

Sustained and transient language control in the bilingual brain

Yapeng Wang^{a,b}, Patricia K. Kuhl^b, Chunhui Chen^a, Qi Dong^{a,*}

^a State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, PR China

^b Institute for Learning and Brain Sciences, University of Washington, Seattle 98195, USA

ARTICLE INFO

Article history:

Received 28 June 2008

Revised 9 December 2008

Accepted 17 December 2008

Available online 8 January 2009

Keywords:

Executive control function

Language control

Language switching

Mixed blocked and event-related

fMRI designs

Sustained language control

Transient language control

ABSTRACT

Bilingual speakers must have effective neural mechanisms to control and manage their two languages, but it is unknown whether bilingual language control includes different control components. Using mixed blocked and event-related designs, the present study explored the sustained and transient neural control of two languages during language processing. 15 Chinese–English bilingual speakers were scanned when they performed language switching tasks. The results showed that, compared to the single language condition, sustained bilingual control (mixed language condition) induced activation in the bilateral inferior frontal, middle prefrontal and frontal gyri (BA 45/46). In contrast, relative to the no switch condition, transient bilingual control (language switching condition) activated the left inferior parietal lobule (BA 2/40), superior parietal lobule (BA 7), and middle frontal gyrus (BA 11/46). Importantly, the right superior parietal activity correlated with the magnitude of the mixing cost, and the left inferior and superior parietal activity covaried with the magnitude of the asymmetric switching costs. These results suggest that sustained and transient language control induced differential lateral activation patterns, and that sustained and transient activities in the human brain modulate the behavioral costs during switching-related language control.

© 2008 Published by Elsevier Inc.

Introduction

The bilingual speaker should not simply be considered the sum of two monolingual speakers (Grosjean, 1998, 2001). Compared to monolingual individuals, bilingual speakers may face more difficulties during language production and comprehension, because they must manage competing phonological, syntactic and prosodic systems, as well as distinct mappings of orthography to phonology (Abutalebi and Green, 2007). In this respect, expressing and comprehending a communicative intention may be an inherently competitive process (e.g., Abutalebi and Green, 2007; Gollan and Kroll 2001; Green, 1998).

Several lines of evidence from bilingual tasks and paradigms, especially evidence from language switching and lexical selection show that bilingual speakers experience interference and competition in the course of language production and comprehension (e.g., Abutalebi et al., 2007, 2008; Khateb et al., 2007; Rodriguez-Fornells et al., 2002, 2005; Wang et al., 2007, 2008). However, bilingual speakers can manage interference and competition from the non-target language to produce or comprehend the words in the target language, and they can easily switch between two known languages.

In this sense, bilingual individuals must have effective neural mechanisms to control and regulate the activation of their two language systems (Abutalebi and Green, 2007; Green, 1986, 1998; Wang et al., 2007, 2008), especially since recent neuroimaging studies reveal that first and second languages have overlapping or partly

overlapping neuroanatomical bases (e.g., Chee et al., 1999, 2003; Klein et al., 1994, 1995, 1999; Illes et al., 1999; Rodriguez-Fornells et al., 2002; Xue et al., 2004a,b).

How do bilingual speakers control two language systems? Some researchers propose that bilingual control is achieved by creating a differential level of activation in the two lexicons, achieved either by increasing the level of activation of the target language (Grosjean, 1998, 2001; La Heij, 2005; Pouliisse and Bongaerts, 1994), or by reactively suppressing the lexical nodes in the non-target language (Green, 1986, 1998).

Studies of bilingual aphasia tend to support these hypotheses. It has been observed that pathological fixation to one language (Aglioti and Fabbro, 1993) or uncontrolled switching between languages may occur after damage to the left prefrontal cortex (Fabbro et al., 2000; Khateb et al., 2007) or to the left inferior parietal cortex (Abutalebi and Green, 2007; Leischner, 1948). In addition, it has been reported that lesion to the left caudate leads to both pathological fixation on a language (Aglioti et al., 1996; Aglioti and Fabbro, 1993) and pathological switching among languages (Abutalebi and Green, 2007; Abutalebi et al., 2000). Furthermore, intraoperative electrocortical stimulation of the left inferior frontal gyrus induced involuntary language switching in bilingual patients (Kho et al., 2007). These observations suggest that bilingual language control relies on a distributed network.

Importantly, functional imaging studies show results similar to bilingual aphasia studies, suggesting that both cortical and sub-cortical areas are involved in bilingual control. For example, in a previous study we employed language switching tasks to explore the

* Corresponding author. Fax: +86 10 58807615.
E-mail address: dongqi@bnu.edu.cn (Q. Dong).

neural correlates of language control. It was observed that language control involved the left prefrontal cortex and other executive regions, and the involvement of executive regions was asymmetric depending on the direction of language switching (Wang et al., 2007). Crinion et al. (2006) reported that the left caudate, a sub-cortical region, plays a universal role in monitoring and controlling language use in bilingual individuals. This pattern of results has been widely reported (e.g., Abutalebi et al., 2007, 2008; Bialystok et al., 2005; Chee et al., 2003; Hernandez et al., 2000, 2001; Jackson et al., 2001; Price et al., 1999; Proverbio et al., 2004; Quaresima et al., 2002; Rodriguez-Fornells et al., 2002, 2005; Wang et al., 2007, 2008; for a recent review, see Abutalebi and Green, 2007).

Taken together, the bilingual aphasia and functional imaging studies indicate that the critical cortical and sub-cortical regions for language control include the bilateral prefrontal and middle frontal cortices, left inferior and superior parietal cortices, ACC, caudate, and supramarginal gyrus. However, it is known that most of these areas are also involved in task switching (e.g., Dove et al., 2000; Kimberg et al., 2000; Sohn et al., 2000) and in general executive control (Collette and Linden, 2002; D'Esposito et al., 1995; Funahashi, 2001; Osaka et al., 2004; Smith and Jonides, 1999). So, it seems that both language control and general executive control share an overlapping, or partially overlapping neural network. Some researchers suggest that language control is achieved through a neural network related to general cognitive processes and language processing (Khateb et al., 2007; Abutalebi et al., 2008). The roles of these regions in the executive control function are well documented. However, the specific roles of the different regions in language control remain unclear.

More importantly, a recent ERP study suggests that bilingual language control might include sustained and transient components (Christoffels et al., 2007). But it is still unknown whether these components involve different neural bases or networks. So, it is essential to determine whether language control involves differential components, and whether different components of language control induce the differential activation patterns. Using the mixed blocked and event-related designs, the present study was designed to explore whether language control involves different components, and whether different components induce differential activation patterns.

Based on previous studies of language control and cognitive control, we predicted that (1) language control might involve both sustained and transient components; and (2) these two components of language control would induce differential lateral activation maps. More specifically, we predicted that sustained language control might induce activation in the bilateral frontal and prefrontal areas, whereas transient language control might induce a left lateralized dominance of activity in the frontal-parietal regions.

Methods

Subjects

Subjects in this study were 15 right-handed native Chinese speakers (8 females). Their mean age was 20.5 years, ranging from 19 to 23 years. All of them grew up in China and began learning English as their second language at a mean age of 12.06 years ($SD = 1.33$). The total time they spent learning English as a second language ranged from 7 to 11 years (mean = 8.40). All subjects had normal or corrected to-normal vision, no history of medical, neurological or psychiatric illness, and were not taking medications for such diseases. Informed consent set by the institutional review board of Beijing Normal University (BNU) imaging center for brain research was obtained from all subjects before the experiments began.

Subjects self-rated their language proficiency on a 5-point scale (1 = "very non-proficient," 5 = "very proficient"). On average, the subjects rated themselves as "non-proficient" (mean = 2.87) in their English listening ability and in their spoken English (mean = 2.93), as

"moderately proficient" in reading English (mean = 3.33), and in writing English (mean = 3.20). In contrast, their ratings of Chinese abilities were all very high, ranging from 4.13 (Listening to Chinese) to 4.53 (reading Chinese). Not surprisingly, *t*-tests showed significant differences between L1 and L2 in listening ability [$t(1,14) = 5.10$, $p = 0.000$], speaking [$t(1,14) = 7.64$, $p = 0.000$], reading [$t(1,14) = 6.00$, $p = 0.000$], and writing [$t(1,14) = 5.87$, $p = 0.000$]. Subjects also reported their exposure (including TV, CD, books, newspapers, daily communication, etc.) to the two languages. They were exposed to L1 for 9.2 h ($SD = 2.40$) and to L2 for 2.8 ($SD = 0.60$) hours each day. It has been reported that the subjective global measures of self-reported proficiency with language history used in the present study provides an effective measure of bilingual ability (Marian et al., 2007).

Procedures

Mixed blocked and event-related designs were employed in the present study. Subjects participated in two scanning sessions, each lasting 8 min. Each run had 160 trials. In mixed blocks, the sequences were jittered and optimized using the GA algorithm (Wager and Nichols, 2003).

During the experiment, subjects were asked to silently name single digits ranging from 1 to 9 exclusively in Chinese (L1) or English (L2) in single blocks, or they were asked to silently name digits in L1 or L2 according to the visual cue "读" (name the digits in Chinese) or "read" (name digits in English) in mixed blocks. The visual cue was presented for 400 ms followed by one single digit for 2600 ms in each trial. In the control task, a small "+" was presented for 400 ms followed by a large "+" for 2600 ms. Subjects were asked to fixate their eyes on the cross silently and no response was required. Behavioral data were acquired for each subject after the fMRI sessions. During behavioral testing, subjects were asked to perform the same tasks, but single digits were named aloud in L1 or L2.

Data acquisition

Functional MRI scans were performed with a 3 T Siemens MAGNETOM Trio at the MRI Center of the Beijing Normal University. Stimuli, programmed with an IBM-compatible laptop, were projected onto a translucent screen via a projector. Subjects viewed the stimuli through a mirror attached to the head coil. A single-shot T2*-weighted gradient-echo, EPI sequence was used for the functional imaging scan with the following parameters: TR = 3000 ms, TE = 30 ms, Flip = 90°, FOV = 200 mm, matrix = 64 × 64, and slice thickness = 4 mm. 33 contiguous axial slices, 164 images were acquired to cover the whole brain for each subject. The high-resolution anatomical images were acquired using a T1-weighted, three-dimensional, gradient-echo pulse-sequence with TR = 2530 ms, TE = 3.39 ms, Flip = 7°, FOV = 256 mm, matrix = 256 × 256, and slice thickness = 1.33 mm. For each subject, the first four 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) running on Matlab 6.5 (Math works, Natick, MA) for image preprocessing and subsequent statistical analysis. The image preprocessing steps included slice timing, realignment and normalization. All functional images were smoothed with a cubic Gaussian filter of 8 mm full width at half maximum. A general linear model was used to estimate the condition effect for each individual subject (Friston et al., 1994). At the first level, significant changes in hemodynamic response for each subject and condition were assessed using *t*-statistics. At the second level, the group-averaged effects were computed with a random-effects model. For group analysis, clusters

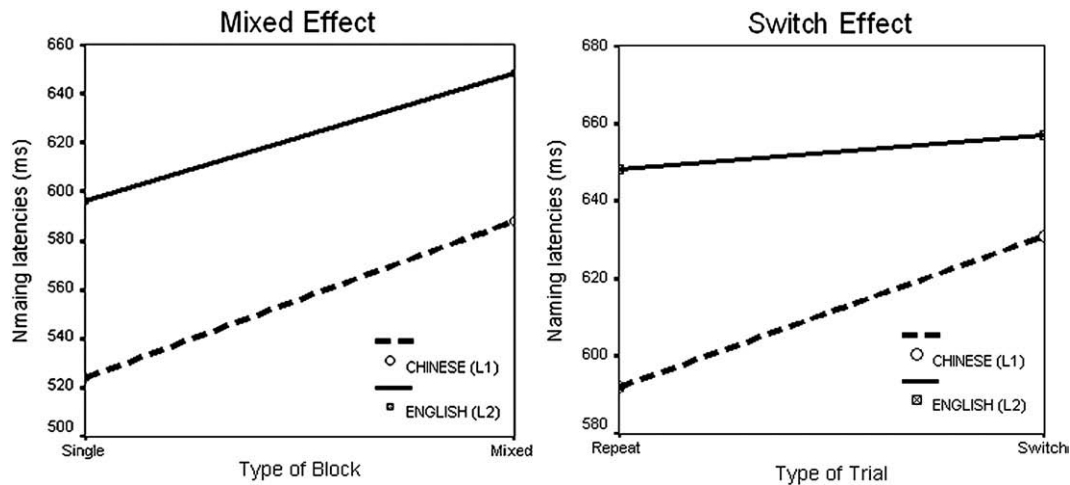


Fig. 1. Mixed effect compares single language blocks with mixed language blocks (left panel). Switching effect compares language repeat trials with language switch trials (right panel).

with more than 10 voxels activated above a threshold of $p < 0.005$ (uncorrected) were considered as significant.

In order to identify the sustained and transient activation patterns in language control, we analyzed sustained and transient activation patterns, respectively. The sustained activation maps were parametrically estimated by the following contrasts: mixed language (ML) versus single Chinese (SC), mixed language versus single English (SE) and mixed language versus single language (SL) (single Chinese and single English); and the transient activation maps were parametrically estimated by the following contrasts: language switching versus Chinese non-switching (CNS), language switching versus English non-switching (ENS) and language switching versus language non-switching (LNS) (Chinese non-switching and English non-switching).

Results

Behavioral results

We first analyzed errors in the behavioral data. Subjects made the following errors when naming the digits: using the wrong language, naming emendation, and extremely slow or fast response (3 SD above or below the mean RT for each subject). In addition, there were recording failures and the recording of nonverbal sounds. No significant effects were observed in error analysis. Trials with errors were excluded from further analyses.

In the analysis of naming latencies, a response language (L1 vs. L2) \times block type (single vs. mixed) repeated-measures ANOVA revealed significant main effects of response language [$F(1, 14) = 70.63$, $p = 0.000$] and block type [$F(1, 14) = 48.67$, $p = 0.000$]. As expected, the reaction times were longer in the mixed language block than in the single language block condition (60 ms). That is to say, subjects showed significant 'mixing costs.' A response language (L1 vs. L2) \times trial type (language switching vs. non-switching) repeated-measures ANOVA on the correct trials revealed significant main effects for response language [$F(1, 14) = 21.05$, $p = 0.000$] and trial type [$F(1, 14) = 17.20$, $p = 0.001$]. The response time was slower for language switching than for non-switching and slower for L2 than for L1. The interaction was also significant [$F(2, 13) = 7.64$, $p = 0.015$], indicating that the magnitude of the switching cost was different depending on the direction of the language switch (L1 to L2: 8 ms; L2 to L1: 43 ms) (Fig. 1). In other words, subjects showed asymmetric switching costs (the magnitude of switching costs is larger when switching from non-dominant L2 to dominant L1 than from dominant L1 to non-dominant L2) during language switching.

Imaging results

Sustained activation in language control

In order to identify regions involved in sustained language control, we analyzed the block-based, state-related contrasts by comparing the mixed language condition with the single Chinese, single English and single language conditions, respectively. These comparisons revealed a pattern of bilateral activation in the broad prefrontal areas for sustained language control (Table 1 and Fig. 2). The mixed language conditions revealed increased activation in the left middle frontal gyrus (BA 46) and right precuneus (BA 7), relative to the single Chinese condition. The mixed language conditions induced increased activation in the bilateral middle frontal gyri (BA 46), cerebellum (BA 18), left inferior frontal gyrus (BA 45) and SMA (BA 6), relative to the single English condition. Compared to the single language conditions, mixed language conditions showed increased activation in the bilateral middle frontal gyri (BA 46), left inferior frontal gyrus, SMA, and right cerebellum (BA 18).

Transient activation in language control

We also examined trial-based, item-related contrasts by comparing language switching with Chinese non-switching, English non-switching and language non-switching trials to identify regions

Table 1

Brain regions activated when contrasting mixed language with single language.

Brain region	BA	Coordinates ^a			Z-value	P
		x	y	z		
<i>Mixed condition relative to single Chinese</i>						
Left middle frontal gyrus	46	-39	42	26	3.49	0.000
Precuneus	7	12	-67	56	3.44	0.000
<i>Mixed condition relative to single English</i>						
Right middle frontal gyrus	46	36	51	25	4.03	0.000
Left inferior frontal gyrus	45	-56	29	7	3.60	0.000
Left middle frontal gyrus	46	-27	48	28	3.18	0.001
Right cerebellum	18	18	-79	-16	3.44	0.000
Left cerebellum	18	-21	-88	-21	3.32	0.000
SMA	6	-6	18	63	3.09	0.001
<i>Mixed condition relative to single language</i>						
Right middle frontal gyrus	46	42	48	28	4.01	0.000
Left middle frontal gyrus	46	-39	39	23	3.15	0.001
Left inferior frontal gyrus		-56	23	2	3.10	0.001
Right cerebellum	18	18	-79	-16	4.45	0.000
SMA		0	9	60	3.05	0.001

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

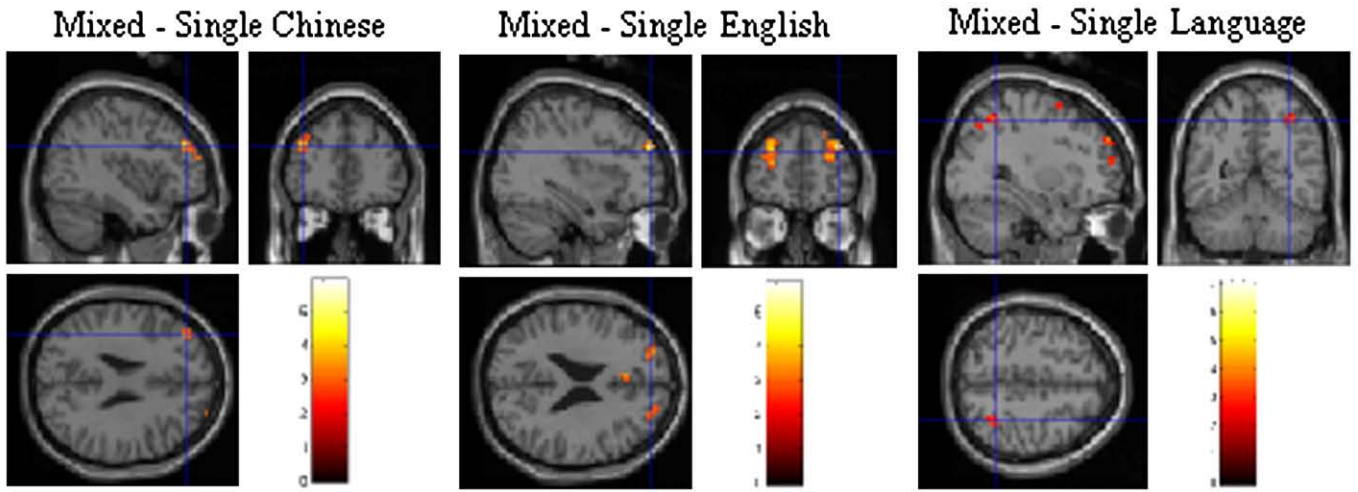


Fig. 2. Activation maps of sustained language control using the standard subtraction technique. (Left panel) Mixed language condition relative to single Chinese. Middle panel: Mixed condition relative to single English. (Right panel) Mixed condition relative to single language. Clusters with more than 10 voxels activated above a threshold of $p < 0.005$ (uncorrected) were considered significant.

involved in transient language control. In general, these contrasts revealed a left lateralized dominance of activity in frontal-parietal regions. Specifically, language switching compared to Chinese non-switching activated the left inferior and superior parietal cortices (BA 2/7), precentral gyrus (BA 6), and cerebellum (BA 37). Language switching compared to English non-switching induced increased activation in the left inferior parietal lobule (BA 2/40), middle frontal gyrus (BA 46), SMA (BA 6), and precentral gyrus (BA 50). Comparison between language switching and language non-switching revealed activation in the left middle frontal gyrus (BA 11) and cerebellum (BA 37) (Table 2 and Fig. 3).

Brain-behavior relationships

To further identify the roles of activated regions in language control, we performed correlation analyses between activated regions and behavioral results. Based on previous studies of language control, we defined the left ACC, caudate, supramarginal gyrus, bilateral inferior frontal and parietal, middle frontal, and superior frontal and parietal cortices as ROIs.

First, we correlated the number of activated voxels in identified ROIs with (1) the magnitude of mixing cost, and (2) the magnitude of asymmetric costs. In addition, we grouped subjects based on the mean magnitude of mixing costs and mean magnitude of asymmetric switching costs: the high mixing cost group (HMCG) in which the magnitude of the mixing cost was larger than the mean of the mixing cost across all subjects, ($n = 6$); the low mixing cost group (LMCG) in which the magnitude of the mixing cost was less than the mean of the mixing cost across all subjects, ($n = 9$); the high asymmetric cost group (HACG) in which the magnitude of the asymmetric switching cost was larger than the mean of the asymmetric switching cost across all subjects, ($n = 9$); and the low asymmetric cost group (LACG) in which the magnitude of the asymmetric switching cost was less than the mean of the asymmetric switching cost across all subjects, ($n = 6$). We compared activity differences in identified ROIs for the HMCG and LMCG, and HACG and LACG groups, respectively.

There was a negative correlation between the mixing cost behavioral measure (sustained control) and the number of activated voxels in the right superior parietal cortex ($r = -0.53$, $p = 0.04$). Importantly, direct comparison showed that the LMCG activated significantly more voxels in the right superior parietal cortex than the HMCG in the mixed language condition. Specifically, relative to both single Chinese ($F = 4.36$, $p = 0.06$; LMCG: 56.67 vs. HMCG: 33.33) and single language ($F = 6.20$, $p = 0.03$; LMCG: 54.67 vs. HMCG: 19.67),

the mixed language activated more voxels in the right superior parietal lobule in LMCG (Fig. 4).

There were negative correlations between the asymmetric cost behavioral measure (transient control) and the number of activated voxels in the left inferior ($r = -0.62$, $p = 0.01$) and superior parietal cortices ($r = -0.64$, $p = 0.01$). Of particular interest, direct comparison between high and low asymmetric cost groups revealed that LACG activated more voxels in the left inferior and superior parietal cortices when language switching is compared to language non-switching, but no significant correlation was observed in the language non-switching conditions. Specifically, LACG activated more voxels than HACG in the left inferior parietal cortex when compared language switching with Chinese non-switching ($F = 11.98$, $p = 0.004$; LACG: 109.50 vs. HACG: 32.11) and English non-switching ($F = 18.72$, $p = 0.001$; LACG: 92.50 vs. HACG: 22.11). Additionally, LACG also activated more voxels in the left superior parietal cortex when comparing language switching with English non-switching ($F = 8.39$, $p = 0.01$; LACG: 67.67 vs. HACG: 18.56) and language non-switching ($F = 20.21$, $p = 0.001$; LACG: 8.67 vs. HACG: 1.67) (Fig. 4).

Discussion

The present study was designed to explore the behavioral and brain correlates of bilingual language control in Chinese-English

Table 2

Brain regions activated when contrasting language switching with language non-switching.

Brain region	BA	Coordinates ^a			Z-value	P
		x	y	z		
<i>Language switching relative to Chinese non-switching</i>						
Left inferior parietal lobule	2	-48	-33	46	3.72	0.000
Left superior parietal lobule	7	-24	-56	44	3.65	0.000
Left cerebellum	37	-33	-51	-30	3.85	0.000
Precentral	6	-50	2	44	4.15	0.000
<i>Language switching relative to English non-switching</i>						
Left inferior parietal lobule	40	-48	-36	46	4.00	0.000
Left middle frontal gyrus	46	-36	47	14	3.90	0.000
SMA	6	0	6	63	4.66	0.000
Precuneus		4	-56	44	3.76	0.000
Precentral	6	-50	5	41	3.70	0.000
<i>Language switching relative to language non-switching</i>						
Left middle orbital frontal gyrus	11	-24	43	-15	3.14	0.001
Left cerebellum	37	-36	-51	-30	3.79	0.000

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

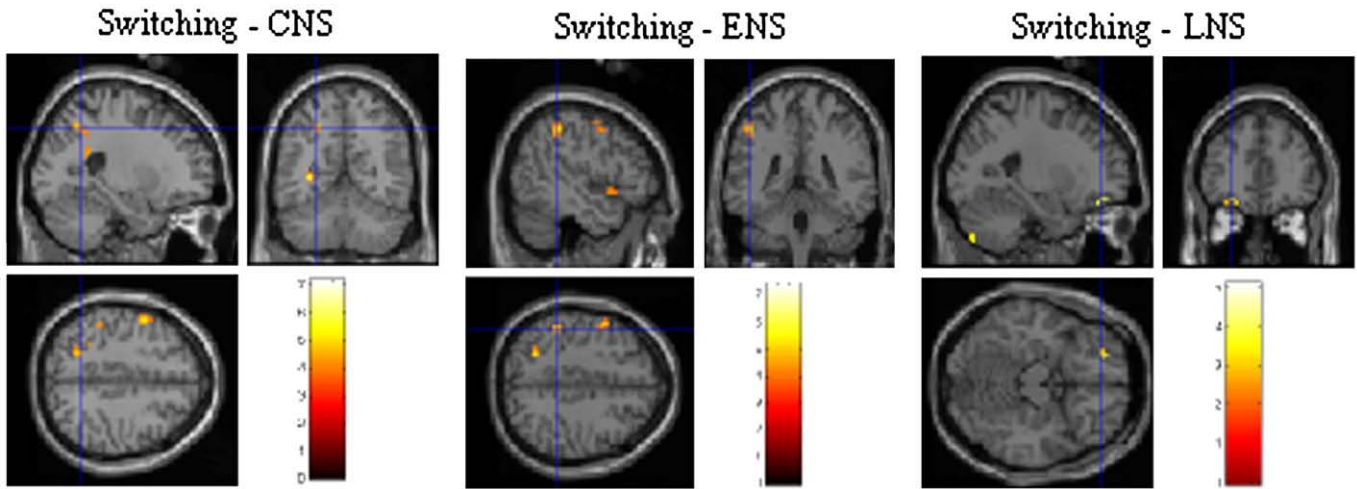


Fig. 3. Activation maps of transient language control using the standard subtraction technique. (Left panel) Switching minus Chinese non-switching (CNS). (Middle panel) Switching minus English non-switching (ENS). (Right panel) Switching minus language non-switching (LNS).

bilingual speakers. Using the mixed blocked and event-related fMRI designs, we identified the state-related, sustained brain activation in bilingual language control by comparing mixed language blocks with single language blocks, and item-related, transient brain activation by comparing the language switching trials with the language non-switching trials when subjects were requested to switch between their first language (L1, Chinese) and second language (L2, English).

Mixing effects and switching effects in bilingual language control

At the behavioral level, performance analysis showed that response latency is longer in the mixed language condition than in the single language condition. In other words, subjects showed a 'mixing cost' during language control. This finding suggests that language context has a profound effect on behavioral performance as demonstrated in previous studies (Abutalebi et al., 2007; Christoffels et al., 2007; Paulmann et al., 2006) and as suggested by the language mode hypothesis. According to this hypothesis, bilinguals find themselves in various language modes that correspond to points on a monolingual–bilingual mode continuum. One end of the continuum represents a monolingual language mode with one language acti-

vated; the other end represents a bilingual language mode with two languages activated at different levels of activation (Grosjean, 1998, 2001). In the single language condition, subjects only need to maintain one language, but in the mixed language condition, they have to activate one language and inhibit (or deactivate) the second language based on the task at hand.

In addition, the present study also showed that response time is longer for language switching than for language non-switching, which suggests that there is a 'switching cost' when re-directing attention between two languages. Interestingly, the present study found that the switching cost is asymmetric based on the direction of language change, a finding consistent with previous studies (Meuter and Allport, 1999; Wang et al., 2007). That is to say, it is more difficult to switch from the weaker language (L2) to the more dominant language (L1) than vice versa. However, some studies failed to find an asymmetric switching cost. Instead, symmetric switching costs were reported for highly proficient bilinguals as well as for unbalanced bilinguals (Costa and Santesteban, 2004; Christoffels et al., 2007). Costa and Santesteban, (2004) argued that the switching abilities of highly proficient bilinguals do not seem to be subject to the same mechanisms as that of L2 learners, but this interpretation could not

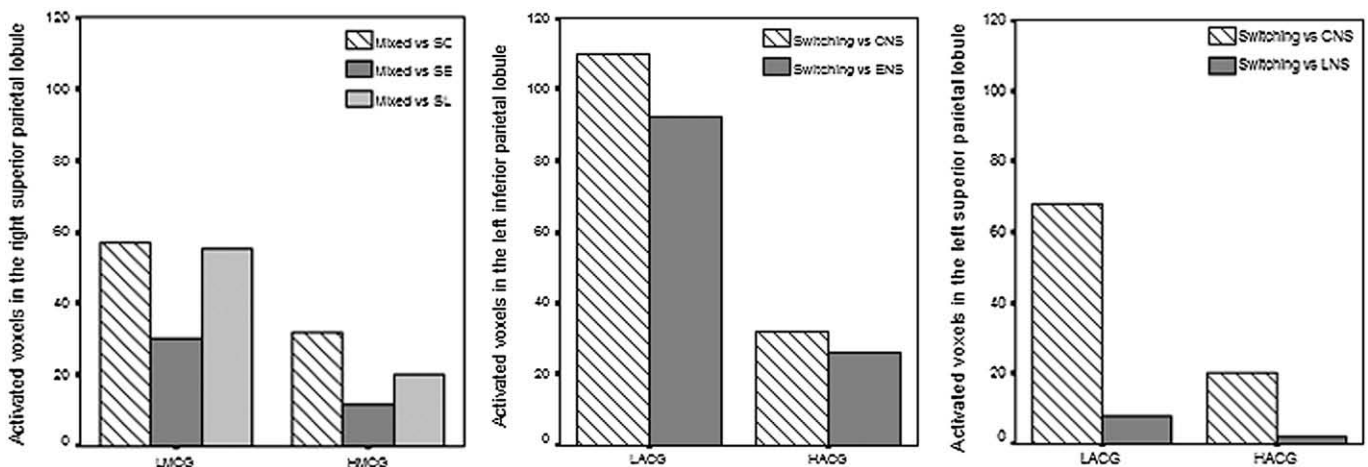


Fig. 4. The relationship between neural activity and behavioral results in ROIs for sustained language control and transient language control. Left panel: Activity differences between LMCG and HMCG in the right superior parietal lobule when compared to the mixed language condition with single Chinese (SC), single English (SE), and single language (SL), respectively; middle panel: activity differences between LACG and HACG in the left inferior parietal lobule when compared to language switching with Chinese non-switching (CNS) and English non-switching (ENS); right panel: activity differences between LACG and HACG in the left superior parietal lobule when compared to language switching with CNS and language non-switching (LNS).

account for results obtained by Christoffels et al. Although subjects in the present study are not proficient in their L2, they must switch between their two languages in their everyday lives. This suggests that daily switching between languages may be an important factor, in addition to language proficiency, that influences language control and switching costs (Christoffels et al., 2007).

Bilateral frontal executive regions and sustained language control

To determine the neural correlates of sustained language control, we compared mixed language with single (blocked) Chinese, single English and single language, respectively. These contrasts showed a pattern of bilateral activation in the prefrontal and frontal gyri (BA 45/46).

Both prefrontal and frontal regions, especially left DLPFC and inferior prefrontal gyrus have been suggested to play a key role in both language control and general executive control (Abutalebi and Green, 2007; Hernandez et al., 2000, 2001; Wang et al., 2007). In previous studies, Hernandez et al. (2000, 2001) observed that the bilateral inferior and middle frontal gyri (BA 45/46) are involved in language switching. Based on their observation, they argued that switching between languages involves increased general executive processing (Hernandez et al., 2000, 2001). However, executive function may include distributed and varied neural networks depending on the specific task. In this sense, different “executive regions” may play differentiated roles in language control.

In a recent bilingual study, Rodriguez-Fornells et al. (2005) compared the activation differences between bilinguals and monolinguals during a go/no-go picture naming task and found that only bilinguals showed activation in the left inferior prefrontal gyrus (BA 45/46). In another study using a lexical access task, they assessed how bilinguals inhibit the non-target language. As reported in the present study, Rodriguez-Fornells et al. (2002) observed greater activation in the left anterior PFC and right middle frontal gyrus. In this sense, it appears that the activation in the left inferior prefrontal gyrus (BA 45/46) might be related to inhibition of the non-target language.

More direct evidence about bilingual control is available from the competitor priming studies. For example, Moss et al. (2005) used a competitor priming task to assess how bilinguals prevent competition from the non-target language. Their results showed increased activation in the left inferior frontal gyrus (pars triangularis) for the competitor condition relative to repetition condition. In another bilingual study which employed a competitor priming task, Zubicaray et al. (2006) found that priming semantic competitors of target picture names significantly increased activation in the left ACC and pars orbitalis of the inferior frontal gyrus. Based on this observation, they argued that lexical selection during competitor priming was biased on top-down mechanisms to reverse associations between primed distractor words and target pictures to select words that meet the current goal of speech.

Investigations of different “executive regions” in executive control have reported correlations between activity in the left inferior frontal gyrus, extending to the middle frontal gyrus (BA 46) and response selection (Pochon et al., 2001), and resolution of interference in verbal working memory tasks (D’Esposito et al., 1999; Jonides et al., 1998). The right prefrontal cortex (PFC) has been linked to sustained attentional functions (Posner and Petersen, 1990). In addition, the right prefrontal gyrus is frequently associated with response inhibition (Aron et al., 2004). Interestingly, a recent fMRI study showed that the right PFC is involved in sustained cognitive control (Braver et al., 2003).

Taken together, the activation in the left inferior PFC, middle PFC, and frontal gyrus may be related to the top-down, sustained attention arousal, and resolution of interference from another language. The activation in the right middle PFC and frontal gyrus may be related to the response inhibition of incorrect or dominant language/lexical candidates since the mixed language condition has a higher working memory load (Braver et al., 2003; Rogers and Monsell, 1995).

The roles of the left frontal and prefrontal cortices in language control may include, but are not restricted to, those mentioned above since they showed increased activation in both sustained and transient language control. The activation pattern found in the present study is basically consistent with that found in the study of Collette et al. about cognitive control. In their study, they found bilateral activation in the inferior (BA 47) and middle frontal gyri (BA 46) in sustained cognitive control related to updating (Collette et al., 2005). However, in another study designed to identify the neural basis of sustained and transient cognitive control, Braver et al. (2003) observed activation only in the right anterior PFC (BA 9/10/46) during sustained cognitive control.

How do we reconcile activity differences between the study of Braver et al. and ours? One possibility is that they masked the transient activation when they identified the neural network involved in sustained cognitive control, and vice versa (Braver et al., 2003). In this situation, common activation in both sustained control and transient control could be masked out. Another possibility is that, although a “switching paradigm” was employed in both studies, they used a semantic classification task, whereas we employed a language production task. It is possible that, during bilingual language control, a language production task requires increased activation, or involvement of broader executive regions.

Surprisingly, our ROI analysis showed a negative correlation between the magnitude of the mixing cost and the activated voxels in the right superior parietal lobule, a region that failed to show additional or increased activation in direct comparisons. Importantly, the low mixing cost group (LMCG) exhibited significantly more activated voxels in this area than the high mixing cost group (HMCG). The double correlations between this area and the mixing cost suggest that the right superior parietal lobule is another potential area involved in sustained language control.

The specific role of this area in language control is unclear. But, it has been suggested that the right superior parietal cortex might involve executive control functions, as evidenced by response shifting (Loose et al., 2006), and representation or selection of the less automatic correct response (Connolly et al., 2000; D’Esposito et al., 2000).

Why then was no activation observed in this area in direct comparisons? One possibility is that the activity intensity in this area is too low to be detected for the high mixing cost group. Another possibility is that these correlations reveal the difference in activated voxels, but all subjects showed a low intensity of activation in this area.

Left frontal-parietal executive circuit and transient language control

In contrast to sustained language control, the brain regions sensitive to the transient aspect of language control revealed a basically left-lateralized pattern of activation, and activated regions included the left inferior (BA 2/40) and superior parietal cortices (BA 7), middle frontal gyrus (BA 11/46), SMA, cerebellum and precentral gyrus. This activation pattern is very similar to patterns of transient activation found in the study of Braver et al. which examined the neural correlations of sustained and transient cognitive control. Braver et al. (2003) found left lateralized activation in the left inferior and superior parietal cortices, and ventrolateral PFC (BA 45/47).

A number of studies show activation in the left inferior and superior parietal cortices for executive control or task switching, but only a few studies reported activation in these two areas for language control. Increased activation in the superior parietal cortex (BA 7) has been observed during translation relative to repetition of auditorily-presented words (Klein et al., 1995). In addition, Jackson et al. (2001) found that switch-related modulation of ERP components was evident over the parietal and frontal cortices during a visually cued numeral naming task (naming digits in L1 or L2). However, switch-related activation at the parietal and frontal electrodes was not observed when using a receptive (input) language switching task (Jackson et al.,

2004). It appears that bilingual control induces activation in the parietal and frontal cortices, but involvement of these areas depends on the specific task. In a previous study, we used a picture naming task and found that the left superior parietal lobule was involved in forward switching (from L1 to L2) relative to backward switching (from L2 to L1) (Wang et al., 2007).

It has been suggested that the left posterior parietal cortex may bias selection away from the previous task whereas the right parietal cortex might bias selection towards the current task (Abutalebi and Green, 2007). Interestingly, it was found that the left inferior parietal cortex shows increased grey matter density for Italian–English bilinguals compared to matched monolingual English speakers (Mechelli et al., 2004). This observation suggests that the left inferior parietal lobule is an area related to L2 learning or language control. However, the contributions of the left inferior and superior parietal cortices in bilingual language control remain unknown.

Importantly, correlation analysis between identified ROIs and behavioral results showed that the activity in both the left inferior and superior parietal cortices covaried with the magnitude of asymmetric costs. Specifically, the activations in these two areas differentiated subjects with high asymmetric cost from those with low asymmetric cost.

In this sense, the inferior and superior parts of the left parietal lobule play a critical role in transient language control. Taken as a whole, the left inferior and superior parietal cortices may be related to response selection. Additionally, since activation in the left parietal lobule covaried with the magnitude of asymmetric cost, the left parietal cortex may also play an important role in overcoming inhibition or reactivating the suppressed language.

The left middle frontal cortex (BA 46) also showed increased activation in sustained language control. In other words, BA46 shows both sustained and transient activation in bilingual language control. In a given executive task, sustained activity might be related to general cognitive processes as well to more specific executive processes (Collette et al., 2006). Additionally, almost all executive tasks induce activation in the left middle frontal cortex (BA 46) (e.g., Abutalebi et al., 2007, 2008; Collette et al., 2006; Khateb et al., 2007; Rodriguez-Fornells et al., 2002, 2005; Wang et al., 2007, 2008). Thus, this area (BA 46) may function as one of the general executive regions.

In addition to BA46, another left middle frontal region, BA11, showed transient activation but no sustained activation during language control. In our previous study, the left middle frontal region showed additional activation when forward switching was compared with non-switching or backward switching. It is possible that the left middle frontal region (BA 11) participates in inhibitory control (Wang et al., 2007).

With regard to the contributions of the bilateral cerebellum and left SMA in language control, the bilateral cerebellum has typically been associated with motor planning and control (Booth et al., 2007), and left SMA, especially pre-SMA has been involved in word selection (Alario et al., 2006; van Heuven et al., 2008). However, since these areas showed increased activation in both sustained and transient language control, they may be task-related regions, and the activation in these areas may be related to articulation.

General discussion

The aim of the present study was to examine sustained and transient language control and related neural correlates during language switching. As we hypothesized, sustained and transient language control induced differential lateral activation patterns. State-related, sustained language control demonstrated bilateral activation in the frontal executive regions. In contrast, item-related, transient language control recruited the left frontal-parietal executive circuit. These differential activation patterns suggest that the sustained and transient components of language control should be distinguished,

and that these two components of language control involve differentiated regions or neural networks.

The frontal-parietal network is consistently regarded as an executive control network (e.g., D'Esposito et al., 1995, 1999, 2000; Collette and Linden, 2002; Collette et al., 2005, 2006; Schumacher et al., 2007). Frontal executive regions may exert their effect during language control in a top-down way. In contrast, the parietal executive regions may exert their effect in a bottom-up way. Sustained activity may be related to general executive function as well to more specific executive processes during bilingual language control since some “general executive regions” also show transient activation in language control.

The present study provides empirical evidence that language control may be fractionated into different component processes, and these components might be associated with specific cerebral areas or networks. But the role of a specific region or network in language control is not fully understood. It is suggested that language control is a part of a more general executive system (Hernandez et al., 2000, 2001), and that the verbal monitor works in a similar way as a general performance monitor (Ganushchak and Schiller, 2006, 2008a,b). In order to better understand the neural basis of language control, it is necessary to use conjunction analysis, connectivity analysis and other neuroimaging techniques to determine the roles of different regions or neural networks in language control, and the relationship between language control and general executive control.

Furthermore, some researchers suggest that second language learning has a profound and prolonged effect on general executive function because there is a correspondence between the mechanisms used to control language and select lexical items and the control and selection of actions in the face of competing cues (Bialystok et al., 2004, 2005; Abutalebi and Green, 2007). If this is a fact, then there should be traces or signatures in the structure and function in key executive regions after second language learning. In this sense, further studies are needed to explore the effects of L2 learning on the executive region and executive function by comparing bilinguals with monolinguals, or by comparing bilinguals with differentially proficient levels in their L2.

Additionally, although a number of studies report that bilinguals exhibit advantages in variety of control functions (Bialystok et al., 2004, 2005, 2008; Bialystok and Feng, 2008; Carlson and Meltzoff, 2008), others have revealed disadvantages in language production compared to monolingual speakers (Gollan et al., 2002, 2005, 2007). It is necessary to assess whether there is an inherent association between reported advantages and disadvantages.

In addition to regions identified in the present study, activation of some other regions has been observed during language control (for example, left ACC, see, Abutalebi et al., 2007, 2008; Crinion et al., 2006; Wang et al., 2007), caudate (e.g., Abutalebi et al., 2007, 2008; Crinion et al., 2006) and supramarginal gyrus (Hernandez et al., 2000, 2001; Price et al., 1999). However, we failed to find activation in these areas. It has been suggested that the activation in ACC is directly related to the degree of response conflict or error detection in a given cognitive task (Botvinick et al., 2001; Carter et al., 1998). Numeral naming is a more automatic process, and both the Chinese and English names of digits are unambiguous. Thus, unlike active-controlled retrieval, the more automatic retrieval during numeral naming may not require involvement of all executive regions. However, further studies are needed to address whether language control depends on the nature of the specific task.

How then do bilinguals control their two languages? Our observations indicate that bilinguals control their two languages by recruiting executive function, but the involvement of executive regions depends on the “control requirement” (sustained control or transient control). By activating frontal-parietal executive circuits, bilinguals inhibit the activation of the non-target language, thus avoiding potential interference from the non-target language. However, it

should be noted that bilinguals might use different strategies to attain this result by either partially or globally inhibiting the non-target language, as has been shown in some studies. For example, in a recent ERP study designed to address language control, Christoffels et al. (2007) observed increased negativity over the frontal areas in language control, but the “frontal negativity effect” is stronger for L1, not L2. Based on their observations, they suggested that bilinguals control their languages by selective adjustment of availability of the L1 only, rather than by adapting the relative activation of both L1 and L2 (Christoffels et al., 2007).

In sum, our present study of native Chinese (L1) speakers learning English as a second language showed that sustained and transient language control induces differential lateral activation patterns, and that sustained and transient activities in the human brain modulate the behavioral costs during switching-related language control.

Acknowledgments

This work was supported by the National Pandeng Project (95-special-09) to Qi Dong, and a Beijing Normal University Social Sciences Grant for Young Teachers to Yapeng Wang. The first author and PKK also received support from a National Science Foundation Science of Learning Center grant to the UW LIFE Center (SLC-0354453, PI, P. Kuhl). We would like to thank two anonymous reviewers for their valuable comments to the manuscript, Denise Padden for her help in preparing this manuscript, and Hui Wu, Litao Zhu and He Li for their technical assistance.

References

- Abutalebi, J., Green, D.W., 2007. Bilingual language production: the neurocognition of language representation and control. *J. Neuroling.* 20, 242–275.
- Abutalebi, J., Miozzo, A., Cappa, S.F., 2000. Do subcortical structures control language selection in bilinguals? Evidence from pathological language mixing. *Neurocase* 6, 101–106.
- Abutalebi, J., Brambati, S.M., Annoni, J.M., Moro, A., Pegna, A.J., Cappa, S.F., Perani, D., 2007. The neural cost of the auditory perception of language switches: an event-related functional magnetic resonance imaging study in bilinguals. *J. Neurosci.* 27, 13762–13769.
- Abutalebi, J., Annoni, J.M., Zimine, I., Pegna, A.J., Seghier, M.L., Hannelore, L.J., Lazeyras, F., Cappa, S.F., Khateb, A., 2008. Language control and lexical competition in bilinguals: an event-related fMRI study. *Cereb. Cortex* 18 (7), 1496–1505.
- Aglioti, S., Fabbro, F., 1993. Paradoxical selective recovery in a bilingual aphasic following subcortical lesion. *NeuroReport* 4, 1359–1362.
- Aglioti, S., Beltramello, A., Girardi, F., Fabbro, F., 1996. Neurolinguistic and follow-up study of an unusual pattern of recovery from bilingual subcortical aphasia. *Brain* 119, 1551–1564.
- Alario, F.X., Chainay, H., Lehericy, S., Cohen, L., 2006. The role of the supplementary motor area (SMA) in word production. *Brain Res.* 1076, 129–143.
- Aron, A.R., Robbins, T.W., Poldrack, R.A., 2004. Inhibition and the right inferior frontal cortex. *Trends. Cogn. Sci.* 8, 170–177.
- Bialystok, E., Feng, X., in press. Language proficiency and executive control in proactive interference: evidence from monolingual and bilingual children and adults. *Brain Lang.* doi:10.1016/j.bandl.2008.09.001.
- Bialystok, E., Craik, F.I.M., Klein, R., Viswanathan, M., 2004. Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychol. Aging* 19, 290–303.
- Bialystok, E., Craik, F.I.M., Grady, C., Chau, W., Ishii, R., Gunji, A., 2005. Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. *NeuroImage* 24, 40–49.
- Bialystok, E., Craik, F., Luk, G., 2008. Cognitive control and lexical access in younger and older bilinguals. *J. Exp. Psychol. Learn. Mem. Cogn.* 34 (4), 859–873.
- Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. *Psychol. Rev.* 108, 624–652.
- Booth, J.R., Wood, L., Lu, D., Houk, J.C., Bitan, T., 2007. The role of the basal ganglia and cerebellum in language processing. *Brain Res.* 1133, 136–144.
- Braver, T.S., Reynolds, J.R., Donaldson, D.I., 2003. Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron* 39, 713–726.
- Carlson, S.M., Meltzoff, A.N., 2008. Bilingual experience and executive functioning in young children. *Dev. Sci.* 11 (2), 282–298.
- Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D., 1998. Anterior cingulate cortex, error detection, and the on-line monitoring of performance. *Science* 280, 747–749.
- Chee, M.W.L., Tan, E.W.L., Thiel, T., 1999. Mandarin and English single word processing studied with functional magnetic resonance imaging. *J. Neurosci.* 19, 3050–3056.
- Chee, M.W.L., Soon, C.S., Ling Lee, H., 2003. Common and segregated neuronal networks for different languages revealed using functional magnetic resonance adaptation. *J. Cogn. Neurosci.* 15, 85–97.
- Christoffels, I.K., Firk, C., Schiller, N.O., 2007. Bilingual language control: an event-related brain potential study. *Brain Res.* 1147, 192–208.
- Collette, F., Linden, M.V., 2002. Brain imaging of the central executive component of working memory. *Neurosci. Biobehav. Rev.* 26, 105–125.
- Collette, F., Hogge, M., Salmon, E., Van der Linden, M., 2006. Exploration of the neural substrates of executive function by functional neuroimaging. *Neuroscience* 139, 209–221.
- Collette, F., Olivier, L., Van der Linden, M., Laureys, S., Delfiore, G., Luxen, A., Salmon, E., 2005. Involvement of both prefrontal and inferior parietal cortex in dual task performance. *Cogn. Brain Res.* 24, 237–251.
- Connolly, J.D., Goodale, M.A., Dosouza, J.F.X., Menon, R.S., Vilis, T., 2000. A comparison of frontoparietal fMRI activation during anti-saccades and anti-pointing. *J. Neurophysiol.* 84, 1645–1655.
- Costa, A., Santesteban, M., 2004. Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. *J. Mem. Lang.* 50 (4), 491–511.
- Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J.T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K., Usui, K., Green, D.W., Price, C.J., 2006. Language control in the bilingual brain. *Science* 312, 1537–1540.
- D’Esposito, M., Detre, J.A., Alsop, D.C., Shin, R.K., Scott, A., Grossman, M., 1995. The neural basis of the central executive system of working memory. *Nature* 378, 279–281.
- D’Esposito, M., Postle, B.R., Jonides, J., Smith, E.E., 1999. The neural substrate and temporal dynamics of interference effects in working memory as revealed by event-related functional MRI. *PNAS* 96, 7514–7519.
- D’Esposito, M., Postle, B.R., Rypma, B., 2000. Prefrontal cortical contributions to working memory: evidence from event-related fMRI studies. *Exp. Brain Res.* 133, 3–11.
- Dove, A., Pollman, S., Schubert, T., Wiggins, C.J., Von Cramon, D.Y., 2000. Prefrontal cortex activation in task switching: an event-related fMRI study. *Cogn. Brain Res.* 9, 103–109.
- Fabbro, F., Skrap, M., Aglioti, S., 2000. Pathological switching between languages after frontal lesions in a bilingual patient. *J. Neurol. Neurosurg. Psychiatry* 68, 650–652.
- Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.B., Frith, C.D., Frackowiak, R.S.J., 1994. Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain Mapp.* 2, 189–210.
- Funahashi, S., 2001. Neuronal mechanisms of executive control by the prefrontal cortex. *Neurosci. Res.* 39, 147–165.
- Gollan, T., Kroll, J., 2001. Lexical access in bilinguals. In: Rapp, B. (Ed.), *A Handbook of Cognitive Neuropsychology: What Deficits Reveal About the Human Mind*. Psychology Press, New York, pp. 321–345.
- Gollan, T.H., Montoya, R.I., Werner, G.A., 2002. Semantic and letter fluency in Spanish–English bilinguals. *Neuropsychology* 16, 562–576.
- Gollan, T.H., Montoya, R.I., Fennema-Notestine, C., Morris, S.K., 2005. Bilingualism affects picture naming but not picture classification. *Mem. Cognit.* 33, 1220–1234.
- Gollan, T.H., Fennema-Notestine, C., Montoya, R.I., Jernigan, T.L., 2007. The bilingual effect on Boston Naming Test performance. *J. Int. Neuropsychol. Soc.* 13 (2), 197–208.
- Ganushchak, L.Y., Schiller, N.O., 2006. Effects of time pressure on verbal self-monitoring. *Brain Res.* 1125, 104–115.
- Ganushchak, L.Y., Schiller, N.O., 2008a. Brain error-monitoring activity is affected by semantic relatedness: an event-related brain potentials study. *J. Cogn. Neurosci.* 20 (5), 927–940.
- Ganushchak, L.Y., Schiller, N.O., 2008b. Motivation and semantic context affect brain error-monitoring activity: an event-related brain potentials study. *NeuroImage* 39, 395–405.
- Green, D.W., 1986. Control, activation and resource: a framework and a model for the control of speech in bilinguals. *Brain Lang.* 27, 210–223.
- Green, D.W., 1998. Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cognit.* 1, 67–81.
- Grosjean, F., 1998. Studying bilinguals: methodological and conceptual issues. *Biling. Lang. Cognit.* 1, 131–140.
- Grosjean, F., 2001. The bilingual’s language modes. In: Nicol, J. (Ed.), *One Mind, Two Languages: Bilingual Language Processing*. Blackwells, Oxford, pp. 1–22.
- Hernandez, A.E., Martinez, A., Kohnert, K., 2000. In search of the language switch: an fMRI study of picture naming in Spanish–English bilinguals. *Brain Lang.* 73, 421–431.
- Hernandez, A.E., Dapretto, M., Mazziotta, J., Bookheimer, S., 2001. Language switching and language representation in Spanish–English bilinguals: an fMRI study. *NeuroImage* 14, 510–520.
- Illes, J., Francis, W.S., Desmond, J.E., Gabrieli, J.D.E., Glover, G.H., Poldrack, R., Lee, C.J., Wagner, A.D., 1999. Convergent cortical representation of semantic processing in bilinguals. *Brain Lang.* 70, 347–363.
- Jackson, G.M., Swainson, R., Cunnington, R., Jackson, S.R., 2001. ERP correlates of executive control during repeated language switching. *Biling. Lang. Cognit.* 4, 169–178.
- Jackson, G.M., Swainson, R., Mullin, A., Cunnington, R., Jackson, S.R., 2004. ERP correlates of a receptive language-switching task. *Q. J. Exp. Psychol. A* 57 (2), 223–240.
- Jonides, J., Smith, E.E., Marshuetz, C., Koeppe, R.A., Reuter-Lorenz, P.A., 1998. Inhibition in verbal working memory revealed by brain activation. *PNAS* 95, 8410–8413.
- Khateb, A., Abutalebi, J., Michel, C.M., Pegna, A.J., Hannelore, L.J., Annoni, J.M., 2007. Language selection in bilinguals: a spatio-temporal analysis of electric brain activity. *Int. J. Psychophysiol.* 65, 201–213.
- Kho, K.H., Duffau, H., Gagnon, P., Leijten, F.S.S., Ramsey, N.F., van Rijen, P.C., Rutten, G.J.M., 2007. Involuntary language switching in two bilingual patients during the Wada test and intraoperative electrocortical stimulation. *Brain Lang.* 101, 31–37.
- Kimberg, D.Y., Aguirre, G.K., D’Esposito, M., 2000. Modulation of task-related neural activity in task-switching: an fMRI study. *Cogn. Brain Res.* 10, 189–196.
- Klein, D., Zatorre, R., Milner, B., Meyer, E., Evans, A., 1994. Left putamen activation when speaking a second language: evidence from PET. *NeuroReport* 5, 2295–2297.
- Klein, D., Milner, B., Zatorre, R., Meyer, E., Evans, A., 1995. The neural substrates underlying word generation: a bilingual functional-imaging study. *PNAS* 92, 2899–2903.

- Klein, D., Milner, B., Zatorre, R.J., Zhao, V., Nikelski, J., 1999. Cerebral organization in bilinguals: a PET study of Chinese–English verb generation. *NeuroReport* 10, 2841–2846.
- La Heij, W., 2005. Monolingual and bilingual lexical access in speech production: issues and models. In: Kroll, J.F., Degroot, A.M.B. (Eds.), *Handbook of Bilingualism: Psycholinguistic Approaches*. Oxford University Press, Oxford, pp. 289–307.
- Leischner, A., 1948. On the aphasia of multilinguals. In: Paradis, M. (Ed.), *Readings on Aphasia in Bilinguals and Polyglots* (1983). Didier, Montreal, pp. 456–502.
- Loose, R., Kaufmann, C., Tucha, O., Auer, D.P., Lange, K.W., 2006. Neural networks of response shifting: influence of task speed and stimulus material. *Brain Res.* 1090, 146–155.
- Marian, V., Blumenfeld, H.K., Kaushanskaya, M., 2007. The Language Experience and Proficiency Questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50 (4), 940–967.
- Mechelli, A., Crinion, J.T., Noppeney, U., O’Doherty, J., Ashburner, J., Frackowiak, R.S., Price, C.J., 2004. Neurolinguistics: structural plasticity in the bilingual brain. *Nature* 431, 757.
- Meuter, R.F.I., Allport, A., 1999. Bilingual language switching in naming: asymmetrical costs of language selection. *J. Mem. Lang.* 40, 25–40.
- Moss, H.E., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., Tyler, L.K., 2005. Selecting among competing alternatives: selection and retrieval in the left inferior frontal gyrus. *Cereb. Cortex.* 15, 1723–1735.
- Osaka, N., Osaka, M., Kondo, H., Morishita, M., Fukuyama, H., Shibasaki, H., 2004. The neural basis of executive function in working memory: an fMRI study based on individual differences. *NeuroImage* 21, 623–631.
- Paulmann, S., Elston-Güttler, K.E., Gunter, T.C., Kotz, S.A., 2006. Is bilingual lexical access influenced by language context? *NeuroReport* 17 (7), 727–731.
- Pochon, J.B., Levy, R., Poline, J.B., Crozier, S., Lehericy, S., Pillon, B., Deweer, B., Le Bihan, D., Dubois, B., 2001. The role of dorsolateral prefrontal cortex in the preparation of forthcoming actions: an fMRI study. *Cereb. Cortex.* 11, 260–266.
- Posner, M.I., Petersen, S.E., 1990. The attention system of the human brain. *Annu. Rev. Neurosci.* 13, 25–42.
- Poullisse, N., Bongaerts, T., 1994. First language use in second language production. *Appl. Linguist.* 15, 36–57.
- Price, C.J., Green, D.W., Von Studnitz, R., 1999. A functional imaging study of translation and language switching. *Brain* 122, 2221–2235.
- Proverbio, A.M., Leoni, G., Zani, A., 2004. Language switching mechanisms in simultaneous interpreters: an ERP study. *Neuropsychologia* 42, 1636–1656.
- Quaresima, V., Ferrari, M., van der Sluijs, M.C.P., Menssen, J., Colier, W.N.J.M., 2002. Lateral frontal cortex oxygenation changes during translation and language switching revealed by non-invasive near-infrared multi-point measurements. *Brain Res. Bull.* 59, 235–243.
- Rodriguez-Fornells, A., Rotte, M., Heinze, H.J., Noesselt, T., Muente, T.F., 2002. Brain potential and functional MRI evidence for how to handle two languages with one brain. *Nature* 415, 1026–1029.
- Rodriguez-Fornells, A., van der Lugt, A., Rotte, M., Britti, B., Heinze, H.J., Muente, T.F., 2005. Second language interferes with word production in fluent bilinguals: brain potential and functional imaging evidence. *J. Cogn. Neurosci.* 17, 422–433.
- Rogers, R.D., Monsell, S., 1995. Costs of a predictable switch between simple cognitive tasks. *J. Exp. Psychol.* 124, 207–231.
- Schumacher, E.H., Cole, M.W., D’Esposito, M., 2007. Selection and maintenance of stimulus–response rules during preparation and performance of a spatial choice–reaction task. *Brain Res.* 1136, 77–87.
- Smith, E.E., Jonides, J., 1999. Storage and executive processes in the frontal lobes. *Science* 283, 1657–1661.
- Sohn, M.H., Ursu, S., Anderson, J., Stenger, V.A., Carter, C., 2000. The role of prefrontal cortex and posterior parietal cortex in task switching. *PNAS.* 97, 13448–13453.
- van Heuven, W.J.B., Schriefers, Herbert, Dijkstra, T., Hagoort, P., 2008. Language conflict in the bilingual brain. *Cereb. Cortex* 18, 2706–2716.
- Wager, T.D., Nichols, T.E., 2003. Optimization of experimental design in fMRI: a general framework using a genetic algorithm. *NeuroImage* 18, 293–309.
- Wang, Y.P., Xue, G., Cheng, C.S., Xue, F., Dong, Q., 2007. Neural bases of asymmetric language switching in second-language learners: an ER–fMRI study. *NeuroImage* 35, 862–870.
- Wang, Y.P., Kuhl, P.K., Li, H., Dong, Q., 2008. Sustained and transient brain activations in bilingual control. *J. Acoust. Soc. Am.* 123 (5), 3890.
- Xue, G., Dong, Q., Jin, Z., Zhang, L., Wang, Y., 2004a. An fMRI study with semantic access in low proficiency second language learners. *NeuroReport* 15, 791–796.
- Xue, G., Dong, Q., Jin, Z., Chen, C.S., 2004b. Mapping of verbal working memory in nonfluent Chinese–English bilinguals with functional MRI. *NeuroImage* 22, 1–10.
- Zubicaray, G.D., McMahon, K., Eastburn, M., Pringle, A., 2006. Top-down influences on lexical selection during spoken word production: a 4 T fMRI investigation of refractory effects in picture naming. *Hum. Brain Mapp.* 27, 864–873.