NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 24 (2005) 40–49

Effect of bilingualism on cognitive control in the Simon task: evidence from MEG

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Received 8 December 2003; revised 30 September 2004; accepted 30 September 2004
Available online 13 November 2004

The present study used magneto-encephalography (MEG) to determine the neural correlates of the bilingual advantage previously reported for behavioral measures in conflict tasks. Bilingual Cantonese–English, bilingual French–English, and monolingual English speakers, performed the Simon task in the MEG. Reaction times were faster for congruent than for incongruent trials, and the Cantonese group was faster than the other two groups, which did not differ from each other. Analyses of the MEG data using synthetic aperture magnetometry (SAM) and partial last squares (PLS) showed that the same pattern of activity, involving signal changes in left and medial prefrontal areas, characterized all three groups. Correlations between activated regions and reaction times, however, showed that the two bilingual groups demonstrated faster reaction times with greater activity in superior and middle temporal, cingulate, and superior and inferior frontal regions, largely in the left hemisphere. The monolinguals demonstrated faster reaction times with activation in middle frontal regions. The interpretation is that the management of two language systems led to systematic changes in frontal executive functions.

Keywords: Bilingualism; Simon task; MEG

Introduction

The early acquisition and regular use of two languages has been shown to enhance the ability of children to exercise cognitive control in a wide range of tasks. Young bilinguals, 4–8 years old, are more skilled than their monolingual peers in solving problems that require attentional control to ignore or inhibit misleading cues (review in Bialystok, 2001). This processing advantage has been found across several domains of thought, including language tasks (Bialystok, 1988; Cromdal, 1999; Galambos and Goldin-Meadow, 1990), concepts of quantity (Bialystok and Codd, 1997; Saxe, 1988), spatial concepts (Bialystok and Majumder, 1998), and problem solving (Kessler and Quinn, 1987; Secada, 1991). The bilingual advantage is confined to tasks that contain a salient but irrelevant cue, usually perceptual; similar problems that do not include this misleading information are solved equally well by children with both language backgrounds.

A possible reason for the enhanced cognitive control demonstrated by bilingual children is that the same control processes are used both to solve these misleading problems and to manage two active language systems. Bilingual children, therefore, have had more opportunity than monolinguals to exercise a crucial cognitive skill, and this practice may then accelerate the development of that skill. Control processes responsible for the regulation and inhibition of information, especially in the presence of conflicting cues, are among the last cognitive skills to emerge in children. This delay has been attributed to the late development of the frontal lobes that mediate these skills (Diamond, 2002). Therefore, bilingualism may have the salutary effect of boosting control processes in nonverbal domains because those same general processes are required to manage two-language systems.

Evidence that two language systems necessitate such management comes from studies of language processing in bilinguals showing that both languages are activated when a bilingual uses one of them (reviews in Brysbaert, 1998; Francis, 1999; Gollan and Kroll, 2001; Kroll and Dijkstra, 2002; Smith, 1997). These effects have been demonstrated with such methods as cross-language priming (Gollan et al., 1997), cross-language Stroop tasks (Chen and Ho, 1986), and cross-language homograph recognition (Dijkstra et al., 1999). In all these paradigms, material presented in one language affects the response produced in the other. For example, bilinguals demonstrate a Stroop cost when the irrelevant

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1053-8119/$ - see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2004.09.044

color word is presented in one language and color naming proceeds in the other. In cross-language homograph recognition, a word that is a homograph in the other language (e.g., "pays" in English and French) is read more slowly in a task requiring word reading in only one of the languages. The joint activation of both languages means that bilinguals must control attention to the selected language in order to achieve fluent performance in the designated language without intrusions from the other system. This situation is similar to that encountered in the attentional control problems described above: A salient but irrelevant cue, in this case, the other language, must be ignored or inhibited in order to perform the task.

Two models that assign a prominent role to inhibitory control have been proposed to explain how bilinguals manage control over the jointly activated languages. The first model, called Bilingual Interactive Activation, is a simulation model in which hierarchically organized representations of words from both languages are activated by input and compete for attention (Dijkstra and Van Heuven, 1998; Van Heuven et al., 1998). A layer of nodes indicates the language tag and represents the role of context in language use. The competition that occurs both within and across languages is resolved by lateral inhibition—adjacent representations inhibit each other, so selection of a particular response reduces the likelihood of selecting the neighboring response. The model successfully simulates data obtained in behavioral studies and is primarily used as an account of how semantic processing is carried out by bilinguals.

The second model, proposed by Green (1998), is called Inhibitory Control. It is based on the supervisory attention system described by Shallice and Burgess (1996), which controls the activation of competing schemes. Green's extension of this work suggests that this system also manages the activation of competing language schemes. Bilinguals must exercise inhibitory control over the nondesignated language to allow the required language system to guide performance. Crucially, the mechanism that reduces attention to the nonrelevant language system is the same as that used to manage attention in all cognitive tasks. Although it is based on the same type of psycholinguistic evidence as the model developed by Dijkstra and his colleagues, Green's model has implications for high-level cognitive processing because the relevant inhibition mechanism is situated in a central process.

In contrast to both these views, Costa et al. (1999) dispute the claim that inhibition is involved in controlling bilingual language use. In a series of experiments involving picture naming, they found cross-language facilitation effects as well as interference across languages. These results extend the models by indicating that the conflict created by two language systems may require resolution at a level other than the lexicon and that the resolution may include both inhibitory and facilitatory processes.

Both the Bilingual Interactive Activation and Inhibitory Control models address the organization of semantic systems in bilinguals and propose inhibitory mechanisms to resolve the conflict produced if access to the lexicon is nonselective for language. Nonetheless, the nature and locus of that inhibition is different. In Dijkstra and Van Heuven's (1998) simulation model, the inhibition is a local mechanism determined by properties of the stimulus; in Green's (1998) behavioral model, inhibition is a central mechanism emanating from higher centers such as the frontal lobes. Because it is data-driven, it is difficult to see how the inhibition proposed by Dijkstra and Van Heuven could generalize across problems and skill areas. The centrally situated inhibitory control model developed by Green, in contrast, provides a plausible basis for understanding how bilinguals could develop a generalized advantage in cognitive control. If the control processes used in the management of language systems described by Green are the same processes recruited for other nonverbal purposes, then the use of these processes during language use would provide an explanation for the enhanced performance of bilinguals on certain nonverbal cognitive tasks. This interpretation leads to the hypothesis that bilinguals are more proficient than monolinguals in tasks requiring inhibitory control.

A nonverbal task that can be used to examine the extent to which bilinguals and monolinguals differ in inhibitory control is the Simon task, an experimental paradigm based on stimulus-response compatibility. In the critical condition, a prepotent association to irrelevant spatial information interferes with a required response (for review, Lu and Proctor, 1995). For example, in a visual display, participants may be told to press the right response key if a blue square appears and the left response key if a green square appears. These stimuli are presented on the left or right sides of the screen so that position information becomes part of the stimulus display although it is not relevant to response selection. In congruent items, the irrelevant spatial position supports the rule-directed correct response (e.g., blue square on right side); in incongruent items, the irrelevant spatial position conflicts with the correct response (e.g., blue square on left side). The task, therefore, requires inhibitory control to ignore the irrelevant position information in the incongruent trials. This is the type of processing in which bilinguals should excel.

The hypothesis that bilinguals would outperform monolinguals in a Simon task was tested in studies including participants in four age groups: children (5 years), young adults (20–30 years), middle-aged (30–60 years), and older adults (over 60 years). The results showed faster reaction times for bilinguals in three of those groups; only the young adults produced equal response times by monolingual and bilingual participants (Bialystok et al., 2004, in press). Moreover, where the bilingual advantage occurred, it was found for both congruent and incongruent trials. The bilingual advantage for congruent trials was surprising. It is possible that the need to switch between congruent and incongruent trials in the mixed designs used in these studies may have imposed a greater challenge on the control processes for monolinguals than for bilinguals, producing a speed advantage in both types of trial.

The only group that did not demonstrate a bilingual advantage was the young adults. This group consisted of undergraduate university students, the population most frequently tested in this type of research. Compared to the participants in the other age groups, these individuals were the most skilled computer users and the most comfortable with tasks involving rapid response to visual stimuli. For those participants who reported spending much of their time playing video games, response speeds were significantly faster than those of their less playful peers (Bialystok et al., in press), a difference also reported in a series of visual attention tasks by Green and Bavalier (2003). Therefore, the experience with computers may improve the efficiency of these participants to such a degree that there was little that bilingualism could do to further improve the reaction times. Even though monolinguals and bilinguals may process these items differently, the differences were not evident in the reaction times for a group of fast responders.

An examination of the areas of cortical activation during this task may illuminate the reason for the bilingual advantage for both congruent and incongruent trials in children and older adults and help to explain the absence of a bilingual advantage in skilled young adults. The present study addressed these issues by using MEG imaging to investigate performance on the Simon task by monolingual and bilingual young adults. The expectation was that differences in electrophysiological signals would be more informative than reaction times in establishing how participants in this age group solve the task. Such data would help to clarify the processing differences underlying responses to the congruent and incongruent trials by participants in the two language groups and the relation between reaction time and these processing patterns even in the absence of reaction time differences between groups.

Research in other domains has used imaging data to reveal the subtle ways that experience affects cognitive processing. Elbert et al. (1995), for example, demonstrated that professional musicians of string instruments had larger cortical representation areas for the fingers used in playing those instruments than non-musicians. Similarly, Schulte et al. (2002) used MEG imaging to demonstrate that repeated exposure to a series of complex tones resulted both in perception of a novel melody and reorganization of the auditory cortex. It is possible that practice emanating from a cognitive experience, namely, bilingualism, similarly influences the organization of mental abilities.

Imaging studies using the Simon and related tasks help to identify areas that may be involved in the processing differences between monolinguals and bilinguals. Two studies by Iacoboni and his colleagues (Iacoboni et al., 1996, 1998) used PET to establish the areas of activation while participants performed a Simon-type task. A flashing light appeared on one side of the display and participants had to press a button on either the same or opposite side. The first study was concerned with the effect of practice (Iacoboni et al., 1996) and the second with potential differences between visual and auditory stimuli (Iacoboni et al., 1998). The design was different from the standard arrangement in that the congruent and incongruent trials were presented in separate blocks so no switching between trials was involved. In both studies, the regions of greatest activation were the superior parietal lobule, posterior parietal, superior frontal sulcus, and dorsolateral prefrontal cortex (DLPFC), all primarily in the left hemisphere. Both DLPFC and parietal cortex are involved in attention and DLPFC in response selection and inhibition as well. Using fMRI, Maclin et al. (2001) presented participants with a Simon task in which arrows pointing to the left or right appeared on the left or right side of the screen. Participants pressed a key to indicate which way the arrows pointed. This task produced activation in the superior frontal gyrus, middle frontal gyrus, right medial frontal gyrus, lingual gyrus, and right precuneus region. Using the same task, Peterson et al. (2002) compared performance on a Simon task to that obtained from a Stroop task for which more neuroimaging data are available. They found that the two tasks produced the same patterns of activation, specifically, in the middle occipital gyrus, anterior cingulate gyrus, inferior temporal gyrus, inferior parietal gyrus, inferior frontal gyrus, and dorsolateral prefrontal cortex. Fan et al. (2003) compared activation during a Stroop task, Simon task, and flanker task using fMRI and found common activity for all tasks in the anterior cingulate and left PFC. More generally, Jonides et al. (1998) showed that inhibitory processing is associated with a lateral portion of the left PFC, and MacDonald et al. (2000) further suggested that areas of the left PFC are involved in representing and monitoring the attentional demands of complex tasks. MacDonald and his group used the Stroop task and found that stronger activations of the left PFC were associated with smaller interference effects, and that stronger activation of the anterior cingulate (ACC) was associated with larger interference effects. Their suggestion is that individuals with good control mechanisms are better at maintaining top-down controlling representations in the PFC, and therefore need to draw less on the conflict resolution processes associated with the ACC (see also Jonides et al., 2002).

A very small number of studies has extended these methods to bilinguals. Hernandez et al. (2000) located the mechanism for language switching in the DLPFC, and research by Posner and DiGirolamo (1998) found that the ACC was involved in translation but not in simple reading. In translation, both languages must be equally available so that the message can be transferred accurately from one to the other whereas reading can proceed through activation of only one language system. This evidence suggests that certain brain areas (specifically left PFC and ACC) are differentially involved by monolinguals and bilinguals in response-conflict tasks, even if RT data do not distinguish between the groups in young adults. The first purpose of the present study was to confirm and elucidate this differential pattern. The second purpose was to understand why the bilingual advantage in RTs occurred for both congruent and incongruent trials (Bialystok et al., 2004, in press). One possibility is that if lifelong experience of bilingualism results in enhanced cognitive control, this may be associated with an improved ability to represent task control in the left PFC (MacDonald et al., 2000). In turn, this greater task control may act in a top-down fashion to improve performance on both congruent and incongruent trials. The present study investigated these issues by examining two groups of bilinguals and a group of monolinguals to determine whether cortical activation during the Simon task was different for participants in the two language groups.

Method

Participants

Thirty healthy, right-handed volunteers (mean age 29 years, range 22–36 years) participated in the study. The sample comprised 10 English monolinguals, 10 French–English bilinguals, and 10 Cantonese–English bilinguals. Gender was matched across the three groups so that each group had seven female and three male participants. Participants were classified as bilingual on the basis of a questionnaire examining their language history using strict criteria for their use of both languages throughout their lives. All bilinguals had learned both languages early in childhood, had continued to use both languages essentially daily throughout their lives, and were completely fluent in both languages. For all the bilinguals, French or Cantonese was the language of their home and English was their language of schooling. English fluency was equivalent for both monolingual and bilingual participants. The participants provided written informed consent for their involvement in the experiment. One Cantonese–English bilingual participant was excluded at the analysis stage because her reaction times were extremely long and were statistical outliers from the rest of the sample of 29 participants, so only nine participants were included in the analysis for the Cantonese–English group. It had been noted that the excluded participant was very tired during the experiment and had difficulty concentrating. Ethics approval for the study was obtained from the Ethics Review Board of Baycrest Centre.

MEG recording and anatomical MRI

MEG data were recorded in a magnetically shielded room using a 151-channel whole head biomagnetometer system (Omega 151, CTF Systems Inc., Canada) with detection coils spaced by 31 mm. Each coil was 20 mm in diameter and was configured as axial first-order gradiometers with a baseline of 50 mm. Each coil was connected to a superconducting quantum interference device (SQUID). The spectral density of the intrinsic noise of each channel was between 3 and 6 fT(rms)/$\sqrt{\text{Hz}}$ in the frequency range above 1 Hz. The magnetic responses were filtered with a 60-Hz notch filter and a 200-Hz low pass filter and digitized at 625 Hz. Epochs in which signal variations were larger than 3 pT in the MEG were treated as artifacts and were excluded from further analysis. The head positions were measured at the beginning and the end of each session and data with mean head movements larger than 6 mm were not accepted.

To convert the source of MEG responses into brain images, magnetic resonance imaging (MRI) scans (1.5-T Sigma scanner, GE Medical Systems, Milwaukee, WI) were obtained for all participants. T1-weighted axial anatomical images with in-plane resolution of 256 × 192 and 128 slices (1.4 mm thickness) were recorded using spoiled gradient echo imaging. The same anatomical landmarks (nasion and center points of the entrance to the bilateral ear canals) were used to create a common head-based 3D coordinate system for MEG and MRI.

Experimental design

Participants were seated comfortably in the MEG and instructed to fixate on the center of the screen. Red or green squares were visually presented on the left or right side of the screen. Participants were instructed to press one response key if a red square appeared and the other if a green square was shown, irrespective of its position. The mapping of stimulus color to response key was counterbalanced across participants within each group. The response keys were placed comfortably one under each hand and participants placed each index finger over one of the keys. Congruent trials were those in which the correct response key was on the same side as the stimulus and incongruent trials were those in which the reverse was true. In addition to the experimental trials, the MEG responses were recorded in a control condition in which the same stimuli were presented in the center of the screen. The response rule that connected the stimulus color to the response key was the same, but because the stimuli were always presented centrally, there was no possibility of conflicting position information. Participants were instructed to respond as quickly as possible without making errors.

Each trial began with a fixation cross as a warning cue shown in the center of the screen for 150 ms and was followed by a 350-ms interval. The stimulus (40-mm square) then appeared for 400 ms on the left or right side for experimental trials or in the center for control trials. After a 900-ms blank interval the warning cue for the next trial appeared, making the total time for a complete trial 1800 ms. The stimulus was projected onto a dark screen in the left or right visual field at 11.6° offset from a central fixation point. The distance between the screen and the nasion of the subject was 880 mm. All cues and stimuli were reflected by mirrors inside the magnetically shielded room from a projection system outside the room.

Each recording block consisted of 52 trials. The first four trials were rejected as dummy stimuli to avoid any primacy effects. Eight blocks of experimental trials (Simon task) and four blocks of the control condition (central stimulus) were alternately tested using pairs of experimental blocks interspersed between the controls and a short rest (6.8 s) between each block. Six hundred and twenty-four (52 × 8 for Simon task and 52 × 4 for control task) trials were thus recorded for each participant.

Data analysis

To detect the task-related cortical states, the signal power differences between predefined time intervals for the experimental task and control stages were computed using synthetic aperture magnetometry (SAM) (Ishii et al., 1999; Robinson and Rose, 1992). In each trial, the time intervals of 0–400 and −400–0 ms with respect to each stimulus onset were defined as the task and control stages, respectively. Signals in these two time-intervals were filtered in the frequency bands of 0–4, 4–8, 8–15, 15–30, 30–60, and 60–200 Hz. SAM is based on the concept of the beam-forming technique applying a spatial filter, specific for each brain voxel, to suppress the interference of the unwanted signals (Robinson and Vrba, 1998). Statistical evaluation of the ratio of the power differences between the active and control windows to the sum of the powers of noise was expressed as a pseudo t value for each voxel. Images of pseudo t values, with resolution of 5 × 5 × 5 mm^3, were computed to reflect the changes of power between the task (i.e., congruent and incongruent trials) and control states for each subject. Z scores of these pseudo t values were then obtained from the images. Data were analyzed from all six bands but significant patterns were detected in only two of them, namely, 4–8 and 8–15 Hz, so results are reported for activity in only these two bands.

To evaluate the SAM results in the group, spatial normalization was performed to transform each individual's SAM images into a common anatomical space. The SAM images of each participant were first co-registered with his or her 3D anatomical MRI based on the landmarks (nasion and ear canals). Each individual's MRI images were then spatially normalized into the SPM T1 template space using SPM99 software (Wellcome Department of Cognitive Neurology, London, UK). The transformation parameters were used to transform the SAM images into the common space for the group analysis.

There were two further steps in the analysis of the SAM images. The first, called *task analysis*, was to test for modulations of brain activity across the control, congruent, and incongruent task conditions; the second, called *behavioral analysis*, was to identify the areas of the brain in which activity was correlated with reaction time in each of the conditions. Because these analytical steps are focused on the integrated activity of dynamic brain networks rather than on any single region acting independently, our approach to image data analysis is designed to reveal these networks through multivariate techniques. Partial Least Squares, or PLS (McIntosh et al., 1996), was used for both analyses. For the task analysis, PLS operates on the covariance between brain voxels and the experimental design to identify a new set of variables (Latent Variables or LVs, similar to principal components) that optimally relate the brain activity and the task conditions. Each LV identifies a pattern of task differences that best accounts for the brain measurements and can identify either areas of activity common across groups or tasks, or areas that differ between groups or conditions. Thus, the analysis identifies a group of brain regions that *together* covary with some aspect of the experimental design.

Each brain voxel has a weight on each LV, known as a salience, which indicates how that voxel is related to the LV. A salience can be positive or negative indicating the direction of the relation between the voxel and the pattern of task differences identified by the LV. In addition, each LV has task saliences for each condition and group in the analysis. The task saliences indicate how brain activity differs across conditions (or groups), as greater activity in brain areas with positive (or negative) saliences on a latent variable are associated with positive (or negative) task saliences for a given condition or group.

For the task analysis, the data from all three groups were entered into the analysis to assess main effects and task by group interactions. For the behavioral analysis, the correlations between activity in all brain voxels and RT were calculated *within* the congruent and incongruent conditions for each group. PLS was used to contrast these correlations *across* conditions and *across* groups. Brain saliences and task saliences, called behavior saliences for this analysis, were calculated as described above. Two statistical measures were obtained from each of these PLS analyses. The statistical significance of each LV as a whole was assessed using a permutation test (Edgington, 1980; McIntosh et al., 1996). In an independent step, the reliability of each brain voxel's contribution to the LV pattern was determined through bootstrap resampling to estimate the standard error of each salience (Efron and Tibshirani, 1986; Sampson et al., 1989). In both the permutation and bootstrap procedures, all saliences are calculated in a single analytical step; hence, there is no significance testing of individual brain regions, and no need for correction for multiple comparisons, as is often done in univariate analyses (McIntosh et al., 1996). A reliable contribution for a given voxel was defined as a ratio of salience to standard error greater than or equal to 3.0, which exceeds the 99% confidence interval (Sampson et al., 1989). Locations of the maxima for each reliable region are reported in terms of brain region, or gyrus, and Brodmann area (BA) as defined in the Talairach and Tournoux atlas (Talairach and Tournoux, 1988).

Results

The mean scores and standard deviations for the behavioral RT data are reported in Table 1. A two-way ANOVA for group (3) and condition (3) showed main effects of group, $F(2, 26) = 4.13$, $P < 0.02$, and condition, $F(2, 52) = 78.37$, $P < 0.0001$, with no interaction. Contrast analyses on the group effect indicated that the reaction times of the Cantonese group were faster than either of the other two groups, which did not differ from each other. The condition effect revealed significant differences between the reaction times for all three conditions (all $P < 0.01$), with fastest times for the control and longest times for the incongruent trials.

The imaging analyses examined the data from the congruent and incongruent conditions in two frequency bands: 4–8 and 8–15 Hz. The first, corresponding largely to theta, is related to focus of attention (Ishii et al., 1999) and the second, corresponding partly to alpha, is related to signal processing (Hari et al., 1997; Schurmann and Basar, 2001). The task PLS analysis in the 4–8 Hz band indicated a significant LV, $P < 0.05$, which identified a contrast between areas associated with responses to the congruent and incongruent trials. The pattern of activation for these different trials is the same for all groups, although it is expressed more strongly in the two bilingual groups than in the monolingual group. Fig. 1 displays the areas of activation, indicating whether they have positive (blue) or negative (red) saliences, and the graph describing the task salience indicates the direction and degree of fit between that activation pattern and the two trial types for each of the groups. The relation between the activity pattern and the congruent trials is negative, so more activity during congruent trials is associated with the regions of negative salience (red areas), specifically, left and medial dorsolateral prefrontal and right cuneus. The relation between the activation pattern and task salience is positive for the incongruent trials, so the greater activation in this case is associated with increased power in the post central and superior frontal regions in the left hemisphere (blue areas). No other significant LVs emerged from the task PLS analysis at either frequency band. The areas indicated in Fig. 1 are listed in Table 2.

The purpose of the behavioral PLS analysis is to determine the relation between the activated regions and behavior as measured by reaction time. These analyses help to identify the areas responsible for faster or slower performance in the task. The analysis in the 4–8 Hz band identified a significant LV, $P < 0.03$, indicating the same pattern for all participants, although it is more weakly expressed in the Cantonese group. The areas correlated with RT, shown in Fig. 2, were largely the same for both congruent and incongruent trials and are listed in Table 3. All the correlations between brain salience and reaction time (behavior salience graph) were positive, so in all cases positive brain salience (red areas) is associated with longer reaction times and negative brain salience (blue areas) is associated with shorter times. Slower reaction times were associated with increased activation of the post central gyrus, insula, cuneus, and inferior parietal areas in the right hemisphere, and faster times with more activation of the middle frontal and cingulate in the right hemisphere and superior frontal, supramarginal, and post central regions in the left hemisphere.

The 8–15 Hz band is generally associated with signal processing and as such provides the most direct test of group differences in task performance. The images obtained from this analysis are displayed in Fig. 3. This was the only analysis to reveal two significant LVs. In LV1, $P < 0.004$, the two bilingual groups express the same pattern of positive correlation between brain salience and RT but the monolingual group shows no correlation with this pattern. The crossblock variance explained by

Table 1
Mean reaction time and accuracy for each condition by group

Group	Condition					
	Control		Congruent		Incongruent	
	RT (SD)	%Accuracy	RT (SD)	%Accuracy	RT (SD)	%Accuracy
Monolingual (N = 10)	425 (76)	97	479 (99)	96	499 (94)	93
French (N = 10)	415 (64)	98	457 (77)	97	475 (80)	96
Cantonese (N = 9)	348 (46)	95	378 (65)	93	397 (62)	91

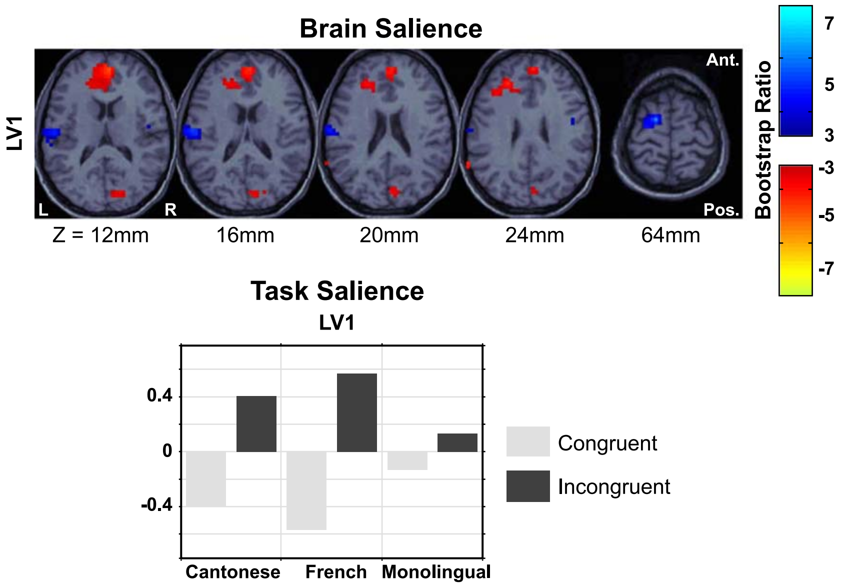

Fig. 1. Brain salience and contrasts in LV1 for congruent and incongruent trials in PLS task analysis for 4-8 Hz band by group.

this LV is 25.3%, $P < 0.004$. The pattern describing the two bilingual groups is positive, so positive brain salience is associated with slower responding. For both congruent and incongruent trials, slower reaction times are associated with more activation in the middle occipital, inferior parietal, and precuneus regions largely in the right hemisphere and faster reaction times are associated with more activity in superior and middle temporal, cingulate, and superior and inferior frontal regions largely in the left hemisphere. A correlation indicating faster reaction times with more activation of the cerebellum was also found, but the cerebellum is not easily detectable by MEG recording, so this result requires further investigation.

LV1 gives no indication about the activation patterns of the monolinguals, but some suggestion about their performance can be found in LV2, $P < 0.05$. The pattern indicated in these data is less robust than that captured by LV1, partly because of the lower significance level and partly because of an interaction between group and condition. The crossblock variance explained by this second LV is 21.0%, $P < 0.045$. There is a strong positive correlation between the monolingual behavior and brain salience, so the LV provides some indication about the performance of that group. In this LV for the monolinguals, slower responses are associated with activation largely in the right precentral region and faster responses are associated with activation in the left middle frontal region. The Cantonese bilinguals express this pattern for the incongruent trials but show the opposite relations between speed and brain salience for the congruent trials. The French bilinguals are not represented by this pattern, so LV2 indicates an aspect of performance that is different for the two bilingual groups. The areas involved in this LV are listed in Table 4.

Table 2
Maxima of areas for LV in task PLS, 4–8 Hz band

Gyrus or region	Hem	BA	*X*	*Y*	*Z*	# Vox	Ratio
4–8 Hz band, positive salience (increased activation for incongruent)							
Post central	L	43	−64	−16	16	50	4.9
Superior frontal	L	6	−20	−4	64	35	5.9
4–8 Hz band, negative salience (increased activation for congruent)							
Middle frontal	L	46	−28	36	24	302	−4.2
Medial frontal	M	9	0	52	12	302	−4.7
Cuneus	R	18	4	−84	20	23	−3.5

X (right/left): Negative values are in the left hemisphere; *Y* (anterior/posterior): Negative values are posterior to the zero point (located at the anterior commissure); *Z* (superior/inferior): Negative values are inferior to the plane defined by the anterior and posterior commissures. The number of voxels is the same for the two frontal regions because these regions were part of the same large activated cluster.

Discussion

All the participants were university students and skilled computer users, yet performance in the Simon task was different for the three groups. For the behavioral measures of reaction time, the Cantonese–English bilinguals were faster than the other two groups. For the electrophysiological measures of regional activation, all three groups were the same for the task PLS analysis describing the differential response to congruent and incongruent trials. In the behavioral PLS analysis, faster reaction times were associated with increased frontal activation for all three groups, replicating previous experimental results (Grady, 2002). However, the behavioral PLS analysis showed that the specific cortical areas involved were largely the same for the two bilingual groups but different for the monolinguals.

One expectation of the present research was that the brain activation data would distinguish between monolingual and bilingual performance even in the absence of reaction time differences between the groups. Consistent with our previous research (Bialystok et al., in press), the French–English bilinguals produced the same RTs as the monolinguals on both congruent and incongruent trials, but the Cantonese–English bilinguals were faster than both of these groups. Also replicating our previous results with children and older adults, the Cantonese group maintained their speed advantage equally for both congruent and incongruent trials. We have no explanation for the faster reaction times of the Cantonese–English bilinguals, but due to the relatively

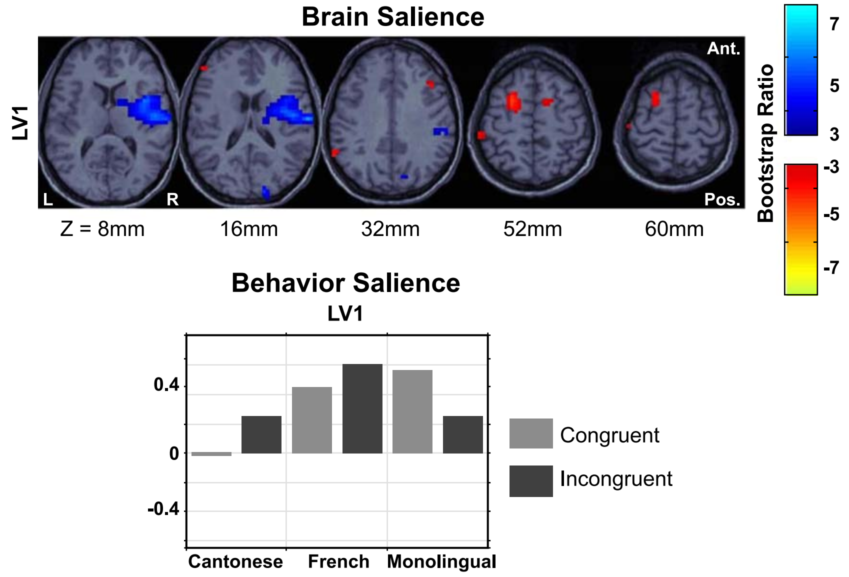

Fig. 2. Brain salience and behavior contrast in LV1 with reaction time for congruent and incongruent trials in 4–8 Hz band by group.

small numbers of participants in each group this result could be due to sampling variability.

The hypothesis for a processing distinction between monolinguals and bilinguals was supported in the behavioral PLS analyses. In the 4–8 Hz band normally associated with attention (Fig. 2), all the groups were similar, although the Cantonese–English bilinguals conformed least to the detected pattern. Faster reaction times were associated with greater activity mostly in left hemisphere regions and slower responses with greater activity in right hemisphere regions. It is possible that these activation patterns partly reflect response speed, since the fast Cantonese bilinguals expressed this pattern to a lesser extent. In spite of the similarity in attention responses, the monolinguals and bilinguals diverged for the activation results indicating processing in the 8–15 Hz band (Fig. 3, LV1). In this case, the French group responded similarly to the Cantonese group with whom they shared bilingualism, but differently from the monolingual group with whom they shared speed. For the bilinguals, faster responding was signaled by greater activation of the right temporal and left frontal and cingulate areas and slower responding by activity in occipital and parietal regions. This pattern in which the left frontal and cingulate areas govern responses to the Simon task is typical for conflict problems of this type (Peterson et al., 2002) and likely indicates engagement of inhibitory processes. The slower responses are characterized by emphasis on the visual (occipital) and spatial (parietal) aspects of the stimuli.

Table 3
Maxima of areas for LV in behavior PLS, 4–8 Hz band

Gyrus or region	Hem	BA	*X*	*Y*	*Z*	# Vox	Ratio
Positive salience (slower RT)							
Post central	R	43	60	−16	16	538	6.2
Insula	R		36	4	8	538	5.6
Cuneus	R	18	16	−96	20	33	5.1
Inferior parietal	R	40	56	−28	36	22	3.6
Negative salience (faster RT)							
Superior frontal	L	6	−28	4	52	73	−4.4
Middle frontal	R	9	44	20	28	21	−3.9
Cingulate	R	32	12	4	48	19	−3.4
Supramarginal	L	40	−72	−60	32	14	−4.0
Post central	L	2	−60	−28	60	12	−3.7

X (right/left): Negative values are in the left hemisphere; *Y* (anterior/posterior): Negative values are posterior to the zero point (located at the anterior commissure); *Z* (superior/inferior): Negative values are inferior to the plane defined by the anterior and posterior commissures. The number of voxels is the same for the post central gyrus and insula because these regions were part of the same large activated cluster.

LV2 of the behavioral PLS analysis in the 8–15 Hz band offers some indication of how processing is carried out by the monolinguals, although the pattern is less clear than the first LV describing the bilingual performance. In LV2, faster reaction times were associated with activity in the left middle frontal region, part of the dorsolateral prefrontal cortex, and slower reaction times with activation in the right frontal and precentral areas. Unlike LV1 where slow responding is mostly attributed to activation in the visual areas, this pattern indicates that slow responding is mostly attributed to activation in the motor areas. The complication in interpreting this pattern is that it applies to the Cantonese bilingual group when they are responding to incongruent trials but operates in reverse for the congruent trials. The Cantonese group responded significantly more rapidly than the French group, so it is plausible that once the large common variance captured by LV1 is identified, there is additional activation expressed by the Cantonese group that distinguishes them from the French bilinguals. This pattern of activation, nonetheless, is still not the same as that found for the monolinguals, as shown by the direction change for the congruent trials.

The Cantonese group was different from the monolinguals in several analyses. An obvious possibility is that the response speed difference demonstrated by this group was associated with different activation patterns, but the difference cannot be attributed entirely to speed. First, the French–English bilinguals performed at the same speed as the monolinguals but showed the same pattern of correlation between brain activation and RT as the Cantonese–English bilinguals. Second, an additional analysis that classified participants by overall reaction time using a median

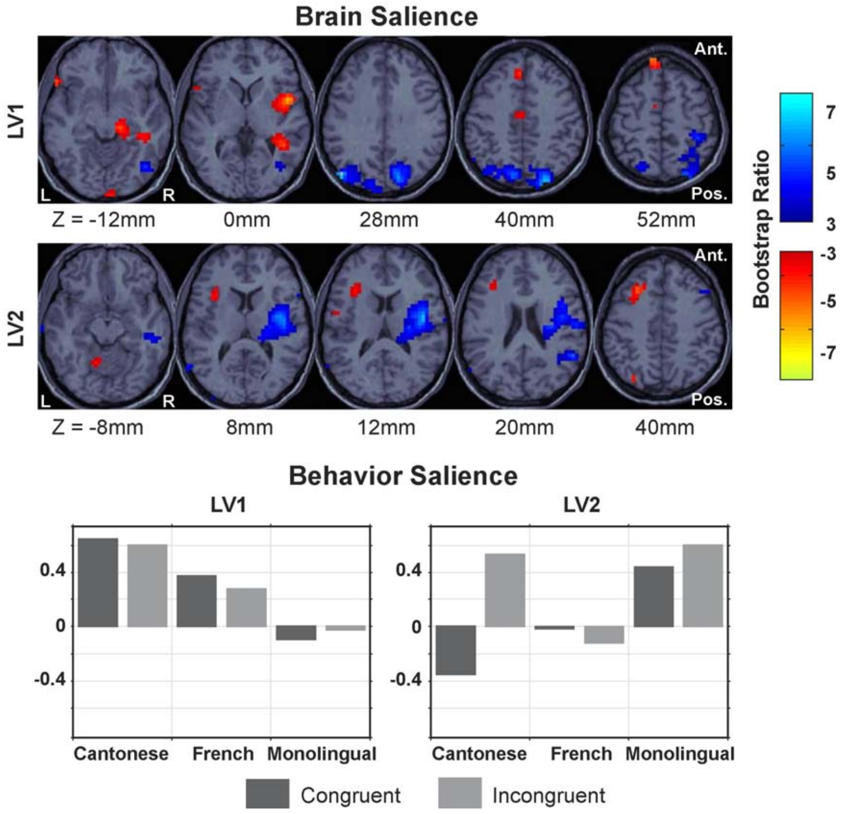

Fig. 3. Brain salience and behavior contrast in LV1 and LV2 with reaction time for congruent and incongruent trials in 8–15 Hz band by group.

split did not replicate the difference between these two groups in brain salience in a behavioral PLS analysis. Therefore, the similarity between the two bilingual groups and the difference between both of these and the monolinguals is the predominant pattern in brain activation in the behavioral analyses. Irrespective of the speed in which performance was carried out, the two

Table 4
Maxima of areas for behavior PLS, 8–15 Hz band

Gyrus or region	Hem	BA	*X*	*Y*	*Z*	# Vox	Ratio
LV1, positive salience							
Middle occipital	L	19	−52	−80	28	344	8.1
Middle occipital	R	19	40	−72	−8	52	5.2
Inferior parietal	R	40	36	−40	52	45	4.7
Precuneus	R	19	24	−96	40	362	6.9
LV1, negative salience							
Superior temporal	R	22	44	4	0	158	−6.1
Middle temporal	R	21	40	−48	4	130	−5.8
Cingulate	L	24	−8	−16	40	12	−3.3
Superior frontal	L	8	−16	48	52	48	−5.1
Inferior frontal	L	47	−60	24	−12	41	−4.4
Inferior frontal	L	45	−48	24	12	15	−3.5
LV2, positive salience							
Inferior frontal	R	45	68	24	8	44	4.3
Middle frontal	R	9	48	20	40	12	3.6
Precentral	R	6	40	−8	12	571	6.7
Middle occipital	L	37	−68	−68	4	17	4.7
Superior temporal	R	22	52	−52	20	32	5.3
LV2, negative salience							
Middle frontal	L	9	−32	24	40	90	−4.7

X (right/left): Negative values are in the left hemisphere; *Y* (anterior/posterior): Negative values are posterior to the zero point (located at the anterior commissure); *Z* (superior/inferior): Negative values are inferior to the plane defined by the anterior and posterior commissures.

bilingual groups demonstrated a common brain activity pattern, distinguishing them from the monolinguals. Even in the absence of reaction time differences, as between the French and monolingual groups, bilinguals are characterized by a unique approach to this task.

Throughout the analyses, there was greater somatosensory activity in the right hemisphere than in the left, but because of the experimental design, this activity cannot represent simple button pressing. First, each participant used both hands equally to respond in each condition, so if the somatosensory activation were related to the button pressing, then it would have the same effect on both congruent and incongruent conditions. Second, because the behavioral PLS was done with mean RT collapsed across right and left hands, and the mapping of hand to response was counterbalanced, a lateralized correlation in somatosensory cortex cannot be related in any simple way to pressing buttons per se. Furthermore, LV2 in the behavioral PLS indicated an interaction with group, so again the correlation cannot be attributable to simple button pressing.

The second goal of the study was to determine whether data from neural activation could help to explain why reaction time differences between groups found in previous research apply equally to both congruent and incongruent trials. The task PLS analysis in the 4–8 Hz band identified a set of regions involved in responding to each of the congruent and incongruent trials, and this pattern of activity characterized both groups of bilinguals, as well as the monolingual participants. More importantly, the behavioral PLS that related the activated regions to reaction time indicated the same relations for both congruent and incongruent trials. Although bilingualism may alter aspects of the processing used to perform the Simon task, it does not appear to affect the manner in which trials are distinguished as congruent or incongruent.

The evidence supports the interpretation that bilinguals perform the Simon task differently from monolinguals even when they respond at the same speed, and that the group differences are evident for both congruent and incongruent trials. The difference between the language groups was not simply in the intensity with which certain regions were involved, although that occurred as well, but rather with the specific areas recruited to perform this task. The areas used by both groups are consistent with areas identified in previous research to be involved in the Simon task (e.g., Fan et al., 2003; Iacoboni et al., 1996, 1998; Peterson et al., 2002), but the two language groups used a different subset of these regions. Fast responding in bilinguals was associated with activation in cingulate, superior frontal, and inferior frontal regions and fast responding in monolinguals with middle frontal, all in the left hemisphere. Therefore, both groups showed faster responding with more activation of left frontal areas even though the specific regions were somewhat different. Many of the areas associated with faster responding in bilinguals were left hemisphere regions that bordered on language centers in the inferior frontal cortex. It is possible that bilingualism enhances those control processes in the left frontal lobe and makes them available for other inhibitory tasks, even nonverbal ones. This interpretation is consistent with hypotheses that follow from Green's (1998) model of inhibitory control for bilingual language processing. Slower responding in both bilinguals and monolinguals, however, was related to activation of substantially different areas. For the bilinguals, slow responding was accompanied by more activation in the visual cortex, and for the monolinguals, by activation in the motor cortex, largely in the right hemisphere in both cases. However, in both cases, slower responding seems to be related to additional processing carried out by sensory or motor regions, suggesting that these types of strategies are less efficient than those that make use of controlled inhibitory processing.

The results of the present study contribute as well to understanding performance on the Simon task. One implication is that performance, and the brain areas underlying this performance, are not determined entirely by the speed or facility with which one can carry out the task itself. Instead, regional activation in this task is determined by at least one type of experience in a completely different cognitive domain that has conferred sustained changes in the organization of specific frontal regions and their availability to engage in specific problems. Although some activated areas are undoubtedly related to response speed, others are related to factors that seem to be irrelevant to the Simon task. The overall regional activations that were uncovered in our analysis correspond to those previously reported for this and other similar tasks, but the specific foci in those general areas were influenced in part by the language background of the participants.

In summary, the combination of behavioral data and images of regional activation derived from MEG have converged to show systematic differences in performance between monolingual and bilingual participants. The task PLS data (Fig. 1) showed that both language groups dealt with differences between congruent and incongruent trials by using the same brain regions, although the pattern was shown more strongly by the two bilingual groups than by the monolingual group. The behavioral PLS data from the 8–15 Hz band (Fig. 3) revealed differential brain–behavior relations for monolinguals and bilinguals, although the two bilingual groups were not themselves identical in all respects (i.e., Fig. 3, LV2). In general, faster responding in the bilingual groups was related to greater involvement of areas in the left PFC and ACC—arguably the same areas that are engaged in the management of two language systems.

Acknowledgments

The research reported in this paper was funded by a grant from the Canadian Institutes of Health Research to Ellen Bialystok and a grant from the Natural Sciences and Engineering Research Council of Canada to Fergus Craik. We are grateful to Anthony Herdman, Terry Picton, and Astrid Schloerscheidt for valuable comments on the manuscript and to Jane Logan, Gigi Luk, and Judy Vendramini for technical assistance with the study.

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