



Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression

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ABSTRACT

To examine the effects of bilingualism on cognitive control, we studied monolingual and bilingual young adults performing a flanker task with functional MRI. The trial types of primary interest for this report were incongruent and no-go trials, representing interference suppression and response inhibition, respectively. Response times were similar between groups. Brain data were analyzed using partial least squares (PLS) to identify brain regions where activity covaried across conditions. Monolinguals and bilinguals activated different sets of brain regions for congruent and incongruent trials, but showed activation in the same regions for no-go trials. During the incongruent trials, monolinguals activated the left temporal pole and left superior parietal regions. In contrast, an extensive network including bilateral frontal, temporal and subcortical regions was active in bilinguals during the incongruent trials and in both groups for the no-go trials. Correlations between brain activity and reaction time difference relative to neutral trials revealed that monolinguals and bilinguals showed increased activation in different brain regions to achieve less interference from incongruent flankers. Results indicate that bilingualism selectively affects neural correlates for suppressing interference, but not response inhibition. Moreover, the neural correlates associated with more efficient suppression of interference were different in bilinguals than in monolinguals, suggesting a bilingual-specific network for cognitive control.

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1. Introduction

Recent research has shown that lifelong bilingual adults perform a variety of cognitive control tasks differently from monolinguals. For example, bilinguals are less distracted by interfering stimulus features than monolinguals on the Simon task (Bialystok, Craik, Klein, & Viswanathan, 2004; Martin-Rhee & Bialystok, 2008), Stroop task (Bialystok, Craik, & Luk, 2008), and flanker task (Costa, Hernández, & Sebastián-Gallés, 2008). This bilingual advantage is usually attributed to the experience of managing two languages that compete for attention (Green, 1998). However, differences between monolinguals and bilinguals are not found in all tasks, even those that are considered to rely on cognitive control.

In an anti-saccade task that required inhibiting the execution of a habitual or primed eye-movement response, bilinguals and monolinguals performed similarly, but another version of the same task that required a manual key press instead of an eye movement elicited faster response times by bilinguals (Bialystok, Craik, & Ryan, 2006). This behavioral difference was likely due to differences

between the two tasks in the level of cognitive control required to execute the response. In the eye-tracker version of the task, the external stimulus automatically attracts a pro-saccade response which must be overridden, or inhibited, to look away from the stimulus. We call this aspect of cognitive control “response inhibition”. Costa et al. (2008) also reported comparable orienting responses by bilinguals and monolinguals using the Attentional Network Task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002). However, in the version of the task in which participants pressed a key on the opposite side to the target stimulus, the conflict between the position of the target and the position of the correct response key must be resolved before executing the response. There is no simple motor response involved as in the saccadic eye movement, but rather a decision about which position cue to attend to and which to ignore. Following a distinction introduced by Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002), we call this aspect of cognitive control “interference suppression”. It is in this situation that bilinguals produce faster responses than monolinguals. In the study by Costa et al. (2008), bilinguals produced faster reaction times than monolinguals on the incongruent trials of the ANT assessing inhibitory control, again conditions that require interference suppression. In some studies (Bialystok et al., 2004; Costa et al., 2008; Martin-Rhee &

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Bialystok, 2008), a bilingual advantage in response time was also observed in congruent trials in which the position of the target and the position of the correct response key are the same, providing these were presented in mixed blocks with incongruent trials.

According to Miller and Cohen (2001), cognitive control involves the active maintenance of information necessary to achieve an internal goal through executing actions and is managed by the prefrontal cortex. In the results of Bialystok et al. (2006), two aspects of cognitive control, namely response inhibition and interference suppression, led to different patterns of behavior for bilinguals relative to monolinguals. In addition to these aspects of inhibition, cognitive control also entails the ability to profit from facilitating information. Conversing in the appropriate language relies on both the ability to take advantage of contextual cues in the environment (facilitation) and the suppression of the interfering inappropriate language (inhibition). Therefore, it is possible that bilingualism simultaneously boosts these two aspects of cognitive control.

The present study had two purposes: (1) to compare the neural correlates of cognitive control in monolinguals and bilinguals, with our main focus on differences between response inhibition and interference suppression, and a secondary emphasis on facilitation and (2) to identify the neural networks that show activity correlating with behavioral performance by monolinguals and bilinguals in these tasks. We used fMRI to study monolinguals and bilinguals performing a flanker task with manipulations designed to isolate processes involved in the two aspects of inhibitory control and facilitation. In addition to identifying processing differences between monolingual and bilingual adults, we aimed to contribute to a more detailed conception of cognitive control that includes a distinction between two components of inhibition, suppression of interference and response inhibition.

There is accumulating evidence that bilinguals manage attention to their two jointly activated languages by suppressing attention to the non-target language (Levy, McVeigh, Marful, & Anderson, 2007; Meuter & Allport, 1999; Philipp & Koch, 2009; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008). In a qualitative review of neuroimaging studies examining bilingual language processing, Abutalebi and Green (2008) suggested that this management of the two languages by bilinguals is handled by a language control network that includes left prefrontal cortex, left anterior cingulate cortex, left caudate nucleus, and bilateral supramarginal gyri, with several studies providing supporting evidence (e.g., Abutalebi et al., 2008; Wang, Kuhl, Chen, & Dong, 2009). Moreover, these areas are also activated in a variety of nonlinguistic tasks that require cognitive control. For example, left prefrontal cortex is activated when performing tasks that require focusing on task-relevant information and ignoring distraction (Brass & von Cramon, 2004). Activation in the left anterior cingulate cortex is related to increased effort to overcome interference in a Stroop task (Melcher & Gruber, 2009; Pardo, Pardo, Janer, & Raichle, 1990), and activation in the left caudate nucleus increases during the encoding and maintenance phase of a verbal working memory task (Chang, Crottaz-Herbette, & Menon, 2007). Finally, the left supramarginal gyrus has been found to be related to visuospatial attentional orientation in a singleton visual search task (Weidner, Krummenacher, Reimann, Müller, & Fink, 2009) and action planning (Króliczak & Frey, 2009); the right supramarginal gyrus is involved in spatial processing, such as locating the midpoint of a line (Oliveri & Vallar, 2009), and temporal processing, such as judging the duration of presentation of two stimuli (Wiener, Hamilton, Turkeltaub, Matell, & Coslett, 2010). The results from these studies suggest that the brain regions included in the Abutalebi and Green (2008) model may mediate cognitive control both during language processing and in a more domain-general way. Additionally, if a general brain network is used regularly by bilinguals over an extended period of time to manage conflict from two language

systems, then there may be modifications to the brain regions involved in that network. Therefore, we expected that the control regions that are engaged to a greater extent in bilinguals will overlap with the network proposed by Abutalebi and Green (2008).

In a preliminary examination of the neural networks used by bilinguals to perform nonverbal cognitive control tasks, Bialystok et al. (2005) employed magneto-encephalography (MEG) to record magnetic field activities generated by monolinguals and bilinguals while performing the Simon task. Participants were instructed to press either the left or right button in response to the color of a square. The squares were presented in the center of the screen (the baseline condition) or on the left or right side of the screen (the experimental conditions). The combination of the presentation side and the correct response key position created trials that were either congruent (matched) or incongruent (conflicting positions). The additional time needed to respond in the incongruent condition is the Simon effect. For the bilinguals, faster response times for incongruent trials correlated with increased activity in right superior and middle temporal regions, the left cingulate, and left superior and inferior frontal areas. These regions are consistent with the areas that Abutalebi and Green (2008) proposed are involved in bilingual management of two languages. Importantly, these brain-behavior correlations were not observed in the monolinguals. The MEG results were interpreted as evidence for a dissociated brain-behavior pattern between bilinguals and monolinguals. Resolving the conflict in the incongruent trials in the Simon task was hypothesized to require processing similar to that needed to resolve the conflict created by two active languages. These results suggest that bilinguals resolve conflict with less effort than monolinguals and that left frontal areas are likely to participate in this advantage in bilinguals. Moreover, the conflict inherent in the critical conditions involved cognitive control at the decision making level, the level at which we suggest bilinguals have their advantage. The motor responses for these critical trials were the same as those needed in other trials, except that there was conflicting information to be resolved before executing the action.

The present study extends the results of Bialystok et al. (2005) by using an adaptation of a flanker task that allows us to examine the effects of facilitation and two different components of inhibition, specifically, response inhibition and interference suppression, to determine more precisely the processes affected by bilingualism. Like the Simon task, the flanker task is a nonverbal task in which participants respond to a target in the face of conflicting cues (Bunge et al., 2002; Eriksen & Eriksen, 1974) and, like the Simon task, bilinguals perform this task more efficiently than monolinguals (Emmorey, Luk, Pyers, & Bialystok, 2008).

The incongruent trials require participants to execute a motor response but they first need to resolve the conflicting information given by the target and distracters. The decision to respond left or right requires focusing attention on the target and ignoring distracters (resolving the symbolic conflict created by the target and distracters) in addition to dealing with competing bimanual responses. The congruent trials contain facilitating information because the target and distracters show compatible symbolic information. In contrast, the no-go trials require participants to pay attention to the distracters (which are more visually prominent than the target because there are four distracters but just a single target) and decide whether a motor response should be executed. There is no need to allocate attention to resolve response conflict induced by the symbolic conflict between target and distracters, but rather the conflict is at the motor level over the need to inhibit responding.

The cognitive demands involved in these two types of trials are not mutually exclusive (Anguera, Yang, Barbhaiya, & Gazzaley, 2009). Therefore, our intention was to integrate the measurements

for these two levels of conflict resolution into a single task. If bilinguals are more practiced in resolving conflict from competing cues but not conflict from motor responses, then they will be better at solving the symbolic conflict between the target and distracters in incongruent trials and we would expect differences in the engagement of brain regions that mediate this conflict between bilinguals and monolinguals. In addition, these brain regions were expected to be partially overlapping with the bilingual control network proposed by Abutalebi and Green (2008). Fewer differences were expected for efficiently processing facilitating information because of the less robust behavioral difference in previous research. Similarly, fewer differences were anticipated for withholding motor responses since both bilinguals and monolinguals presumably have similar experience with this type of conflict.

The fMRI data were analyzed with a multivariate technique (partial least squares, PLS, McIntosh, Bookstein, Haxby, & Grady, 1996; McIntosh, Chau, & Protzner, 2004) to identify brain regions that have covarying levels of activation across the various experimental conditions. PLS has the advantage of considering activation across the whole brain and identifies regions that participate in functionally interacting networks. This type of analysis is appropriate because bilingual processing involves multiple cortical areas distributed across the brain as well as subcortical areas (for reviews, see Abutalebi, 2008; Abutalebi & Green, 2008), although no studies have attempted to assess these regions as a coherent network.

To summarize, the purpose of the study was to identify the networks used to respond to suppression of interference and response inhibition in monolingual and bilingual participants. The hypothesis was that bilinguals' experience of selecting a target language from a competing alternative would result in different brain regions recruited to resolve interference suppression but no difference in those used for response inhibition. A dissociation between the networks would contribute to a more precise concept of inhibition in general.

2. Method

2.1. Participants

Twenty healthy right-handed young adults participated in the study. Ten of the participants were monolingual English speakers (mean age 22 years, range from 19 to 25) and 10 were bilinguals (mean age 20 years, range from 19 to 27) who had spoken English and another language on a daily basis since the age of six. One bilingual and one monolingual participant reported intensive action video-game playing experience and had the fastest response times in all the flanker conditions across both groups. We excluded these two participants from all analyses because research has shown that action video-gaming experience improves attention (Dye, Green, & Bavelier, 2009) and early visual processing (West, Stevens, Pun, & Pratt, 2008). Additionally, video-gaming experience may modulate the influence of bilingualism on performance of cognitive tasks (Bialystok, 2006; Green & Bavelier, 2003). The final sample included nine monolinguals (one male) and nine bilinguals (one male). All participants gave informed consent prior to testing. Ethics approval for this experiment was obtained from the Research Ethics Boards of Baycrest Hospital and York University.

The nine bilingual speakers were fluent in English and one of these languages: Cantonese (3), French (2), and one each in Farsi, Bulgarian, Hebrew and Russian. The inclusion of bilinguals with heterogeneous non-English languages allows us to extend the interpretation to a general bilingual sample. Three of the bilinguals reported English to be their first language; the others reported that they learned to speak the non-English language before learning to

speak English. Nonetheless, all of the bilingual speakers used both languages regularly. On a self-rated language proficiency scale from 1 to 10 (10 being native-like proficiency), bilinguals reported high ratings for both English ($M = 7.8$, $s.d. = 1.0$) and the non-English languages ($M = 7.1$, $s.d. = 1.1$). These ratings were marginally higher for English than for the non-English languages, $t(9) = 2.14$, $p < .07$.

2.2. Materials

To ensure that the two groups of participants were comparable in basic cognitive functioning, standardized behavioral tests of vocabulary, nonverbal reasoning skills, and spatial memory span were administered to all participants in a separate session prior to scanning.

2.2.1. Cattell culture fair intelligence test (Cattell, 1957)

This test measures an individual's nonverbal reasoning skills and includes four subtests. Participants were asked to choose one (or two, in the second test) answer(s) from a number of alternatives to complete a series of pictures. Raw scores were transformed to standardized scores on a normal distribution with a reported mean of 100 and a reported standard deviation of 15.

2.2.2. Peabody picture vocabulary test III (Dunn & Dunn, 1997)

PPVT-III was used to measure receptive vocabulary level. The reported median Cronbach's alpha of PPVT-III is .95 (Dunn & Dunn, 1997). A series of words were spoken by the experimenter, each accompanied by a page of four black-and-white line drawings. Participants were asked to choose the picture that best described the word, either by saying the number of the picture or pointing to the picture. Items were grouped in sets of 12 and arranged in increasing level of difficulty. Base and ceiling sets were established for each participant established by the number of errors made in a set. A base set was established when one or no error was made; a ceiling set was established when eight or more errors were made, at which point testing was terminated. The raw score was obtained by subtracting the number of errors from the number of the last item in the ceiling set and converted to standardized scores using an age-corrected norm table. Standardized scores were used in analyses.

2.2.3. Spatial span subtest from the Wechsler memory scale-III (WMS-III, Wechsler, 1997)

Ten blue blocks were secured to a white platform in a random pattern. The numbered sides of the blocks faced the experimenter during the administration of the task. Participants were asked to repeat a sequence tapped by the experimenter both in the same order (forward) and reverse order (backward). Both the forward and backward conditions started with two test items and increased one item at a time. There were two trials for each length of test items. Testing terminated when participants responded incorrectly to two trials at the same length. Raw scores were the number of correct trials in the forward and backward conditions. The maximum possible raw scores for forward and backward conditions were 14 and 16, respectively. Raw scores were transformed to standardized scores controlling for age according to tabled norms.

2.2.4. The Flanker task

Participants were instructed to respond to the direction of a red¹ target chevron that was surrounded by various other symbols. Samples of the different flanker trials are presented in Fig. 1. In

¹ For interpretation of color in Figs. 1–4, the reader is referred to the web version of this article.

baseline trials, the target chevron was presented alone in the middle of the screen. In neutral trials, the flanking stimuli were black diamonds providing no interfering information to the target chevron but had the same number of items as the other (non-baseline) trials in the array. The baseline and neutral trials served as the non-experimental trials because there is either no flanker (baseline) or the existence of flankers does not provide any facilitation or interference to making a response (neutral). In congruent trials, the target chevron was flanked by four black chevrons pointing in the same direction as the target. In incongruent trials, the four flanking chevrons pointed in the direction opposite to that indicated by the target, creating conflict. Finally, in the no-go trials, the target was flanked by four black X's and participants were told to refrain from responding. A total of 40 baseline trials (2 chevron directions \times 20 trials) and 480 experimental trials (4 conditions \times 2 chevron directions \times 3 chevron positions in the series \times 20 trials) were presented during the scanning session.

Each trial started with a fixation screen (which varied from 700 ms to 2700 ms in 500 ms steps), then a stimulus was presented for 1000 ms, followed by a 300 ms blank screen. Finally, a buffer blank screen that lasted less than 100 ms was included to adjust for the screen refresh rate. The average duration of each trial was 3000 ms but individual trial durations varied from 2000 ms to 4000 ms. The experiment was programmed in Presentation[®] software (Version 12.1, www.neurobs.com). By using the flanker task, which makes minimal demands on language processing, but differentiates between types of cognitive control, we hoped to identify brain networks responsible for the enhanced cognitive control observed in bilinguals when carrying out demanding cognitive tasks, without any influence from differences that might be due to the processing of verbal information.

2.3. Procedure

During the scanning session, there were three 10.4-min runs of five blocks. In the first run, a block of 40 fixation trials was presented, followed by four experimental blocks of 40 trials each. The five types of trial were intermixed in each block and were presented randomly. There was a 6-s break between each block. At the end of the first run, a 2-min break was given during which the participants remained in the scanner. The second run involved five blocks of 40 experimental trials and the third run had four blocks of 40 experimental trials with another block of 40 fixation trials at the end. After the fMRI scanning, there was an anatomical scan lasting 6 min and 30 s.

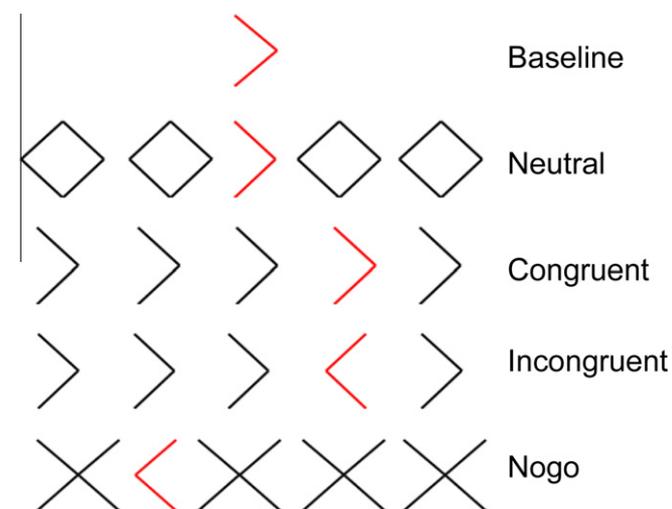


Fig. 1. Sample stimuli in the Flanker task.

2.4. Functional MRI data acquisition and analysis

Both the functional and anatomical scans were conducted using a Siemens Trio 3-T scanner with a 12-channel head coil. We collected T1-weighted anatomical images which were 3D magnetization prepared rapid gradient echo (MPRAGE) oblique axial images (192 slices, 1 mm thick, FOV = 256 mm). Thirty-eight oblique axial slices with a thickness of four mm were obtained for each functional image using a T2*-weighted pulse sequence with echo planar imaging (TR = 3000 ms, TE = 30 ms, FOV = 200 mm, 64 \times 64 matrix). The oblique axial plane was chosen to avoid orbits and sinuses.

Functional and anatomical images were reconstructed and pre-processed using Analysis of Functional Neuro-Images (AFNI; Cox & Hyde, 1997). The images were corrected for slice timing and co-registered to account for head motion; volumes with motion greater than 1.5 mm were excluded in subsequent analyses. The functional and anatomical images were then spatially normalized to standard Montreal Neurological Institute (MNI) space following the 152-subject template and smoothed with an 8 mm full-width-at-half-maximum Gaussian filter to reduce signal noise. Final voxel size was 4 mm isotropic.

The fMRI data were analyzed with PLS (McIntosh et al., 1996, 2004) to identify neural networks recruited to solve the flanker task in monolinguals and bilinguals. PLS is a multivariate technique similar to principal components analysis that identifies signal changes in areas that covary according to experimental conditions. An advantage of employing PLS is its assumption that brain areas covary together as networks rather than functioning as independent and isolated modules. In addition, as a multivariate approach, PLS is more sensitive than univariate analysis (Lukic, Wernick, & Strother, 2002; Nichols & Holmes, 2002), and because it is a data-driven approach, it allows for unbiased identification of coherent brain networks at the whole-brain level. The technique also allows all conditions to be entered together in the analysis so they can be contrasted simultaneously; PLS therefore avoids the problem of multicollinearity and the need for radical post hoc correction of *p*-values due to multiple comparisons (McIntosh et al., 2004). Using singular value decomposition applied to the covariance matrix of task and functional activation, PLS extracts ranked 'components', or latent variables (LVs) that express how well brain activity covaries with each condition. As this was an event-related design, patterns of brain activity were calculated for five repetition times (TRs), thereby providing information on the time course of activity associated with the experimental conditions (over 15 s post-stimulus onset). Since assumptions about condition contrasts are not usually specified in advance, PLS results are largely data-driven and the LVs are output in the descending order of covariance in the data that are accounted for by each. Within each TR, individual voxels have weighted values or 'salience' according to how they covary with the task. By multiplying voxel salience by BOLD signal and summing these values across all brain voxels, one can extract a 'brain score' which conveys the degree to which a person expresses the pattern of the LV. Significance of LVs was calculated with a permutation test (McIntosh et al., 1996). With 500 permutations, the lowest possible *p* value for an LV was *p* < .002. To provide reliability measures of the contribution of each voxel to the LV, we used a bootstrap that resampled the data one hundred times to estimate the standard error of each voxel's salience (Efron & Tibshirani, 1986). Using the ratio of each salience to its standard error (bootstrap ratio), clusters of interest were extracted using a ratio threshold of ± 3 , *p* < .0027, and specifying a minimum size of 10 voxels. The MNI coordinates for the maximum of each cluster were then imported to SPM5 which provided anatomical labels via the anatomy toolbox (Eickhoff et al., 2005). The bootstrap also estimated the 95% confidence intervals for the

mean brain scores in each condition, collapsed across the five time points. The confidence intervals provide estimates of whether activity in each condition for each group is reliably different from the overall mean activity across groups and conditions, as well as a conservative test of differences between conditions both within and between groups. That is, non-overlapping confidence intervals between two conditions within a group or between groups can be used to assess task and group effects, respectively.

Two types of analysis are included in the present report: task PLS and behavioral PLS. In task PLS analysis, LVs are identified that represent sets of brain regions with covarying activation across the different experimental conditions and groups. Task analyses were initially conducted to examine group differences in patterns of activity across the experimental conditions. Bilingual and monolingual participants were entered as separate groups and conditions of interest were specified in the same analysis. After determining that task conditions were significantly different from baseline and neutral conditions, the latter two conditions were dropped from further task PLS analyses. Subsequent analyses focused on the congruent, incongruent, and no-go trials. Results from task PLS represent pattern of activity in brain regions identified in each LV corresponding to experimental conditions included in the analysis. The overall patterns of activity are represented in brain scores and are presented separately for the two groups. Two sets of brain regions, associated with positive (coded as red and yellow) and negative (coded as blue and green) brain scores and showed correlating activity, are identified in each LV for each analysis. Therefore, task PLS results reveal the overall activity pattern in two sets of distinct brain regions that best represents monolinguals and bilinguals across experimental conditions.

Behavioral PLS analysis complements task PLS analysis to examine individual differences in brain-behavior associations by correlating behavioral measures, such as response time, with brain activity. In behavioral PLS, LVs are extracted that represent sets of brain regions in which activity covaries with the behavioral measure across participants. Subsequently, correlations between the resulting brain scores and behavioral measures were plotted in a scatterplot to determine the correlation coefficients. The significance of correlation coefficients was again determined by examining the 95% confidence intervals from bootstrapping. Similar to task PLS results, two sets of brain regions were identified in behavioral PLS, each associated with positive (coded as red and yellow) and negative (coded as blue and green) brain scores. For the present behavioral analyses, the measure of interest was difference RTs for each participant in incongruent and congruent trials relative to neutral trials, resulting in two behavioral variables for each participant.

3. Results

3.1. Behavioral results

Mean performance on the neuropsychological tests and mean response times to the flanker task by language group are shown in Table 1. Bilinguals obtained lower scores than monolinguals in PPVT-III, $F(1, 16) = 5.2$, $MSE = 105.8$, $p < .04$, but the two groups did not differ in the Cattell Culture Fair Test, $F < 1$, or the spatial span subtest, $F(1, 16) = 1.4$, $MSE = 13.9$, *ns.*, suggesting comparable basic cognitive performance between groups. The observation of lower PPVT scores in the bilingual sample replicated previous findings in children (Bialystok, Luk, Peets, & Yang, 2010) and adults (Portocarrero, Burright, & Donovick, 2007). Since the flanker tasks demanded minimal language processing, the group difference in PPVT-III was not expected to interact with subsequent fMRI data. Accuracy in the flanker task was high for all types of trials (greater

Table 1

Mean scores on neuropsychological measures and mean response time to flanker task for monolinguals and bilinguals.

	Monolinguals		Bilinguals	
	M	SD	M	SD
<i>Neuropsychological measures</i>				
PPVT-III standard score	105.8	7.6	94.8	12.4
Cattell Test standard score	121.6	13.7	117.0	12.1
Spatial span subtest standard scores	10.1	2.1	8.1	3.7
<i>Response times in flanker task</i>				
Baseline	552.4	24.5	551.3	43.6
Neutral	587.4	42.4	584.5	46.8
Congruent	560.8	41.5	546.9	46.6
Incongruent	636.0	46.8	616.1	40.8

than 0.96) so, due to the lack of variability, no further analysis was conducted on the accuracy rates. There were no significant group differences in response times for all trials, $F < 1$, or trials by group interaction, $F < 1$, but a strong trial effect, $F(3, 48) = 57.0$, $p < .0001$ indicating faster response time in baseline and congruent trials, which were not different from each other, $F < 1$, followed by neutral, $F(1, 16) = 21.7$, $p < .0004$, and incongruent trials, $F(1, 16) = 69.0$, $p < .0001$.

3.2. Task PLS analysis on fMRI data

In the first task analysis, an LV accounting for 22.1% of the variance, $p = .012$, showed a pattern contrasting baseline and the two inhibition trials, namely the incongruent and no-go trials, in both bilinguals and monolinguals (Fig. 2). Table 2 presents the brain regions identified in this LV. The regions showing more activity for both groups in the baseline trials included right medial frontal gyrus, left rolandic operculum and bilateral postcentral gyrus. During the incongruent and no-go trials, both monolinguals and bilinguals activated the right inferior frontal area, left SMA, left inferior parietal lobule, bilateral cerebellum, bilateral middle and posterior cingulate cortex and bilateral middle temporal gyrus.

This first analysis showed that both groups responded similarly to baseline trials in contrast to the conflict trials, namely the incongruent and no-go trials. The groups did not differ in their response to congruent trials. In the second analysis, the baseline and neutral trials were excluded to examine whether the two groups showed different levels of activation across the congruent, incongruent and no-go trials. Although both incongruent and no-go trials involved inhibition, we hypothesized that, because the incongruent trials involve interference suppression, there would be a difference between language groups but because the no-go trials require response inhibition, the language groups would respond similarly.

The analysis involving congruent, incongruent and no-go trials revealed one LV accounting for 35.5% of the variance, $p = .004$. As shown in Fig. 3a, monolinguals and bilinguals showed contrasting patterns of activation for the congruent and incongruent trials, but had similar activity in the no-go trials. Table 3 lists the brain regions identified by this LV. Monolinguals showed more activity in the left temporal pole and superior parietal cortex during the incongruent trials (regions with positive salience on this LV), relative to the congruent trials. In contrast, bilinguals engaged a widespread set of regions, including subcortical areas, fusiform gyri, inferior frontal gyri, SMA and inferior parietal regions, more during the incongruent trials (regions with negative salience on this LV), relative to the congruent trials. Moreover, both groups used this set of regions during the no-go trials. These brain regions are shown in Fig. 3b.

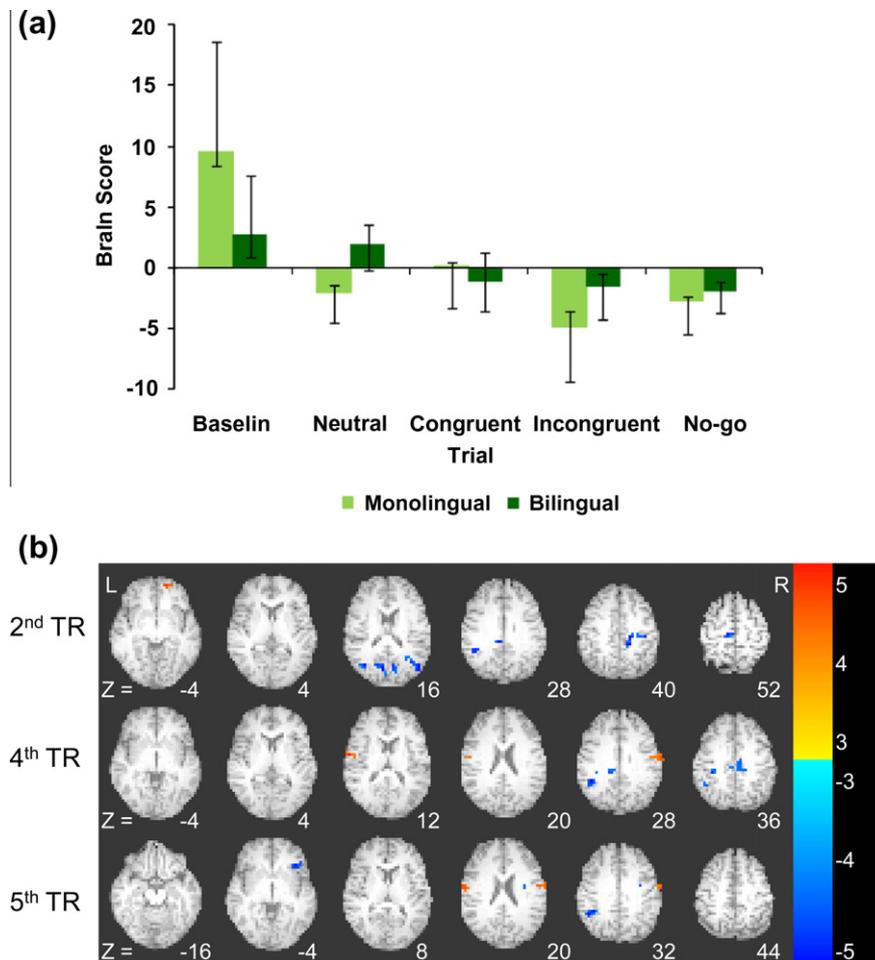


Fig. 2. (a) Task brain scores for all conditions in the Flanker task for monolinguals and bilinguals (first task analysis). 95% Confidence intervals are plotted around the mean. (b) Axial slices showing brain regions associated with positive and negative brain scores. Bootstrap ratios from the second, fourth and fifth TRs representative of the activated regions were superimposed onto an anatomical brain image averaging across all participants' T1 images. A bootstrap ratio threshold of 3.0 and cluster size of 10 were used to filter the colored areas in the brain images. Positive bootstrap ratios are associated with the orange areas (and increased activity during baseline) and negative bootstrap ratios are associated with the blue areas (and increased activity during incongruent and no-go trials).

Table 2

Brain areas with differential activity for baseline vs. incongruent and no-go trials.

Region	BA	MNI coordinates			TR	Ratio
		X	Y	Z		
<i>Increased activity in baseline for monolinguals and bilinguals</i>						
Left postcentral gyrus	1	-64	-4	20	5th	4.0
Left Rolandic operculum	44	-60	-4	12	4th	4.9
Right superior medial gyrus	8	12	40	48	4th	4.2
Right medial frontal gyrus	10	12	56	-4	2nd	5.2
Right postcentral gyrus	1	64	-4	28	5th	5.7
<i>Increased activity in incongruent and no-go trials for monolinguals and bilinguals</i>						
Left inferior parietal lobule	40	-40	-44	32	5th	-5.0
Left middle temporal gyrus	39	-36	-64	12	2nd	-7.3
Left SMA	6	-12	-24	56	2nd	-7.2
Left calcarine gyrus	18	-8	-76	16	2nd	-6.7
Left posterior cingulate cortex	23	-8	-32	28	2nd	-5.1
Right cerebellum	-	12	-28	-28	4th	-4.1
Right middle cingulate cortex	31	8	-16	36	4th	-3.9
Right inferior frontal gyrus	47	36	28	-4	5th	-5.2
Right postcentral gyrus	4	40	-24	40	2nd	-4.9
Right middle temporal gyrus	39	48	-72	16	2nd	-7.3

3.3. Behavioral PLS analysis on fMRI data

In the task PLS, bilinguals and monolinguals engaged a widespread group of brain areas to a comparable extent in no-go trials,

but showed different activation patterns when solving incongruent trials. The bilinguals used this same set of areas for incongruent trials, whereas the monolinguals used different areas. Although this analysis showed that different areas were engaged during the

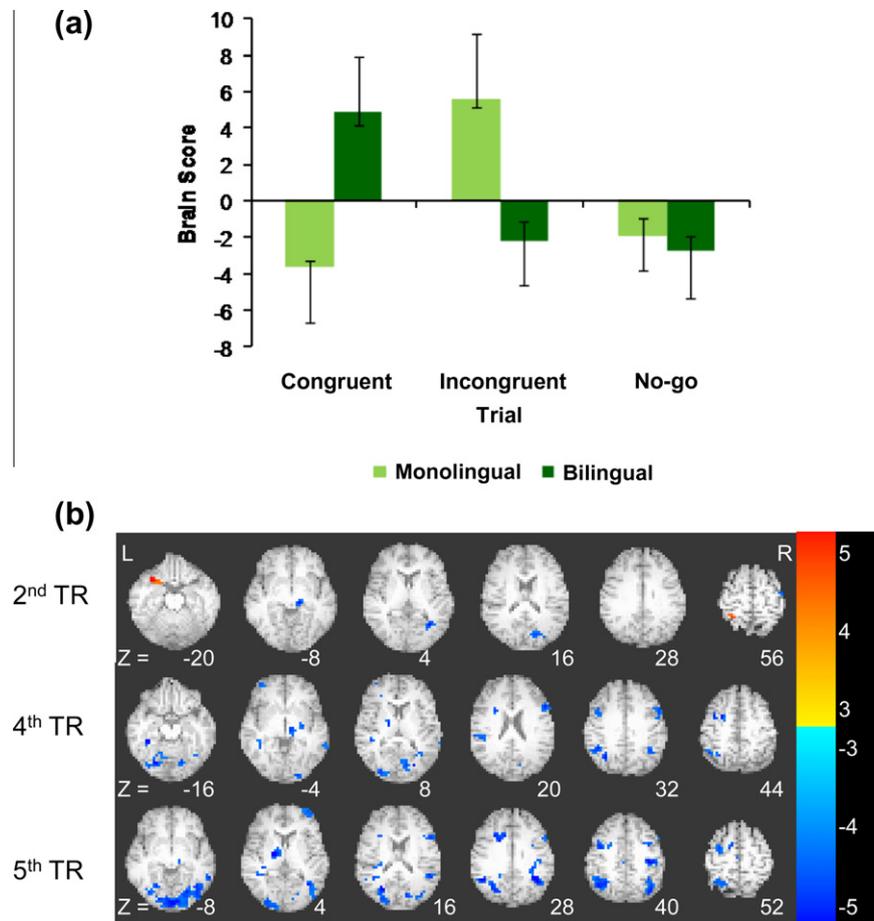


Fig. 3. (a) Task brain scores for congruent, incongruent and no-go conditions in the Flanker task for monolinguals and bilinguals (second task analysis). 95% Confidence intervals are plotted around the mean. (b) Axial slices showing the brain regions identified in this LV. Bootstrap ratios from the second, fourth and fifth TRs representative of the activated regions were superimposed onto an anatomical brain image averaging across all participants' T1 images. A bootstrap ratio threshold of 3.0 and cluster size of 10 were used to filter the colored areas in the brain images. Positive bootstrap ratios (shown in red) indicate regions with more activity during incongruent trials in monolinguals and congruent trials in bilinguals. Negative bootstrap ratios (shown in blue) indicate regions with increased activity during incongruent and no-go trials in bilinguals and no-go trials in monolinguals.

Table 3
Brain areas with activity differentiating congruent, incongruent and no-go trials for monolinguals and bilinguals.

Region	BA	MNI coordinates			TR	Ratio
		X	Y	Z		
<i>Regions associated with positive bootstrap ratios</i>						
Left temporal pole	38	-32	12	-20	2nd	5.6
Left superior parietal lobule	2	-32	-48	56	2nd	4.1
<i>Regions associated with negative bootstrap ratios</i>						
Left inferior frontal gyrus p. Triangularis	44/45	-36	32	16	4th	-4.1
Left angular gyrus	39	-32	-64	32	4th	-4.9
Left superior/middle frontal gyrus	6	-28	4	44	4th	-4.8
Left fusiform gyrus	18	-24	-72	-16	4th	-5.0
Left caudate nucleus	-	-20	12	28	5th	-5.8
Left superior/middle temporal gyrus	27	-16	-36	0	5th	-5.8
Left thalamus	-	-16	-12	4	5th	-7.2
Left SMA	6	-4	-16	48	5th	-4.2
Right lingual gyrus	28	8	-28	-8	4th	-5.1
Right cerebellum	-	12	-24	-12	2nd	-4.8
Right superior occipital gyrus	17	24	-76	12	4th	-5.3
Right fusiform gyrus	37	36	-44	-20	5th	-6.9
Right angular gyrus	39	36	-52	28	5th	-6.0
Right middle frontal gyrus	10	36	60	4	5th	-3.9
Right inferior frontal gyrus p. Triangularis	44/45	52	20	20	4th	-4.7

incongruent trials, it does not provide information on the brain activity that underlies specific aspects of behavior on this task. For this purpose we used behavioral PLS, which examined the

relationship between individual differences in brain activity and behavioral measures from the flanker task in the congruent and incongruent conditions. For behavioral measures, we used the

differences in response time (DRTs) for congruent and incongruent trials relative to neutral trials. DRTs were chosen over raw response times because neutral trials provide information on basic motor response and visual search performance. Differences between congruent and incongruent trials relative to neutral trials thus control for visual search and the basic motor response. For congruent trials, a larger negative DRT (further away from zero) relative to neutral trials (i.e., congruent–neutral) indicates more efficient facilitation; for incongruent trials (i.e., incongruent–neutral), a smaller positive DRT (closer to zero) relative to neutral trials indicates better suppression of interference. Although the difference between monolinguals and bilinguals for both the congruent–neutral DRT (Bilinguals: $M = -37.6$ s, $SD = 10.5$; Monolinguals: $M = -26.6$ s, $SD = 13.9$) and incongruent–neutral DRT (Bilinguals: $M = 32.9$ s, $SD = 22.8$; Monolinguals: $M = 48.7$ s, $SD = 20.2$) did not reach statistical significance, $t(16) > 1.5$, $p < .15$, the DRTs were in the expected direction of smaller DRTs in bilinguals.

The pattern of brain activity related to the DRTs accounted for 30.1% of the overall variance, but was only significant at a more liberal level, $p = 0.11$. Nevertheless, all the correlations between

behavior and brain scores were reliable (we carried out an additional 200 bootstrap steps to confirm this). The scatterplot presented in Fig. 4a indicates that negative correlations between brain activity and DRTs in congruent trials were observed for monolinguals, $r(7) = -.88$; 95% (confidence intervals: $-.85, -.97$) and bilinguals, $r(7) = -.75$; 95% (confidence intervals: $-.60, -.96$). That is, better performance for both groups in congruent trials (more negative values) was associated with more activity in bilateral middle occipital gyrus, left fusiform gyrus, left lingual gyrus, bilateral cerebellum, right caudate and inferior frontal gyrus (brain regions listed in the top panel of Table 4 and shown in warm colors in Fig. 4b). However, the two groups diverged in the brain-behavior relationship with DRTs for incongruent trials. In monolinguals the same brain areas associated with better performance in congruent trials were also associated with better performance in incongruent trials, $r(7) = -.59$ (95% confidence intervals: $-.50, -.93$). However, in bilinguals, better performance during incongruent trials was associated with more activity in the bilateral cerebellum, bilateral superior temporal gyri, left supramarginal gyri, bilateral postcentral gyri and bilateral precuneus, $r(7) = .57$, (95% confidence

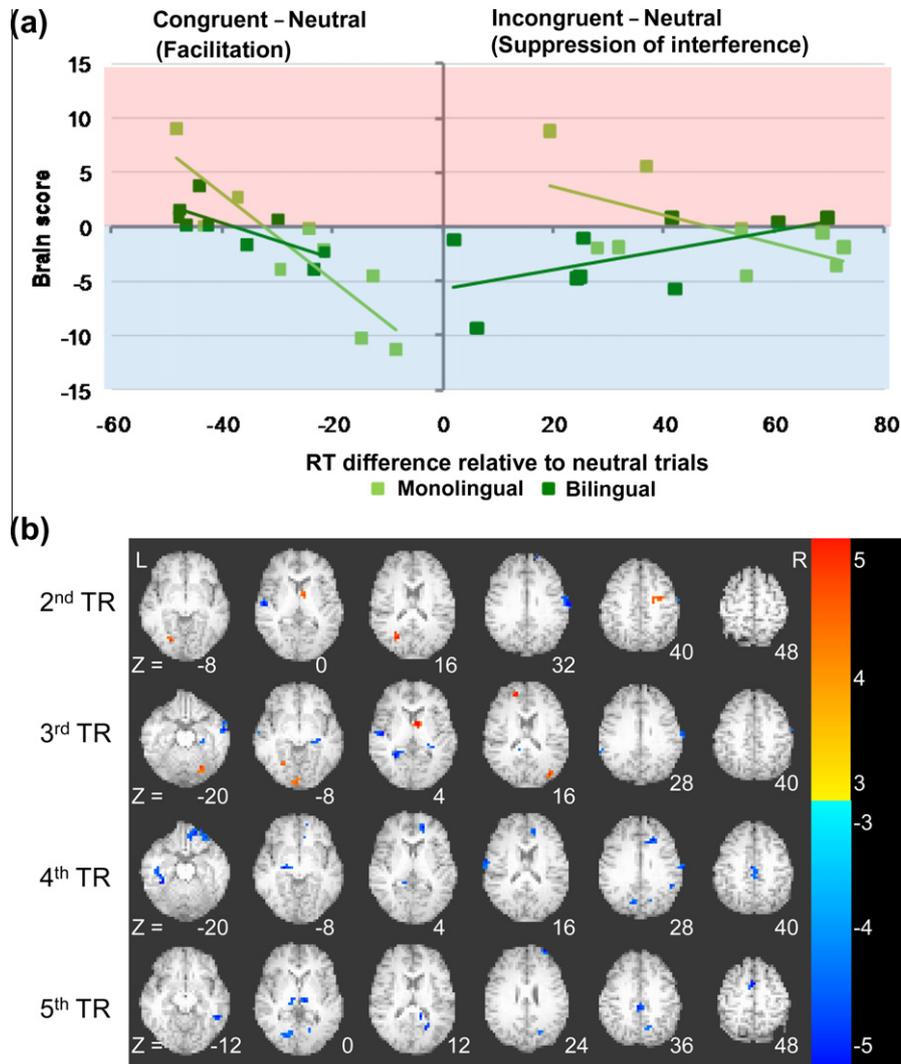


Fig. 4. (a) Scatterplot of brain-behavior correlations for monolinguals and bilinguals between brain scores and DRTs in congruent and incongruent trials relative to neutral trials. All the correlations were significant as determined by the 95% confidence intervals from bootstrapping. Directions of correlations are highlighted with the linear functions in the plot. Positive brain scores lie in the red shaded panel while negative brain scores lie in the blue shaded panel in the scatterplot. These brain scores represent activity level in brain regions that have corresponding colors coded in (b). (b) Axial images of brain regions identified in the behavioral PLS. Bootstrap ratios from the second to fifth TRs representative of the activated regions were superimposed onto an anatomical brain image averaging across all participants' T1 images. A bootstrap ratio threshold of 3.0 and cluster size of 10 were used to filter the colored areas in the brain images.

Table 4

Brain areas with increased activation associated with facilitation and/or suppression of interference identified by the behavioral PLS analysis.

Region	BA	MNI coordinates			TR	Ratio
		X	Y	Z		
<i>Regions associated with positive bootstrap ratios</i>						
Left middle occipital gyrus	17	–28	–64	12	2nd	7.2
Left lingual gyrus	19	–24	–60	–12	3rd	6.7
Left fusiform gyrus	19	–24	–72	–8	2nd	4.5
Left superior frontal gyrus	10	–20	48	16	3rd	6.3
Left cerebellum	18	–4	–84	–16	3rd	3.7
Right caudate nucleus	–	4	4	0	3rd	7.3
Right pallidum	–	8	0	0	2nd	7.6
Right cerebellum	–	24	–68	–20	3rd	4.6
Right inferior frontal gyrus p. Opercularis	6	28	–4	36	2nd	4.8
Right middle occipital gyrus	19	36	–80	16	3rd	4.0
<i>Regions associated with negative bootstrap ratios</i>						
Left postcentral gyrus	4/6	–64	–4	16	4th	–4.5
Left supramarginal gyrus	40	–60	–40	24	3rd	–5.8
Left superior temporal gyrus	21	–56	–12	0	3rd	–6.2
Left cerebellum	–	–40	–52	–36	5th	–5.4
Left fusiform gyrus	20	–40	–40	–20	4th	–5.6
Left precuneus	18/19	–28	–48	4	3rd	–6.4
Left thalamus	–	–12	–20	8	5th	–4.4
Left posterior cingulate cortex	29	–12	–44	8	4th	–4.3
Left middle cingulate cortex	31	–4	–16	40	4th	–4.8
Left SMA	6	0	8	48	5th	–5.3
Pons	–	0	–20	–36	5th	–4.6
Right cerebellum	–	8	–76	–48	4th	–9.7
Right thalamus	–	8	–20	0	5th	–4.7
Right precuneus	7	12	–64	32	5th	–4.4
Right anterior cingulate cortex	32	16	44	8	4th	–7.4
Right superior frontal gyrus	10	20	60	24	2nd	–5.8
Right parahippocampal gyrus	36	28	–16	–28	5th	–5.1
Right middle frontal gyrus	10	28	60	24	5th	–5.0
right inferior frontal gyrus p. orbitalis	47	32	32	–20	4th	–4.0
Right medial temporal pole	38	36	8	–32	2nd	–5.4
Right inferior temporal gyrus	37	52	–44	–12	5th	–5.6
Right postcentral gyrus	1	64	–16	28	2nd	–6.8

intervals: .34, .95; Brain regions listed in the bottom of Table 4 and shown in blue in Fig. 4b).

4. Discussion

The present study confirms previous work showing that young adults who differ in language experience also show different neural correlates when performing a nonverbal cognitive task (Bialystok et al., 2005). Furthermore, these results indicate different neural correlates for monolinguals and bilinguals in interference suppression but similar networks for response inhibition. Although the monolinguals and bilinguals responded equally rapidly and accurately to the stimuli, they showed different activation patterns in response to different experimental trials in the flanker task. Equivalent performance in the two groups allows meaningful interpretation of the differences in functional neural correlates without the possible confound of behavioral differences. Therefore, our findings extend previous research showing that highly proficient bilinguals increased brain activation relative to monolinguals in the anterior prefrontal regions when the response required inhibition of interference from another language (Rodríguez-Fornells, Rotte, Heinze, Nosselt, & Munte, 2002) by providing evidence that bilingualism influences the brain networks that are utilized for interference suppression, but not response inhibition, during a non-language task. Moreover, the brain areas that we identified for bilinguals during interference suppression correspond to areas suggested by Abutalebi and Green (2008) to be part of the bilingual control network.

The first objective of the present study was to compare the neural correlates of cognitive control recruited by monolinguals and

bilinguals for two aspects of inhibition–interference suppression and response inhibition. This was achieved by the task PLS analysis which indicates patterns for whole-brain activation in relation to different experimental conditions. The results showed that bilinguals and monolinguals recruited a common pattern of activity during both incongruent and no-go trials, relative to baseline. These areas may represent a general cognitive control network that is utilized regardless of language experience for dealing with interference suppression and response inhibition. This network also involved the right inferior frontal regions, which have been implicated in control by other work (Goghari & MacDonald, 2009). In the second analysis, we included only congruent, incongruent and no-go conditions to examine group differences in facilitation, suppression of interference and response inhibition. The hypothesis was that the experience of handling two languages would be similar to suppressing interference because the decision to respond lies in choosing one of the two (or multiple) competing languages based on contextual cues.

As expected, the second task analysis showed that bilinguals and monolinguals differed in the brain regions engaged during the congruent and incongruent trials, but activation in similar brain regions was observed in no-go trials. This analysis identified one network, consisting only of increased activity in left temporal pole and left superior parietal lobule, and another that was widely distributed, and associated with increased activity in bilateral inferior frontal, SMA, temporal and subcortical regions. For bilinguals, the wider network was recruited for both types of inhibition, i.e., the incongruent and no-go trials, whereas for monolinguals, the two types of inhibition were resolved through different networks – the spatially-restricted network for incongruent trials and the larger distributed network for no-go and congruent trials. The

finding that the same brain areas were engaged for these two types of conflict trials in bilinguals might be interpreted as contradicting our hypothesis that bilingualism selectively affects suppression of interference but not response inhibition. However, the critical observation is that monolinguals and bilinguals engaged different brain regions when they performed response selection (congruent and incongruent trials), but not when they performed response inhibition.

In regard to the two types of inhibitory control, the task PLS results confirmed that suppression of interference and response inhibition are separable but related constructs. In the first task PLS results (see Fig. 2), both incongruent and no-go trials were represented by one set of regions in the two groups, suggesting these constructs were resolved by similar areas. In the second analysis a wider set of regions was identified for the bilinguals solving incongruent and no-go trials, which included some regions seen in the first analysis, such as left parietal cortex. Differential engagement of this more extensive set of regions during incongruent trials in the two groups suggests that bilinguals can recruit this control network for interference suppression more effectively than monolinguals, consistent with their tendency to show less interference in terms of RT. Moreover, the same extensive network was recruited by both the monolinguals and bilinguals in no-go trials. The observation that the bilinguals activated an extensive network for both the incongruent and no-go trials suggests that regions in the extensive network were recruited for general control of attention. The findings could be inferred as a consequence of the bilinguals' constant practice of suppressing the interference from the unwanted language in their mind. Brain regions that were identified in the extensive network, such as bilateral middle and inferior frontal cortex and bilateral pre-supplementary motor area, were also consistent with previous research examining cognitive control (Aron, Behrens, Smith, Frank, & Poldrack, 2007; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). The monolinguals also recruited these brain regions when solving the congruent and no-go trials, but not for the incongruent trials which involve interference, suggesting these regions may be relevant to bilinguals when resolving interference.

Another objective of the present study was to identify the neural correlates responsible for individual differences in behavior between monolinguals and bilinguals in nonverbal cognitive tasks. In addition to task PLS, results from the behavioral PLS analysis confirmed a difference in the brain-behavior correlation between monolinguals and bilinguals in relation to facilitation and suppression of interference. Although the overall pattern did not reach statistical significance at a conventional alpha level of 0.05, the correlations between activation in the identified brain regions and DRTs were strong and reliable. The first finding revealed that monolinguals and bilinguals showed activation in similar brain regions that correlated with facilitation, as measured by more negative DRTs relative to neutral trials for congruent trials. The brain regions that showed activity correlating with suppression of interference (measured by DRTs for incongruent trials), however, were different for monolinguals and bilinguals. While the monolinguals activated the same regions to achieve efficient facilitation and suppression of interference, bilinguals recruited different brain regions to reach optimal performance in these two processes. These findings suggest that bilinguals and monolinguals differ in the neural correlates of cognitive control that is responsible for the degree of interference suppression seen on the task. The different brain regions identified in the bilinguals for facilitation and suppression of interference indicates that bilingualism selectively affects the neural networks when encountering conflicting information. Unlike the bilinguals, monolinguals did not respond to facilitation and suppression of interference using different brain networks, leading to fewer neural resources being recruited when performing the flanker task.

The regions showing brain-behavior correlations overlap with the bilingual control network proposed by Abutalebi and Green (2008) in left anterior cingulate cortex, left inferior frontal gyrus and right caudate nucleus. The cingulate and inferior frontal regions showed correlations between activity and DRTs during incongruent trials in the bilinguals, whereas caudate activity was related to facilitation in both groups. Of the other two areas proposed by Abutalebi and Green, bilateral supramarginal gyrus, the left region was identified by the task PLS indicating group differences in congruent and incongruent trials (see Table 3), but not by the behavioral PLS. None of our analyses identified the right supramarginal gyrus, although we did find differential activity in the right angular gyrus, which is located adjacent to the supramarginal gyrus (see Table 3). In addition, we found evidence for a bilingual effect in bilateral inferior frontal gyrus, instead of the left inferior frontal gyrus alone as proposed by Abutalebi and Green. This could be the consequence of the nature of the materials. The bilingual cognitive control model proposed by Abutalebi and Green was derived from studies that examined verbal production in bilinguals, but the flanker task used in this study was based on nonverbal stimuli. The difference in material type may explain activity in both hemispheres instead of the left lateralized pattern previously reported. In addition, the right inferior frontal region showed a similar pattern of activity in response to conditions across the two groups, relative to baseline. Therefore, this region along with the left supramarginal gyrus, may perform common cognitive control functions for both monolinguals and bilinguals. Results from behavioral PLS reflected brain regions showing activity related to individual differences in behavior in the two groups, and identified regions where activity correlated with less interference specifically in the bilinguals. Therefore, these regions may reflect a network that enhances behavioral performance and that is specific to the bilinguals. However, this pattern of activity was not as robust as the patterns identified by the task PLS, so further research with larger sample sizes is needed to verify the relation between brain activity and performance on interference tasks in bilinguals. On the other hand, the task-related patterns of activity that we found showed reliable group differences despite the relatively small sample sizes, indicating that these differences are robust.

In conclusion, the present study showed that bilinguals and monolinguals with highly similar backgrounds except for their language experience revealed different neural correlates in different conditions of the flanker task. These results were observed using multivariate techniques that showed covarying brain activation at the whole-brain level. The two groups recruited different networks for trials that required response selection and suppression of interference, but showed similar activation levels in the same network for response inhibition. These results support the proposition that bilingualism influences cognitive control of inhibition at the attention level, but not motor control of prepotent responses. They also corroborate the view that suppression of interference and response inhibition, normally grouped together as examples of inhibition, are cognitively distinct (e.g., Bialystok et al., 2006). Furthermore, examination of individual differences in behavior and brain activity showed a different set of brain regions involved in suppressing interference in monolinguals and bilinguals. These findings indicate that bilingualism modifies the neural networks responsible for achieving effective general cognitive control of nonverbal stimuli. Bilingualism, despite being a language experience, extends its influence to cognitive processing that has minimal linguistic demands. Moreover, brain regions identified in the present study partially overlap the bilingual control network (Abutalebi & Green, 2008). Future research should incorporate both verbal and nonverbal versions of a single paradigm in larger samples of bilinguals and monolinguals to determine if there is a

common network for processing both verbal and nonverbal stimuli in bilinguals.

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