Neural bases of asymmetric language switching in second-language learners: An ER-fMRI study

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Using the ER-fMRI technique, the present study was designed to investigate the neural substrates of language switching among second-language learners. Twelve Chinese college students who were learning English were scanned when they performed language switching tasks (naming pictures in their first [L1, Chinese] and second [L2, English] languages according to response cues). Compared to non-switching conditions, language switching elicited greater activation in the right superior prefrontal cortex (BA9/10/32), left middle and superior frontal cortex (BA8/9/46), and right middle cingulum and caudate (BA11). When the direction of switching was considered, forward switching (from L1 to L2), but not backward switching (from L2 to L1), activated several brain regions related to executive functions (i.e., bilateral frontal cortices and left ACC) relative to non-switching conditions. These results suggest that neural correlates of language switching differ depending on the direction of the switch and that there does not seem to be a specific brain area acting as a "language switch".
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Introduction

Bilingual speakers often need to switch between two languages during speech production. They evidently need to separate their two languages (Costa and Santesteban, 2004) and select the right lexical candidates from the right language for effective communication (e.g., Costa et al., 1999). In that process, bilingual individuals must have effective neural mechanisms to prevent interference or competition between the two languages, especially considering that first and second languages have overlapping

neuro-anatomical bases as revealed by recent neuroimaging studies (e.g., Illes et al., 1999; Rodriguez-Fornells et al., 2002; Xue et al., 2004a,b).

Two types of neuro-cognitive models have been proposed regarding lexical selection mechanisms. One type of models assumes that only words in a given language are activated (i.e., Costa et al., 1999; Costa and Santesteban, 2004; Roelofs, 1998). Thus, a language switch is required to turn on and off the entire language system.

In contrast, the other type of models assumes that the lexical selection mechanism is not specific to a given language (e.g., Green, 1986, 1998; Hermans et al., 1998; Poulisse and Bongaerts, 1994; also see Costa and Santesteban, 2004). According to these models, words in both languages are activated and the individual has to consider all activated lexical nodes, irrespective of the language to which they belong. Successful selection of the proper lexical node (i.e., in the correct language) is achieved by creating a differential level of activation in the two lexicons.

How does the language production system produce an imbalance of activation between the two lexicons? According to the Inhibitory Control (IC) model (Green, 1986, 1998), differential levels of activation in the two lexicons are achieved by the involvement of an inhibitory control mechanism. Specifically, the IC model assumes that lexical selection in bilingual speakers entails the reactive inhibition of lexical items belonging to the unintended or non-response language (Green, 1986, 1998; also see Costa and Santesteban, 2004 and Price et al., 1999). That is, in order to produce words in one language, bilingual speakers must inhibit the schema for word production in the other language.

A direct consequence of the inhibition of activated words in the non-response language is that inhibition takes time and should yield a switching cost (Price et al., 1999). The amount of inhibition would depend on two factors: the level of activation of the words that need to be suppressed, and the speakers' proficiency level in the non-response language (Green, 1986, 1998; also see Costa and Santesteban, 2004).

Due to the typical differential proficiency levels of L1 and L2, the amount of inhibition required for the two languages is

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asymmetric. When speaking in L1, not much inhibition is required for the less dominant L2 because the baseline level of activation of L2 lexical items is lower than that of L1 lexical items. However, when speaking in the less dominant L2, L1 representations must be strongly inhibited in order to ensure that L2 lexical items are selected (Costa and Santesteban, 2004).

Theoretically, this asymmetric pattern of inhibition should result in an asymmetric switching cost (i.e., a greater cost during the L2-to-L1 switch than during the L1-to-L2 switch). Indeed, Meuter and Allport (1999) reported such a finding. However, several imaging studies have found an opposite asymmetric pattern of language switching costs. Alvarez et al. (2003) study of English/Spanish bilinguals and Proverbio et al. (2004) study of native Italian professional interpreters found a greater effect of language switching on N400 amplitude in the L1-to-L2 than in the L2-to-L1 direction. Similarly, Jackson et al. (2001) studied native English speakers and found a significant frontal N2 effect when switching from L1 to L2, but not when switching from L2 to L1. Therefore, it remains to be seen whether language switching incurs a greater cost during the L1-to-L2 switch or during the L2-to-L1 switch.

Researchers have attempted to understand the neural substrates of language switching using various techniques such as PET, EEG, and fMRI. For example, Price et al. (1999) used PET to investigate the neural system underlying translation and language switching. They asked proficient German–English adult bilinguals to translate between German (L1) and English (L2) and to read visually presented words in L1 and L2. Results showed that switching the input language resulted in activation at Broca's area and supramarginal gyri, areas associated with phonological recoding.

Using a high temporal resolution 12-channel near-infrared continuous-wave spectroscopy (NIRcws) system, Quaresima et al. (2002) investigated the neural substrates of translation and language switching with proficient Dutch–English bilingual students. Their results showed that translation and language switching resulted in a consistent and incremental rise in oxy-hemoglobin accompanied by a smaller decrease in deoxyhemo-globin in the left inferior frontal cortex (including Broca's area).

Jackson et al. (2001) conducted an ERP study to examine the time course of language switching during a visually cued numeral-naming task (naming digits in L1 or L2). They found that switch-related modulation of ERP components was evident over parietal and frontal cortices. Specifically, the N2 component (+320 ms) recorded over the left frontal–central region of the scalp was significantly more negative for switching trials compared to non-switching trials. More important, the frontal N2 effect varied according to the direction of language switching: the effect was significant when switching from L1 to L2 but not significant when switching from L2 to L1. It is worth noting that the frontal N2 component of ERP has been found in prior research to be associated with response suppression in tasks such as the Go/No-Go task (Konishi et al., 1999).

In another study of theirs, Jackson et al. (2004) investigated the ERP correlates of receptive (input) language switching in native English speakers (Jackson et al., 2004). In that study, number words were presented in L1 and L2, and participants were required to judge whether the numbers were odd or even (i.e., parity judgment). Their results showed that receptive language switching was associated with early switch-related activity over central sensors and was not language-specific. They did not find switch-related activity in the frontal and parietal electrodes. Based on

these results, Jackson et al. suggested that there was no language-specific lexical selection mechanism.

As mentioned above, Proverbio et al. (2004) also conducted an ERP study to explore the neural mechanisms for code switching for professional interpreters. ERPs were recorded from native Italian simultaneous interpreters and monolingual controls during a semantic processing task in which the subjects had to evaluate the sensibleness of the final word of incomplete sentences. Sentences could be entirely in Italian or in English (the unmixed condition). Alternatively, the body of the sentences could be in English and the final word in Italian or vice versa (the mixed condition). Results of this study showed that the N400 component of ERPs depended on the direction of language switching (greater effect during the L1-to-L2 switch than during the L2-to-L1 switch).

Hernandez et al. (2000) used fMRI to investigate the brain activation associated with picture naming when using either of Spanish–English bilinguals' two languages and when switching between them. Results of this study revealed that activation of the dorsolateral prefrontal cortex (BA46 and 9) was greater (in terms of both signal intensity and spatial extent) in the mixed language (i.e., switching) condition than in the single-language (i.e., non-switching) conditions. These results suggest that the dorsolateral prefrontal cortex was involved in language switching during picture naming.

Hernandez et al. (2001) further examined within- and between-language switching in Spanish–English bilinguals. In the within-language switching condition, participants were presented with a set of pictures and asked to name (only in English) either the actions or the objects depicted in the pictures or to switch between these two types of responses. In the between-language switching condition, they asked subjects to switch between languages to name the pictures. Their results showed increased intensity of activation in the right dorsolateral prefrontal cortex for between-language switching relative to no switching. This suggests that switching between languages in picture naming involves increased executive function.

Although activation patterns for language switching found in different neuroimaging studies vary, almost all of them showed that the prefrontal cortex, especially dorsolateral prefrontal cortex, was involved in language switching. Combining these findings with the evidence of lateral prefrontal cortex's involvement in other cognitive switching tasks (e.g., Dove et al., 2000; Kimberg et al., 2000; Sohn et al., 2000) and in executive control in general (Collette and Linden, 2002; Funahashi, 2001; Osaka et al., 2004; Smith and Jonides, 1999), it seems that language switching involves inhibitory control function located in the lateral prefrontal cortex.

Although previous brain imaging research has highlighted the importance of the lateral prefrontal cortex in language switching, several questions remain to be addressed regarding the neural bases of language switching. First, all previous researches involved bilingual subjects whose two languages were both alphabetical languages. It is not clear whether a switch between two types of languages (such as between logographic and alphabetic languages) would involve different and/or additional brain regions. Past research has indicated both similarities and differences in the processing of alphabetic and logographic languages (see Bolger et al., 2005 for a recent meta-analysis).

Second, researchers have not adequately examined the neural mechanisms involved in different directions of language switching. Previous fMRI studies used the block design, which prevented

researchers from separating neural substrates for the two directions of language switching. Although some ERP studies (e.g., Jackson et al., 2001, 2004; Proverbio et al., 2004) examined the effects of the direction of language switching, as mentioned above, ERP is not the ideal technique to localize brain areas for different cognitive functions due to its limited spatial resolution.

Using the event-related (ER)-fMRI technique, the present study was designed to investigate the neural substrates of language switching among Chinese speakers who were learning English as their second language. Compared to the traditional block design, the event-related design would allow us to specifically investigate the effect of switching direction.

Based on the neuro-cognitive models regarding lexical selection mechanisms discussed above and previous neuroimaging studies of language switching (especially those with productive switching tasks), we made two predictions about the neural substrates involved in language switching. First, we predicted that language switching would recruit brain areas involved in executive functions. Second, regarding potential substrates that might be involved in the different directions of switching, we further predicted that executive control areas may be more active in forward switching (i.e., L1-to-L2 switching) than in backward switching (L2-to-L1 switching) because the second-language learners in our study were not yet proficient in their L2.

Methods

Subjects

Subjects for this study were 12 right-handed native Chinese speakers (six male, six female). Their mean age was 19.5 years, ranging from 18 to 21 years. All subjects had normal or corrected-to-normal vision. They had not had a history of any medical, neurological or psychiatric illness and were not taking any medications for such diseases. All subjects grew up in China and started to learn English as their second language at a mean age of 12.67 years (SD=0.78). None of the subjects had passed the CET-4 (Level 4 of the college English test), indicating a low-to-middle level of L2 proficiency. Informed consent was obtained from all subjects before the experiment.

Subjects also self-rated their language proficiency on a 5-point scale (1="very nonproficient", 5="very proficient"). On average, the subjects rated themselves as "nonproficient" (mean=2.58) in their English listening ability and as "moderately proficient" in their spoken English (mean=3.00), in reading English (mean=3.30), and in writing in English (mean=3.10). In contrast, their ratings of Chinese abilities were all very high, ranging from 4.50 (writing in Chinese) to 4.75 (reading Chinese). Not surprisingly, *t*-test showed significant differences between L1 and L2 in listening ability [$t(1,11)=10.795$, $p=0.000$], speaking [$t(1,11)=7.416$, $p=0.000$], reading [$t(1,11)=5.613$, $p=0.000$], and writing [$t(1,11)=5.613$, $p=0.000$].

Materials

A total of 60 simple black–white line drawings were used in the present study. All pictures were chosen from those used in a previous study of picture naming (Zhang and Yang, 2003). Chinese names of all pictures are two-character words, and their English equivalents are either monosyllabic or two-syllable words with 3–7 letters.

Experimental procedure

Rapid ER-fMRI design was used in the present study. Subjects participated in two scanning sessions, each lasting 6 min and 24 s. Each run had 120 trials. The sequences were jittered and optimized using the GA algorithm (Wager and Nichols, 2003). Behavioral data were acquired for each subject after the fMRI sessions.

During the experiment, subjects were asked to silently name pictures according to the visual cue "read" (name the picture in English) or "读" (name the picture in Chinese). The visual cue was presented for 200 ms followed by a picture for 2800 ms. In the control task, a small "+" was presented for 200 ms followed by a large "+" for 2800 ms. Subjects were asked to fixate their eyes on the cross silently and no response was required. Before the experiment, subjects first learned Chinese and English names of all pictures and did practice tasks similar to experimental tasks.

Experimental trials were assigned to the following conditions: Chinese (L1) non-switching, English (L2) non-switching, forward switching (from L1 to L2), backward switching (from L2 to L1), and control trials.

Data acquisition

Functional MRI scans were performed with a 1.5 T Siemens whole-body MRI scanner at the MRI Center of the Beijing XuanWu Hospital. Stimuli, programmed with an IBM-compatible computer, were projected onto a translucent screen. Subjects viewed the stimuli through a mirror attached to the head coil. A single-shot T2*-weighted gradient-echo, EPI sequence was used for functional imaging scan with the following parameters: TR/TE/Flip=3000 ms/50 ms/90°, FOV=230 mm×210 mm, matrix=64×64, and slice thickness=6 mm. Twenty contiguous axial slices, 136 images were acquired to cover the whole brain with 1.8 mm gap for each subject. The high-resolution anatomical images were acquired using a T1-weighted, three-dimensional, gradient-echo pulse-sequence with TR/TE/Flip=1970 ms/3.93 ms/15°, FOV=250×235 mm, matrix=169×256, and slice thickness/gap=1.9 mm/0.95 mm. For each subject, the first five volumes in each scan series were discarded because they were collected before magnetization reached the equilibrium state.

Data analysis

We used SPM2 (Wellcome Department of Cognitive Neurology, London, UK) for image preprocessing and subsequent statistical analysis. The image preprocessing steps included EPI functional image realignment, anatomic–functional image co-registration, and normalization (Friston et al., 1995). All functional images were smoothed with a cubic Gaussian filter of 8 mm full width at half maximum. General linear model was used to estimate the condition effect for each individual subject (Friston et al., 1994). Significant changes in hemodynamic response for each subject and condition were assessed using *t*-statistics. The group-averaged effects were computed with a random-effects model. For group analysis, clusters with more than 10 voxels activated above a threshold of $p<0.001$ (uncorrected) were considered as significant.

Individual activation maps were parametrically estimated by the following contrasts: language non-switching minus fixation, language switching minus language non-switching, language non-switching minus language switching, (forward switching minus L2 non-switching) minus (backward switching minus L1

Table 1
Brain regions activated by language switching relative to language non-switching

Brain region	BA	Coordinates[a]			Z	p
		x	y	z		
Left superior frontal gyrus[b]	BA9	−15	43	39	3.94	<0.001
Left middle frontal gyrus[b]	BA46	−18	51	25	4.65	<0.001
Right superior frontal gyrus	BA9	18	45	34	3.40	<0.001
Right middle cingulate		15	−18	48	3.68	<0.001
Right caudate	BA11	15	23	−4	3.30	<0.001

[a] *x*, *y*, and *z* are Talairach coordinates. *Z* refers to the highest *Z* score within a region.
[b] These were regions of interest (ROIs).

non-switching), and (backward switching minus L1 non-switching) minus (forward switching minus L2 non-switching).

Based on previous studies, three brain regions related to executive control (i.e., left dorsolateral prefrontal cortex, medial frontal cortex, and anterior cingulate cortex) were defined as ROIs. Because the supramarginal gyrus has been suggested as an area intimately tied to language switching (see Hernandez et al., 2000), we also included it as an ROI.

Results

Behavioral results

We first analyzed the errors in behavioral data. Subjects made the following types of mistakes when naming the pictures: using the wrong language, using a wrong name, naming emendation, and extreme slow response (3 SD above the mean RT for each subject). In addition, there were recording failures and the recording of nonverbal sounds. Error analysis showed that the amount of errors did not vary by response language nor by the type of trials nor their interaction. Trials with errors were excluded from further analyses.

A response language (L1 vs. L2) × type of trials (language switching vs. non-switching) repeated-measures ANOVA on the correct trials revealed significant main effects of response language [$F(1,11) = 15.954$, MSe = 5498.285, $p = 0.002$] and type of trials [$F(1,11) = 9.470$, MSe = 9142.370, $p = 0.011$]. Response time (RT) was slower for language switching than for non-switching and slower for L2 than for L1. The interaction was also significant [$F(2,10) = 5.390$, MSe = 2775.521, $p = 0.040$], indicating that the magnitude of the switching cost was different for the two languages (L1-to-L2: 21.09 ms; L2-to-L1:64.53 ms).

Imaging results

Language non-switching vs. control condition
Relative to fixation, both Chinese and English picture naming activated left inferior frontal gyrus (BA47/48), middle occipital lobe (BA17), bilateral cerebellum (BA19), right hippocampus (BA20), vermis, and bilateral insula (BA48). In addition, for the L1 but not the L2 non-switching condition, we found additional activation in right superior temporal gyrus (BA48), left precentral and postcentral gyri (BA3/6); and, for the L2 but not for the L1 non-switching condition, we found additional activation in right inferior parietal lobe (BA40), fusiform and lingual gyri (BA18), and bilateral precuneus.

Previous studies showed that these regions would be activated in bilingual production tasks and other bilingual processing tasks involving phonological and semantic retrieval (Bleser et al., 2003; Chee et al., 1999, 2001, 2003; Klein et al., 1995, 1999, 2006; Price et al., 1999; Tan et al., 2005).

Language switching vs. non-switching

Analysis revealed several regions significantly activated by language switching relative to language non-switching (Table 1). As expected, language switching activated broad bilateral frontal cortices and right cingulum cortex. We further analyzed brain regions involved in forward switching and backward switching (see Table 2 and Fig. 1). Results showed that no regions related to executive control showed additional activation for backward switching compared to L1 non-switching. However, several executive function-related regions, including broad bilateral frontal cortices and left ACC, showed increased activation for forward switching relative to L2 non-switching.

Forward vs. backward switching

In order to explore whether the activation patterns were different depending on the direction of language switching, we compared forward switching with backward switching with the following contrasts: (forward switching minus L2 non-switching) minus (backward switching minus L1 non-switching), (backward switching minus L1 non-switching) minus (forward switching minus L2 non-switching). Relative to backward switching, forward switching showed increased activation in the right frontal cortex (BA10/11/46), left medial frontal cortex, ACC (BA32), super parietal cortex, supramarginal gyrus (BA40), angular gyrus (BA39), middle temporal cortex (BA21), right super occipital cortex (BA18), and precentral cortex (BA6) (Table 3 and Fig. 2).

Relative to forward switching, backward switching showed increased activation in left cerebellum (BA19/37), fusiform gyrus (BA37), precentral gyrus (BA6), right inferior occipital lobe (BA19), and lingual gyrus (BA17) (Table 4 and Fig. 2).

Table 2
Brain regions activated when contrasting forward and backward switching with non-switching

Brain region	BA	Coordinates[a]			Z	p
		x	y	z		
(A) Forward switching relative to L2 non-switching						
Left medial frontal gyrus[b]	BA32	0	25	43	3.60	<0.001
Left anterior cingulate[b]	BA32	0	47	14	3.96	<0.001
Left mid-orbital frontal gyrus	BA11	0	40	−12	3.47	<0.001
Left SMA	BA6	−12	−1	47	3.65	<0.001
Left angular	BA39	−42	−59	39	3.30	<0.001
Left middle temporal gyrus	BA21	−65	−26	1	3.32	<0.001
(B) Backward switching relative to L1 non-switching						
Right supramarginal[b]	BA48	65	−16	20	3.26	<0.001
Right parahippocampal	BA37	27	−41	−3	3.48	<0.001
Left cerebellum		−24	−66	−35	3.92	<0.001
Left thalamus		−3	−17	9	3.54	<0.001

[a] *x*, *y*, and *z* are Talairach coordinates. *Z* refers to the highest *Z* score within a region.
[b] These were regions of interest (ROIs).

Forward switching *minus* L2 non-switching   Backward switching *minus* L1 non-switching
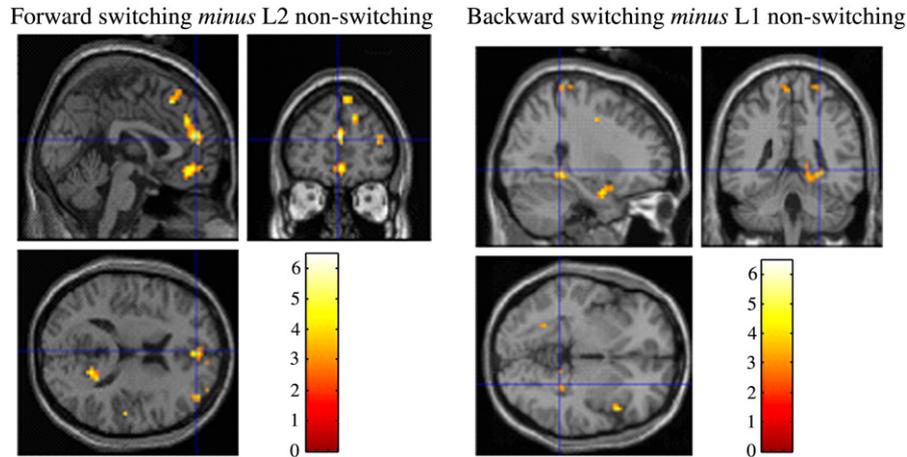

Fig. 1. Activation maps of forward switching (from L1 to L2) relative to L2 non-switching (left panel) and of backward switching (from L2 to L1) relative to L1 non-switching (right panel). Clusters with more than 10 voxels activated above a threshold of $p<0.001$ (uncorrected) were considered as significant.

ROI analysis

For each ROI, we performed 2 (type of trials: language switching vs. non-switching)$\times 2$ (switching direction: forward vs. backward switching) analysis of variance on the numbers of activated voxels. There was a main effect of type of trials in DLPFC: language switching activated more voxels than did language non-switching [$F(1,11)=5.879$, MSe$=9492.188$, $p=0.034$]. ROI analysis for MFC also showed a main effect of switching direction: forward switching activated more voxels than did backward switching [$F(1,11)=5.393$, MSe$=2537.521$, $p=0.040$]. The analysis for the ACC did not yield any significant results either for type of trials or for switching direction. For the supramarginal gyrus, there was a marginally significant main effect of switching direction [$F(1,11)=4.117$, MSe$=12969.187$, $p=0.060$] and a marginally significant interaction between type of trials and switching direction [$F(2,10)=3.63$, MSe$=9213.021$, $p=0.080$].

Discussion

The present study was designed to investigate whether language switching involves the inhibitory control function, and specially whether the involvement of inhibitory control function is different according to the direction of language switching. In the following sections, we will summarize and discuss our findings.

Switching vs. non-switching

Our results showed that language switching mainly elicited greater activation in the bilateral superior frontal gyri, right middle cingulum cortex, and caudate than did language non-switching. It has been well documented that the bilateral frontal cortex is involved in general executive function (Cohen et al., 2000; D'Esposito et al., 1995; DiGirolamo et al., 2001; Gehring and Knight, 2000; MacDonald et al., 2000) and has been found to be active when switching between different tasks (Dove et al., 2000; Kimberg et al., 2000; Sohn et al., 2000). The ACC is activated by many different cognitive tasks, including the selection of appropriate response in tasks of selective attention as well as in the monitoring of responses for errors (Badgaiyan and Posner, 1998; Botvinick et al., 1999, 2001; Veen et al., 2001). Therefore, it

seemed that language switching involved the inhibitory control function, just as Green (1986, 1998) proposed.

Based on these and previous results, we believe that the activations of the frontal regions and cingulate cortex in our language switching tasks were related to the general executive function. More specifically, it is possible that bilateral superior frontal cortex was involved in the control or inhibition of non-targeted language or inappropriate responses, and cingulate cortex, especially bilateral ACC (BA32), was involved in the selection of the appropriate language, monitoring of errors and competition, and conflict detection in language switching. Recently, Crinion et al. (2006) found that the left caudate played a role in monitoring and controlling bilinguals' use of languages. It should be pointed out, however, that the present study showed increased activation of the right caudate in language switching (rather than the left caudate as found by Crinion et al. (2006)). Further studies are needed to explore the specific roles of the right vs. the left caudate in language switching.

Our results differed from those found by Hernandez et al. in their study of language switching. They found increased intensity of activation in the dorsolateral prefrontal cortex (BA46/9) for mixed language blocks compared to single-language blocks (Hernandez et al., 2000, 2001). Several differences between the

Table 3
Brain regions activated by forward switching relative to backward switching

Brain region	BA	Coordinates[a]			Z	p
		x	*y*	*z*		
Left medial frontal gyrus[b]		0	29	46	3.72	<0.001
Left anterior cingulate[b]	BA32	0	39	26	3.02	<0.001
Left supramarginal[b]	BA40	−62	−36	34	3.15	<0.001
Right middle frontal gyrus	BA10	36	59	5	3.47	<0.001
Right middle frontal gyrus	BA46	39	50	9	3.57	<0.001
Right mid-orbital frontal gyrus	BA11	3	43	−12	3.45	<0.001
Left middle temporal gyrus	BA21	−62	−29	1	3.71	<0.001
Right superior occipital gyrus	BA18	18	−89	27	3.36	<0.001
Right precentral gyrus	BA6	39	2	50	3.97	<0.001

[a] *x*, *y*, and *z* are Talairach coordinates. *Z* refers to the highest *Z* score within a region.
[b] These were regions of interest (ROIs).

(Forward– L2) *minus* (backward– L1)   (Backward– L1) *minus* (forward– L2)
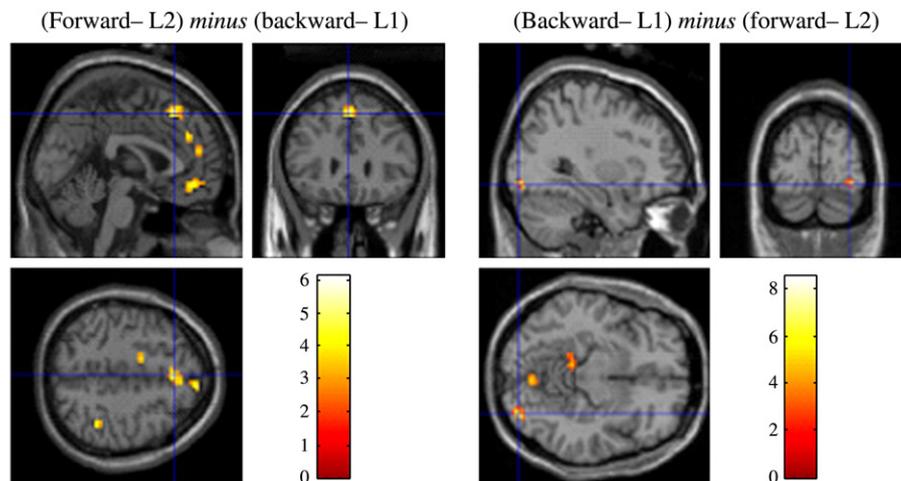

Fig. 2. Activation maps of forward vs. backward switching. Left panel: (forward switching minus L2 non-switching) minus (backward switching minus L1 non-switching); right panel: (backward switching minus L1 non-switching) minus (forward switching minus L2 non-switching).

present and Hernandez et al. studies may account for these differing results. First, Hernandez et al. used a block design in their imaging studies, whereas we used an event-related design. Second, subjects in Hernandez et al. studies were proficient bilinguals, but our subjects were nonproficient second-language learners. Third, Hernandez et al. used alternated language switching paradigm (AABBAA…), but we used a random switching paradigm. Subjects might prepare their responses in advance in an alternated switching paradigm. In contrast, in our study that used the random switching paradigm, subjects could not anticipate their response language.

Forward L1-to-L2 switching

In order to explore whether the involvement of inhibitory control function varies by the direction of language switching, we compared two directions of language switching (forward and backward switching) with two types of language non-switching (L2 and L1 non-switching). In the forward switching condition, we found increased intensity of activation in left middle orbital frontal gyrus, left medial frontal cortex (BA32), and ACC (BA32). The latter two areas showed increased activation for language switching relative to language non-switching as mentioned earlier.

We also compared forward with backward switching. Relative to backward switching, forward switching elicited greater activation not only in several task-related regions but also in executive function-related regions such as right middle frontal gyri (BA11/46) and left anterior cingulate cortex (BA32). Some of these areas (e.g., the right middle frontal gyrus, etc.) appeared, as mentioned above, to play a very important role in the inhibition of non-targeted language or inappropriate responses. This function may be especially important in forward switching because backward switching did not show additional activation in this area (see below). In addition to the right middle frontal gyrus, other areas that may participate in the inhibitory control during forward switching included the left superior medial frontal cortex (BA32) and middle orbital frontal region (BA11) as well as the right middle frontal regions (BA10/46). The SMA might be involved in the inhibition of incorrect responses and representation or selection of the less automatic correct responses (Sylvester et al., 2003), and the SMA

was also found to be activated in task switching that required key-press responses (Dove et al., 2000). Therefore, activation in the SMA may be related to both inhibition of incorrect responses and selection of the less automatic but correct responses in forward switching.

The role of two other regions (the middle temporal regions [BA21] and angular gyrus) that were activated to a greater extent by forward switching as compared to L2 non-switching and backward switching is unclear although they might also be related to inhibitory control. An alternative explanation of this activation pattern is that forward switching may activate more areas specifically relevant to L2. A recent meta-analysis examining phonological processing of written word forms in Chinese and English found that only English elicited activation in left temporo-parietal region (including middle temporal gyrus, supramarginal gyrus, and inferior parietal lobule) and it was significantly greater than that elicited by Chinese. It was suggested that these areas are involved in the mapping between letters (graphemes) and sounds (phonemes) in English (Tan et al., 2005).

Backward L2-to-L1 switching

There was increased activation in right parahippocampus (BA37), left cerebellum, and thalamus for backward switching (L2-to-L1) relative to L1 non-switching. Relative to forward switching, backward switching recruited left cerebellum (BA37), right inferior occipital lobe (BA19), and lingual gyrus (BA17). Notably, the backward switching condition did not show additional

Table 4
Brain regions activated by backward switching relative to forward switching

Brain region	BA	Coordinates [a]			Z	p
		x	y	z		
Left cerebellum	BA37	−24	−48	−23	4.21	<0.001
Right inferior occipital gyrus	BA19	33	−85	−3	4.17	<0.001
Right lingual gyrus	BA17	3	−73	−4	3.46	<0.001

[a] x, y, and z are Talairach coordinates. Z refers to the highest Z score within a region.

activation or increased intensity of activation in brain regions related to inhibitory control (executive control).

Past studies found that divided attention resulted in additional activation in the left lateral cerebellum while switching attention resulted in activation within the right lateral cerebellum. It was hypothesized that the cerebellum is required for complex attentive control (e.g., Barrett et al., 2001). In human studies using PET, the thalamus was activated by tasks requiring selective attention (LaBerge and Buchsbaum, 1990). It is believed to play a role in visual search (Barrett et al., 2001). Therefore, the increased activations in the left cerebellum and thalamus during backward switching as compared to L1 non-switching and forward switching may have been due to attention control. An alternative explanation is that these activations may have been related to the processing of Chinese language. One previous study found that Chinese phonological processing activated bilateral thalamus, cerebellum, occipital lobe, and lingual gyrus (Kuo et al., 2004). Other studies also found that the right visual system (BA17/18/19) was involved in reading Chinese relative to reading English (Liu and Perfetti, 2003; Tan et al., 2001). These patterns of activations for Chinese processing may have been linked to the logographic nature of Chinese characters (thus the right visual systems) and Chinese phonological processing or orthography–phonology transformation (OPT).

General discussion

Taken together all above comparisons, it was evident that, relative to both L2 non-switching and backward switching, forward switching elicited greater activation in right middle frontal cortex (BA10/46) and left superior frontal cortex. In addition, there was increased intensity of activation in left superior frontal cortex for language switching compared to language non-switching. In other words, language switching involved "executive control" regions, and the involvement of executive control function was asymmetric depending on the direction of language switching. That is, several frontal areas and ACC, which are recognized as "executive" regions, showed increased activation in forward switching, but they did not show increased activation in backward switching. The activation patterns for forward vs. backward switching found in our study are generally consistent with those found by Jackson et al. (2001) in their ERP study. Jackson et al. (2001) found that frontal N2 component (+320 ms) recorded over the left fronto-central region of the scalp was significant when switching from L1 to L2 but not when switching from L2 to L1. Similarly, Alvarez et al. (2003) and Proverbio et al. (2004) also found significant effects of language switching on the N400 amplitude during the L1-to-L2 switch, but not during the L2-to-L1 switch. However, it should be noted that the N400 effect and the activation of executive regions may not necessarily represent the same cognitive functions in language switching. As Alvarez et al. (2003) pointed out, language switching effects found in their study (using a semantic categorization task) should be distinguished from switching costs involving language selection. The latter type of switching cost is more likely to be related to the executive control (Jackson et al., 2001).

Results of the ROI analysis showed that, although main effects failed to reach significance in some ROIs, the basic tendency was that language switching and forward switching activated more voxels than language non-switching and backward switching in all ROIs. Specifically, DLPFC showed more voxels of activation for language switching compared to language non-switching, but showed no significant differences between forward and backward switching. It is possible that language switching, regardless of its direction (forward or backward switching), requires the involvement of DLPFC. In contrast, there were more voxels activated in MFC and supramarginal gyrus for forward switching than for backward switching. It may be that the activation of MFC and supramarginal gyrus depended on the direction of language switching. Namely, forward switching, but not backward switching, may strongly depend on the involvement of MFC and supramarginal gyrus.

Finally, we should comment on an important benefit of using event-related fMRI to study language switching. With this design, we could avoid the shortcomings of the block design used in several previous studies of language switching. Block design confounded language switching with working memory load because working memory in language switching blocks is higher than in single-language blocks (Dove et al., 2000; Rogers and Monsell, 1995). Thus, the activated regions in previous studies may have been due to the higher working memory load in the language switching blocks.

In summary, our present study of native Chinese (L1) speakers learning English (L2) showed that language switching involved both "general" executive regions and task-related regions, but we did not find the specific regions in charge of language switching. Importantly, it seemed that the involvement of "general" executive regions was asymmetric depending on the direction of language switching—several "general" executive regions exhibited additional activation in forward switching as compared to backward switching.

Acknowledgments

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