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Sustained and transient brain activations in bilingual control

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Abstract: Bilingual individuals must have effective neural mechanisms to control and manage their two languages. However, the neural basis of bilingual language control is not well understood. Using mixed blocked and event-related design, the present study explored the sustained and transient activations during bilingual control. 15 Chinese-English bilingual speakers were scanned when they performed language switching tasks. The results showed that, compared to the single language condition, the mixed language condition (sustained control) induced activation in the bilateral inferior frontal, middle prefrontal and frontal gyri (BA45/46). In contrast, relative to the no switch condition, language switching (transient control) activated the left inferior parietal lobule (BA2/40), superior parietal lobule (BA7), and middle frontal gyrus (BA11/46). Importantly, the right superior parietal activity correlated with the magnitude of the mixed cost, and the left inferior and superior parietal activity covaried with the magnitude of the asymmetric switching cost. These results suggest that sustained and transient language control induced differential lateral activation patterns; and that sustained and transient activities in human brain modulate the behavioural costs during switching-related language control.

Key words: language control; mixed blocked and ER design; sustained control; transient control

Introduction

The bilingual speaker should not simply be considered the sum of two monolingual speakers (Grosjean, 1998). 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 & Green, 2007). In this respect, bilingual individuals must have effective neural mechanisms to control and regulate the activation of two language systems (Abutalebi & Green, 2007; Green, 1986; Wang et al., 2007).

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 (Grojean, 1998; La Heij, 2005), or by reactively suppressing the lexical nodes in the non-target language (Green, 1986).

Studies about bilingual aphasia and functional imaging studies suggest that bilingual language control relies on a distributed network (Fabbro et al., 2000; Khateb et al., 2007; Abutalebi & Green, 2007). The regions for language control include the bilateral prefrontal and middle frontal cortex, left inferior and superior parietal cortexes, ACC, caudate, and supramarginal gyrus. However, it is known that most of these areas are also involved in general executive control (Collette & Linden, 2002; Funahashi, 2001; Sohn et al., 2000). So, it seems that both language control and general executive control share an overlapping, or partially overlapping neural network. The roles of these regions in the executive control function are well documented. However, the specific roles of the different regions in language control remains unclear.

It's essential to determine whether language control involves general control (universal control/task-general control) and task-specific control systems, or sustained and transient components, and whether different systems or components of language control induce the differential activation patterns.

Based on previous studies about 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 the differential lateral activation maps.

Methods

Subjects

Subjects for this study were 15 right-handed native Chinese speakers (8 female). 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=8.4). 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.

Procedures

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

During one scanning session, 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.

Data acquisition

Functional MRI scans were performed with a 3 T Siemens MAGNETOM Trio at the MRI Center of the Beijing Normal University. A single-shot T2*-weighted gradient-echo, EPI sequence was used for the functional imaging scan with the following parameters: TR/TE/Flip =3000 ms/30 ms/90°, FOV=200mm, 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/TE/Flip=2530 ms/3.39 ms/7°, FOV=256 mm, matrix=256×256, and slice thickness =1.33 mm.

Data analysis

We used SPM2 (Wellcome Department of Cognitive Neurology, London, UK) run on Matlab 6.5 (Math works, Natick, MA) for image preprocessing and subsequent statistical analysis. 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 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 maps in language control, we analyzed sustained and transient activation patterns, respectively.

Results

Behavioural results

In the analysis of naming latencies, a response language (L1 vs. L2) × block type (single vs. mixed) repeated-measures ANOVA revealed significant main effects of response language [$F(1, 14) = 70.631, p = 0.000$] and block type [$F(1, 14) = 48.671, p = 0.000$]. As expected, the reaction times were longer in mixed block than in single block condition (60ms). That is to say, subjects showed significant mixed cost.

A response language (L1 vs. L2) × trial type (language switching vs. non-switching) repeated-measures ANOVA on the correct trials revealed significant main effects for response language [$F(1, 14) = 21.053, p = 0.000$] and trial type [$F(1, 14) = 17.203, p = 0.001$]. The response time was slower for language switching than for non-switching and slower for L2 than for L1. The interaction was also significant [$F(2, 13) = 7.640, p = 0.015$], 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 cost (the magnitude of switching cost is bigger 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 performed 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 Figure 1). Relative to the single Chinese, mixed language conditions revealed increased activation of the left middle frontal gyrus (BA46) and right precuneus (BA7). Relative to the single English, mixed language conditions revealed increased activation of the bilateral middle frontal gyri (BA46), cerebellum (BA18), left inferior frontal gyrus (BA45) and SMA(BA6). Compared to the single language, mixed language conditions revealed increased activation in the bilateral middle frontal (BA46), left inferior frontal, SMA, and right cerebellum (BA18).

Table 1. Brain regions activated when contrasting mixed language with single language

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

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

Transient activation in language control

We also performed trial-based, item-related comparisons by comparing language switching with Chinese non-switching, English non-switching and language non-switching trials to identify regions 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 cortexes (BA2/7), precentral gyrus (BA6), and cerebellum (BA37). Language switching compared to English non-switching showed increased activation in the left inferior parietal lobule (BA2/40),

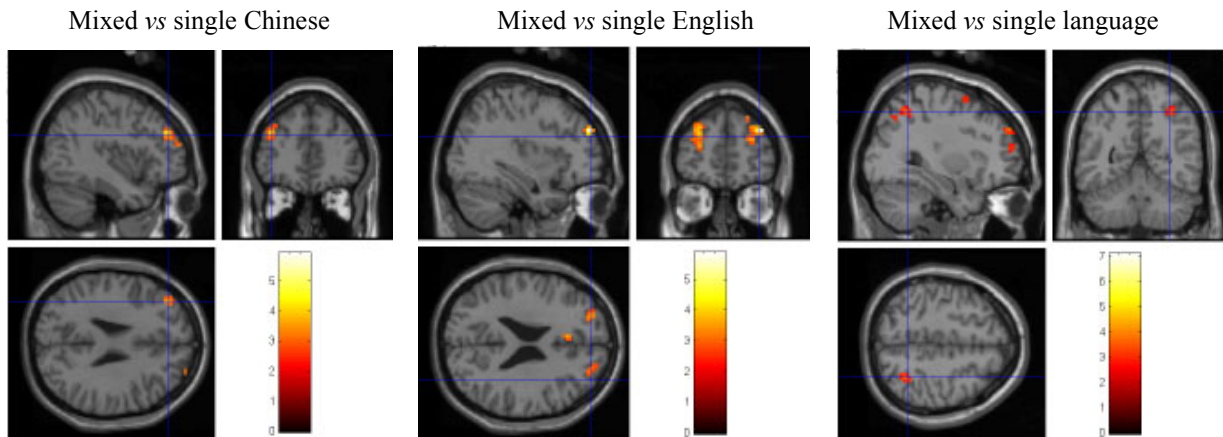


Fig.1. Activation maps of sustained language control. Left panel: Mixed language condition relative to single Chinese; middle panel: mixed condition relative to single English; right panel: mixed condition relative to single language .Clusters with more than 10 voxels activated above a threshold of $p < 0.005$ (uncorrected) were considered as significant.

middle frontal gyrus (BA46), SMA (BA6), and precentral gyrus (BA50). Comparison between language switching and language non-switching revealed activation in the left middle frontal gyrus (BA11) and cerebellum (BA37) (Table 2 and Fig.2).

Table 2. Brain regions activated when contrasting language switching with language non-switching

Brain region	BA	Coordinates ^a			Z-value
		x	y	z	
A. language switching relative to Chinese non-switching					
Left inferior Parietal	2	-48	-33	46	3.72
Left superior Parietal	7	-24	-56	44	3.65
Left cerebellum	37	-33	-51	-30	3.85
Precentral	6	-50	2	44	4.15
B. language switching relative to English non-switching					
Left inferior Parietal	40	-48	-36	46	4.00
Left middle Frontal	46	-36	47	14	3.90
SMA	6	0	6	63	4.66
Precuneus		4	-56	44	3.76
Precentral	6	-50	5	41	3.70
C. language switching relative to language non-switching					
Left middle orbital frontal	11	-24	43	-15	3.14
Left cerebellum	37	-36	-51	-30	3.79

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

Brain-behaviour relationship

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

We correlated the number of activated voxels in identified ROIs and the magnitudes of mixed cost and asymmetric cost. In addition, based on the means of the magnitudes of mixed cost and asymmetric switching cost of subjects, we grouped subjects as high mixed cost group (HMCG) (the magnitude of the mixed cost was larger than the mean of the mixed cost in all subjects, 6 subjects) and low mixed cost group (LMCG), and high asymmetric cost group (HACG) (the magnitude of the asymmetric switching cost was larger than the mean of the asymmetric switching cost in all subjects, 9 subjects) and low asymmetric cost group (LACG), and compared activity differences in identified ROIs for the high mixed cost group (HMCG) and low mixed cost group (LMCG), and high asymmetric cost group (HACG) and low asymmetric cost group (LACG), respectively.

There was a negative correlation between the mixed cost behavioural measure (sustained control) and the number of activated voxels in the right superior parietal cortex ($r = -.534$, $p = .041$). The low mixed cost group (LMCG) activated significantly more voxels in the right superior parietal cortex than the high mixed cost group (HMCG).

There were negative correlations between the asymmetric cost behavioural measure (transient control) and the number of activated voxels in left inferior ($r = -.622$, $p = .013$) and superior parietal cortex ($r = -.641$, $p = .010$). 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 cortex when language switching is compared to language non-switching, but no significant correlation was observed in the language non-switching conditions.

General discussion

The aim of the present study was to examine the sustained and transient language control and related neural correlates during language switching. As we hypothesized, the sustained and transient language control induced differential lateral activation patterns. State-related, sustained language control demonstrated bilateral

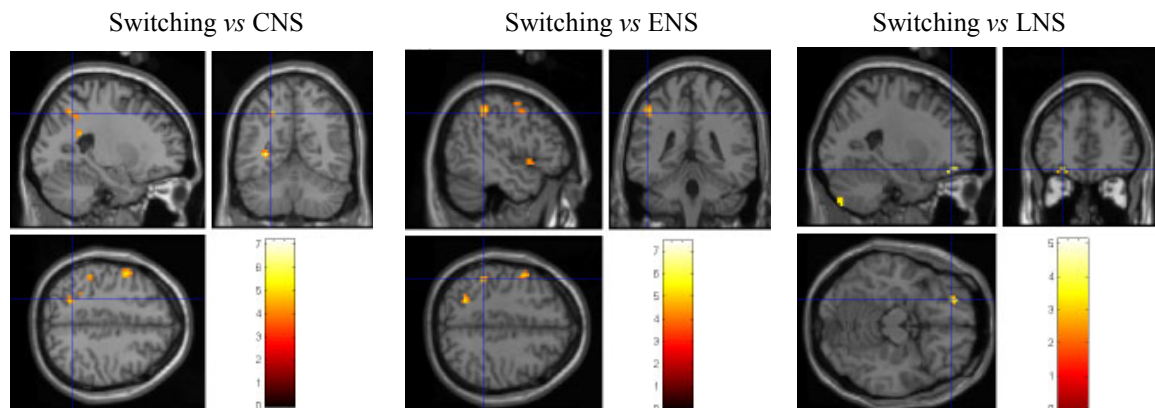


Fig.2. Activation maps of transient language control. Left panel: Switching minus Chinese non-switching (CNS); middle panel: Switching minus English non-switching (ENS); right panel: switching minus language non-switching (LNS).

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, bilingual language control may involve a distributed neural network and sub-networks. However, different regions or sub-networks may play different roles in sustained and transient language control. In particular, 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 the transient activation in language control. On the other hand, this finding indicates that language non-switching trials within mixed-language blocks may have significantly increased cognitive control demands relative to language non-switching trials within single language blocks since the mixed language condition exhibited bilateral activation in “executive regions” (Braver et al., 2003). In this sense, language context may play an important role in determining if a given bilingual task involves a specific executive region or neural network.

The frontal-parietal network is consistently regarded as an executive control network (e.g., D’Esposito et al., 1995, 1999; Collette et al., 2002, 2006; Schumacher et al., 2005). 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.

In addition to regions identified in present study, activation of some other regions have been observed during language control (for example, left ACC (e.g., Abutalebi et al., 2007a, 2007b; Crinion et al., 2006; Wang et al., 2007), caudate (e.g., Abutalebi et al., 2007a, 2007b; 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 present in a given cognitive task (Botvinick et al., 2001; Carter et al., 1998). Thus, unlike active-controlled retrieval, the more automatic retrieval during numeral naming may not require involvement of all executive regions.

In studies related to executive control, it has been suggested that executive functions might be fractionated into different component processes, and these components might associate with specific cerebral areas (Collette et al.,

2006). But, the role of a specific regions or networks in language control is not fully understood. In order to better understand the neural basis of language control, it’s necessary to use conjunction analysis, connectivity and other related techniques to determine the roles of different regions or neural networks in language control.

Some researchers suggest that second language learning or training 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 & Green, 2007). If this is a fact, then there should exist some 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.

In sum, our present study of native Chinese (L1) speakers learning English as a second language showed that the sustained and transient language control induced differential lateral activation patterns. Sustained language control involved activation in the bilateral frontal executive regions, but the transient language control induced activation in the left frontal-parietal executive regions. Importantly, the activation in the left inferior and superior parietal areas covaried with the magnitude of asymmetric cost in language control.

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