Press.
- Brysaert, M. (1998). Word recognition in bilinguals: Evidence against the existence of two separate lexicons. *Psychologica Belgica, 38*, 163–175.
- Canada Census 1996. (n.d.). *Catalogue No. 93F0024XDB96003*. Retrieved August 5, 2001, from <http://www.statcan.ca/english/census96>
- Cattell, R. B., & Cattell, A. K. S. (1960). *The individual or group Culture Fair Intelligence Test*. Champaign, IL: Institute for Personality and Ability Testing.
- Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology, 37*, 715–730.
- Christ, S. E., White, D. A., Mandernach, T., & Keys, B. A. (2001). Inhibitory control across the life span. *Developmental Neuropsychology, 20*, 653–669.
- Craik, F. I. M. (1986). A functional account of age differences in memory. In F. Klix & H. Hagendorf (Eds.), *Human memory and cognitive capabilities, mechanisms, and performance* (pp. 409–422). Amsterdam: North-Holland.
- Craik, F. I. M., & Salthouse, T. A. (Eds.). (2000). *The handbook of aging and cognition* (2nd ed.). Mahwah, NJ: Erlbaum.
- de Groot, A. M. B., & Kroll, J. F. (Eds.). (1997). *Tutorials in bilingualism: Psycholinguistic perspectives*. Mahwah, NJ: Erlbaum.
- Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12*, 45–75.
- DMDX. (n.d.). DMDX display software [Computer software]. Retrieved March 30, 2001, from <http://www.u.arizona.edu/~kforster/dmdx/dmdx.htm>
- Duncan, S. E., & De Avila, E. A. (1979). Bilingualism and cognition: Some recent findings. *National Association for Bilingual Education Journal, 4*, 15–50.
- Dunn, L. M., & Dunn, L. M. (1981). *Peabody Picture Vocabulary Test—Revised*. Circle Pines, MN: American Guidance Service.
- Dunn, L. M., & Dunn, L. M. (1997). *Peabody Picture Vocabulary Test—Third Edition*. Circle Pines, MN: American Guidance Service.
- Francis, W. (1999). Cognitive integration of language and memory in bilinguals: Semantic representation. *Psychological Bulletin, 125*, 193–222.
- Gollan, T. H., & Kroll, J. F. (2001). The cognitive neuropsychology of bilingualism. In B. Rapp (Ed.), *What deficits reveal about the human mind/brain: A handbook of cognitive neuropsychology* (pp. 321–345). Philadelphia: Psychology Press.
- Gollan, T. H., Montoya, R., & Werner, G. (1992). Semantic and letter fluency in Spanish–English bilinguals. *Neuropsychology, 16*, 562–576.
- Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition, 1*, 67–81.
- Harrington, M., & Sawyer, M. (1992). L2 working memory capacity and L2 reading skill. *Studies in Second Language Acquisition, 14*, 25–38.
- Harris, R. J. (Ed.). (1992). *Cognitive processing in bilinguals*. Amsterdam: North-Holland.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.
- Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian

- arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII* (pp. 653–675). Cambridge, MA: MIT Press.
- Hay, J. F., & Jacoby, L. L. (1996). Separating habit and recollection: Memory slips, process dissociations, and probability matching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1323–1335.
- Hay, J. F., & Jacoby, L. L. (1999). Separating habit and recollection in young and older adults: Effects of elaborative processing and distinctiveness. *Psychology and Aging*, *14*, 122–134.
- Kessler, C., & Quinn, M. E. (1980). Positive effects of bilingualism on science problem-solving abilities. In J. E. Alatis (Ed.), *Current issues in bilingual education: Proceedings of the Georgetown Roundtable on Languages and Linguistics* (pp. 295–308). Washington, DC: Georgetown University Press.
- Kessler, C., & Quinn, M. E. (1987). Language minority children's linguistic and cognitive creativity. *Journal of Multilingual and Multicultural Development*, *8*, 173–186.
- Kieley, J. M., & Hartley, A. A. (1997). Age-related equivalence of identity suppression in the Stroop color-word task. *Psychology and Aging*, *12*, 22–29.
- Kramer, A. F., & Strayer, D. L. (2001). Influence of stimulus repetition on negative priming. *Psychology and Aging*, *16*, 580–587.
- Kroll, J. F., & Dijkstra, A. (2002). The bilingual lexicon. In R. Kaplan (Ed.), *Handbook of applied linguistics* (pp. 301–321). Oxford, England: Oxford University Press.
- Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language*, *33*, 149–174.
- Lu, C.-H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*, 174–207.
- Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General*, *130*, 199–207.
- Macnamara, J. (1966). *Bilingualism and primary education*. Edinburgh, Scotland: Edinburgh University Press.
- Martin, M. M., & Bialystok, E. (2003, October 24–26). *The development of two kinds of inhibition in monolingual and bilingual children: Simon vs. Stroop*. Poster presented at the meeting of the Cognitive Development Society, Park City, Utah.
- May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Memory & Cognition*, *27*, 759–767.
- McDowd, J. M., & Shaw, R. J. (2000). Attention and aging: A functional perspective. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 221–292). Mahwah, NJ: Erlbaum.
- Michael, E. B., & Gollan, T. H. (in press). Being and becoming bilingual: Individual differences and consequences for language production. In J. R. Kroll & A. de Groot (Eds.), *Handbook of bilingualism*. New York: Oxford University Press.
- Miyake, A. (1998). Individual differences in second language proficiency: The role of working memory. In A. F. Healy & L. E. Bourne Jr. (Eds.), *Foreign language learning: Psycholinguistic studies on training and retention* (pp. 339–364). Mahwah, NJ: Erlbaum.
- Park, D. C. (2000). The basic mechanisms accounting for age-related decline in cognitive function. In D. C. Park & N. Schwarz (Eds.), *Cognitive aging: A primer* (pp. 3–21). Philadelphia: Psychology Press.
- Rabbitt, P. (1965). An age decrement in the ability to ignore irrelevant information. *Journal of Gerontology*, *20*, 233–238.
- Ransdell, S. E., & Fischler, I. (1989). Effects of concreteness and task context on recall of prose among bilingual and monolingual speakers. *Journal of Memory and Language*, *28*, 278–291.
- Raven, J. C. (1958). *Standard Progressive Matrices*. London: Lewis.
- Rosenblum, T., & Pinker, S. A. (1983). Word magic revisited: Monolingual and bilingual children's understanding of the word-object relationship. *Child Development*, *54*, 773–780.
- Salthouse, T. A. (1982). Duration estimates of 2 information-processing components. *Acta Psychologica*, *52*, 213–226.
- Salthouse, T. A. (1991). *Theoretical perspectives on cognitive aging*. Hillsdale, NJ: Erlbaum.
- Simon, J. R., & Wolf, J. D. (1963). Choice reaction time as a function of angular stimulus-response correspondence and age. *Ergonomics*, *6*, 99–105.
- Smith, M. C. (1997). How do bilinguals access lexical information? In A. M. B. de Groot & J. F. Kroll (Eds.), *Tutorials in bilingualism: Psycholinguistic perspectives* (pp. 145–168). Mahwah, NJ: Erlbaum.
- U.S. Census Bureau. (2003, February 25). *Table 1. Language use, English ability, and linguistic isolation for the population 5 years and over by state: 2000*. United States Census 2000. Retrieved May 1, 2003, from <http://www.census.gov/population/cen2000/phc-t20/tab01.pdf>
- Van der Lubbe, R. H. J., & Verleger, R. (2002). Aging and the Simon task. *Psychophysiology*, *39*, 100–110.
- Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, *35*, 205–213.
- Wingfield, A., & Stine-Morrow, E. A. L. (2000). Language and speech. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 359–416). Mahwah, NJ: Erlbaum.
- Zacks, R. T., & Hasher, L. (1994). Directed ignoring: Inhibitory regulation of working memory. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory mechanisms in attention, memory, and language* (pp. 241–264). San Diego, CA: Academic Press.
- Zacks, R. T., Hasher, L., & Li, K. Z. H. (2000). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 293–357). Mahwah, NJ: Erlbaum.

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