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In-context language control with production tasks in bilinguals: An fMRI study

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ABSTRACT

Bilinguals exhibit a feat to control their two languages in conversation. The neural substrates of bilingual language control have been well investigated with language switching paradigm. Yet, most of those studies have taken single lexical items (i.e., words outside a context) as the investigative tool. In the present study, we examined the neural substrates of in-context language control in unbalanced bilinguals with a sentence-end switching paradigm. Our results showed that in-context language control in bilinguals recruited the neural mechanisms that were similar in kind to those responsible for cognitive control in general. When the direction of switching was considered, we found that backward switching called for more cognitive/language control relative to forward switching. Behaviorally, symmetric switching costs were found regardless of the switching factor (switching vs. non-switching) and the language factor (L1 vs. L2). We interpreted our imaging and behavioral results as the effects of context when unbalanced bilinguals controlled their two languages in a context.

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1. Introduction

It has been an intriguing topic as to how to control two languages with one brain (Crinion et al., 2006; Rodriguez-Fornells et al., 2002). In a bilingual community, the speaker or the listener has a feat to avoid interference between languages and focus his/her attention on the target language during a conversation. The neuro-cognitive mechanism of bilingual language control has aroused great interest of research.

Two types of models have been proposed to account for this issue. One type of models posit that lexical access is language

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non-specific (De Bot and Schreuder, 1993; Green, 1986, 1998; Poulisse, 1997). In this view, the lexical items in both languages are activated in parallel, but there are differences between the activation levels of lexical items in the target and non-target languages. Differential activations can be achieved, according to Green's Inhibitory Control (IC) model (Green, 1986, 1998), by reactively suppressing the lexical items in the non-target language. Thus, only the lexical item in the target language receiving the highest level of activation is selected while the item in the non-target language is inhibited. The direct empirical evidence for the language suppression hypothesis has come from language switching in bilinguals. As a consequence of inhibiting the activated lexical items of the non-target language, there is increased time cost or switching cost for switching conditions relative to non-switching conditions. Moreover, asymmetric switching costs were constantly found due to differential proficient levels of L1 and L2 (Alvarez et al., 2003; Hosoda et al., 2012; Jackson et al., 2001; Meuter and Allport, 1999; Proverbio et al., 2004; Wang et al., 2007, 2009).

The other type assumes that lexical access is language-specific (Costa et al., 1999; Roelofs, 1998) in the sense that a lexical selection mechanism only considers the activation-levels of lexical items in the target language. According to this idea, the language-specific lexical selection mechanism is powerful enough to guarantee that only lexical items in the target language are accessed. Consequently, no interference between languages will be found and thus no time cost will be present. Behavioral, electrophysiological and brain-imaging measures have demonstrated a very efficient blocking of the non-target language in bilinguals (Rodriguez-Fornells et al., 2002). Generally, the controversy over the presence of the between-language interference in bilingual lexical selection may account for the vital difference between the two types of models.

Functional neuroimaging techniques offer an important tool to understand language control in bilinguals. Functional magnetic resonance imaging (fMRI) evidence has demonstrated that prefrontal cortex, parietal cortex, cingulate cortex and caudate are involved in bilingual language control (Abutalebi et al., 2007, 2008, 2013; Bradley et al., 2013; Crinion et al., 2006; Garbin et al., 2011; Guo et al., 2011b; Hernandez et al., 2001; Hosoda et al., 2012; Wang et al., 2007, 2009). Those brain regions have been traditionally associated with cognitive control functions. Thereby, bilingual language control has been assumed to be intimately linked to cognitive control in general (Abutalebi et al., 2008; Hernandez et al., 2001; Wang et al., 2009).

Here a notable fact is that the majority of the past studies of bilingual language control used out-of-context lexical items (words) as the investigative tool. It therefore sets us to question the neural bases of in-context language control in bilinguals. The use of context to examine bilingual language control, which somehow resembles the real-life processing, may better unravel the full scope of the neural bases of language control in bilinguals.

Studies of bilingual language control beyond word level have remained relatively scarce. In two visual target-naming studies with auditory sentential priming in bilinguals, the results did not provide supportive evidence to reactive cross-language inhibition hypothesis (Hernández, 2002; Hernandez et al., 1996). A few event-related potential (ERP) studies have examined language switching in sentence comprehension, finding an increased N400 component over left frontocentral sites in language switching as compared to non-switching conditions (Alvarez et al., 2003; Moreno et al., 2002; Proverbio et al., 2004). Only one fMRI study has addressed the neural mechanism of bilingual language control beyond word level. In a study of language switching in auditory discourse comprehension, inferior prefrontal cortex and superior temporal cortex were found to be significantly activated during switching relative to non-switching conditions (Abutalebi et al., 2007).

No fMRI studies have investigated the neural bases of in-context language control with production tasks to date. Production differs from comprehension not only in modality but also in activeness (Abutalebi et al., 2007). Comprehension is a more passive process. On the other hand, in-context language control differs from the word-level language control in that the former will exhibit apparent context-induced preparation effects and exert contextual constraints on language control.

In the present study, our main purpose is to investigate the neural bases of in-context language control in bilinguals. The second purpose is to investigate the issue of asymmetric in-context language switching in less proficient bilinguals. We adopted a sentence-end language switching paradigm with production tasks using a block fMRI design. A visually presented context provided a scenario. Unbalanced Chinese–English subjects were required to view the context and then produce a highly context-constrained word at the sentential end in the target language which was either the same as or different from the language used in the context. If the IC model holds true, it may predict inhibitory control due to between-language interference and predict time cost in responses. Or there is no between-language interference and time cost, as predicted by models of language-specific lexical access.

At the neural level, based on the findings from the previous word-level studies, we hypothesize that prefrontal cortex, parietal cortex, cingulate cortex and caudate might be significantly activated during the switching conditions relative to non-switching conditions, and that differential degrees of cognitive control may be needed considering the switching direction (i.e., forward switching or L1-to-L2 switching, and backward switching or L2-to-L1 switching). At the behavioral level, based on the assumption that the switching cost might be reduced but not eliminated by an opportunity of preparation (Monsell, 2003), we hypothesize that the switching cost might be much reduced due to the preparation effects in our study.

2. Results

2.1. *Behavioral results*

Production of wrong language, non-verbal production, ahead-of-time production (production ahead of the presence of the cue), and slow production (3 SD above the mean RT for each subject) were counted as null results. Trials of null results (3.2%) were excluded from further analysis. The analysis of the subjects' response time using a type of trials (language switching vs. non-switching) × language of production (Chinese vs. English) repeated-measures ANOVA showed no significant effects of type of trials [$F(1,20)=2.333$, $MSe=27{,}127.934$, $p=0.128$] and language

of production [$F(1,20)=1.912$, MSe=18,594.215, $p=0.168$]. No interaction was observed.

2.2. Imaging results

2.2.1. Language switching versus non-switching

To examine the neural substrates of switch-specific language control, we compared language switching with non-switching conditions. There was more activity to language switching than to language non-switching within a widespread network including left middle frontal gyrus (part of BA 9, BA 46), left inferior frontal gyrus (part of BA 44, BA 45), bilateral superior/middle frontal gyrus (BA 6), left superior/middle frontal gyrus (BA 8), bilateral superior parietal lobule (BA 7), left inferior parietal lobule (BA 40) and left precentral/postcentral gyrus (see Table 1 and Fig. 1A).

2.2.2. Forward C–E switching versus C–C non-switching

Relative to C–C non-switching control condition, forward C–E switching activated left occipital gyrus (BA 17/18), left caudate, left superior frontal gyrus (BA 8) (see Table 1 and Fig. 1B).

2.2.3. Backward E–C switching versus E–E non-switching

Relative to E–E non-switching control condition, backward E–C switching activated bilateral occipital gyrus (BA 17/18), left middle temporal gyrus (BA 21), left superior temporal gyrus (BA 22), left middle frontal gyrus (BA 9/46), superior parietal lobule (BA 7), inferior parietal lobule (BA 40), precentral gyrus (BA 6) (see Table 1 and Fig. 1C).

2.2.4. Backward E–C switching versus forward C–E switching

To examine the asymmetry in brain activity sensitive to switching direction of languages, we compared (forward C–E switching minus C–C non-switching) minus (backward E–C switching minus E–E non-switching), and (backward E–C switching minus E–E non-switching) minus (forward C–E switching minus C–C non-switching), respectively. The results showed that the backward switching elicited greater activation relative to forward switching in left inferior/middle frontal gyrus (BA 9/44), left precentral gyrus (BA 6), right inferior frontal gyrus (BA 9), bilateral superior parietal lobe (BA 7), right insula and bilateral occipital lobe (BA 17/18/19) (see Table 1 and Fig. 1D). But there was no significantly increased activation for the forward switching relative to the backward switching.

Table 1 – Brain regions activated for the contrasts testing the effect of switching and switching direction.

Brain region	Cluster size	Peak MNI coordinates			BA	P
Switching vs. non-switching						
Middle/inferior frontal gyrus (L)	42	−48	44	1	10 44 45 46	<0.001
Middle/inferior frontal gyrus (L)	120	−54	8	34	9	<0.001
Superior/middle frontal gyrus (L)	41	−3	23	55	8	<0.001
Superior/middle frontal gyrus (L)	43	−30	−1	58	6	<0.001
Superior/middle frontal gyrus (L)	10	−3	−4	64	6	<0.001
Superior/middle frontal gyrus (R)	29	30	2	61	6	<0.001
Precentral/postcentral gyrus (L)	21	−21	−37	70	2 3 4 5	<0.001
Superior/inferior parietal lobule (L)	249	−36	−58	58	7 40	<0.001
Superior/inferior parietal lobule (R)	13	30	−61	46	7	<0.001
CE vs. CC						
Cuneus/lingual gyrus (L)	24	−18	−100	−8	17 18	<0.001
Caudate (L)	19	−6	5	19		<0.001
Superior/middle frontal gyrus (L)	34	−3	20	55	8	<0.001
EC vs. EE						
Middle temporal gyrus (L)	42	−63	−31	−14	21	<0.001
Cuneus/lingual gyrus (R)	63	15	−73	1	17 18	<0.001
Cuneus/lingual gyrus (L)	18	−12	−82	4	17	<0.001
Superior/middle temporal gyrus (L)	12	−54	−52	7	22	<0.001
Middle/inferior frontal gyrus (L)	117	−54	8	34	6 9 46	<0.001
Superior/inferior parietal lobule (R)	143	36	−61	58	7 19 39 40	<0.001
Precentral/postcentral gyrus (L)	71	−45	−19	34	6	<0.001
Superior/inferior parietal lobule (L)	231	−36	−70	46	7 19 39 40	<0.001
EC vs. CE						
Cuneus/lingual/fusiform gyrus (L/R)	1428	15	−82	10	17 18 19 31	<0.001
Inferior/middle frontal gyrus (L)	132	−51	−1	25	6 9 44	<0.001
Middle temporal/occipital gyrus (R)	53	39	−76	4	19	<0.001
Inferior frontal gyrus (R)	15	48	5	28	9	<0.001
Insula (R)	19	33	−28	25		<0.001
Superior parietal lobule (R)	10	36	−73	52	7	<0.001
Superior parietal lobule/precuneus (L)	22	−24	−73	43	7	<0.001

L=left hemisphere; R=right hemisphere; CC=C–C non-switching; CE=C–E switching; EE=E–E non-switching; EC=E–C switching.

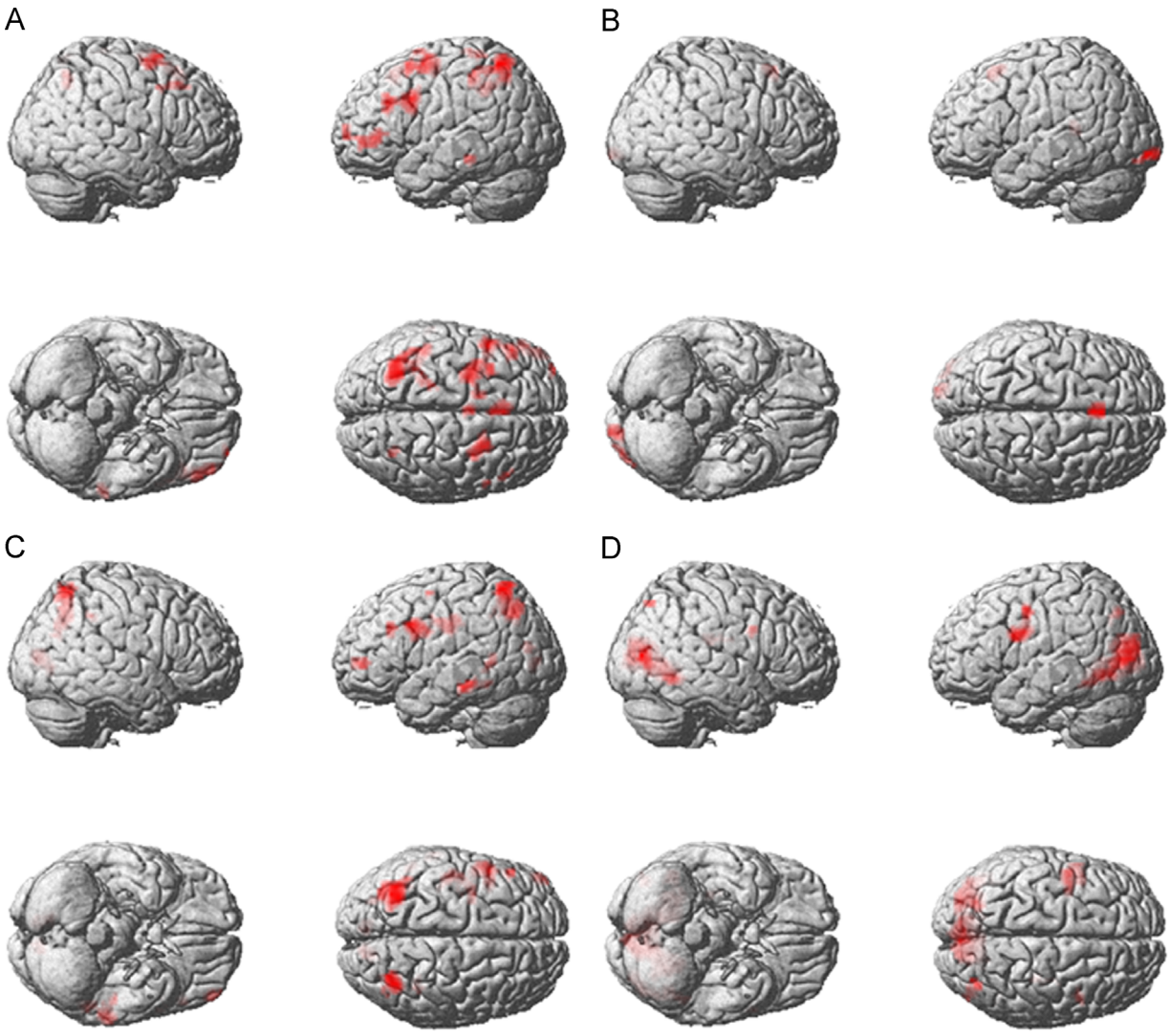

Fig. 1 – Activation maps. (A) Switching vs. non-switching; (B) C–E vs. C–C; C. E–C vs. E–E; D. E–C vs. C–E. Clusters with more than 10 voxels activated above a threshold of $p<0.001$ (uncorrected) were considered as significant.

3. Discussion

3.1. *Switching vs. non-switching*

Our results demonstrated that language switching mainly elicited greater activation in the middle frontal gyrus, inferior frontal gyrus, superior parietal lobule, inferior parietal lobule, premotor cortex than did language non-switching. These activated brain regions may reflect the function of inhibitory control mechanism during switching.

It is well-established in neuroscience that dorsolateral prefrontal cortex (DLPFC) serves executive cognitive control such as the selection of different response alternatives (D'Esposito et al., 1995; Garavan et al., 2000) and the switching between tasks (Dreher et al., 2002; Sohn et al., 2000). In the case of bilingual language switching or selection, DLPFC has been found to play a crucial role (Abutalebi et al., 2007, 2008; Guo et al., 2011b; Hernandez et al., 2001; Wang et al., 2007, 2009).

Increased blood flow in ventrolateral prefrontal cortex (VLPFC) has been attributed to the selection of goal-relevant knowledge or inhibition of irrelevant competitors (Fletcher et al., 2000; Moss et al., 2005; Thompson-Schill et al., 1999). The role of this region has been constantly found in many other studies of language switching (Abutalebi et al., 2007; Hosoda et al., 2012; Kho et al., 2007; Price et al., 1999; Quaresima et al., 2002; Venkatraman et al., 2006; Wang et al., 2007).

The superior parietal lobule is believed to play a role in reconfiguring stimulus-response mappings (Barber and Carter, 2005; Booth et al., 2002; Stoet and Snyder, 2004), while the supramarginal gyrus engagement suggests the increased demands for phonological recording during language switching (Hernandez et al., 2001; Khateb et al., 2007; Price et al., 1999; Venkatraman et al., 2006; Wang et al., 2007). The supplementary motor area (SMA) engagement in bilingual language control suggests that it plays an important role in inhibition (Guo et al., 2011b; Hernandez, 2009; Rodriguez-Fornells et al.,

2005) or between-language word selection (Alario et al., 2006; van Heuven et al., 2008).

3.2. Direction of switching

The contrasts between forward and backward switching showed that backward switching activated bilateral brain regions relative to forward switching while there were no significantly activated brain regions during forward relative to backward switching. And switching conditions showed more brain activation than non-switching conditions. Besides some activated regions which involved cognitive control, other regions might also be involved in language switching.

The middle temporal gyrus is specifically engaged for linguistic integration at the discourse level (Scott et al., 2000). The superior temporal gyrus is also assumed to be engaged in linguistic integration and orthography–phonology mapping (Baldo et al., 2006; Price et al., 1997; Tan et al., 2003). This region has been found to be active in some other studies of language switching (Garbin et al., 2011; Guo et al., 2011b; Hosoda et al., 2012; Wang et al., 2007). The increased activation in lingual gyrus, ceneus, and fusiform gyrus may reflect the selection for lexical candidates in both languages (Guo et al., 2011b).

The role of caudate in language switching remained a puzzle because some studies reported its activation (Abutalebi et al., 2008; Ali et al., 2010; Crinion et al., 2006; Garbin et al., 2011; Wang et al., 2007) while others not (Hernandez et al., 2001; Hernandez, 2009; Wang et al., 2009). A recent multimodal imaging study found that the second language use-dependence experience shaped the brain structure: an increase of gray matter volume in the inferior frontal gyrus pars opercularis and its connectivity with the caudate nucleus in the right hemisphere (Hosoda et al., 2013). On the other hand, Crinion et al. (2006) suggested that the left caudate played a vital role in monitoring and controlling the language in use. Thus, the two findings seem to depict a complementary role of the left and right caudate nucleus in the second language processing. In our study, the left caudate was more related to forward switching relative to Chinese non-switching, consistent with a finding of Garbin et al. (2011). ACC activation is directly related to the degree of response conflict or detection of response for errors in a given cognitive task (Carter et al., 1998; MacDonald et al., 2000; Wang et al., 2009). One possible interpretation for the absence of ACC in our study might be due to low degree of response conflict.

3.3. In-context language control in bilinguals

3.3.1. Neural accounts of in-context language control in bilinguals

In-context language switching in our study presented switching-elicited neural activities as did out-of-context language switching. The frontal-parietal network was active during switching conditions relative to non-switching conditions. Cognitive/language control is likely carried out through this network of brain areas, each contributing with specific complementary control functions (Abutalebi and Green, 2007). Frontal executive regions may exert their effect during language control in a top-down (goal-driven) way while the parietal executive regions may exert their effect in a bottom-up (stimulus-driven) way (Buschman and Miller, 2007; Stoet and Snyder, 2004). Our findings lend evidence to the assumption that in-context language control in bilinguals recruits the neural mechanisms that are similar in kind to those responsible for cognitive control in general, well in line with findings from studies of word-level language control in bilinguals (Abutalebi et al., 2008, 2013; Wang et al., 2007, 2009). To distinguish the areas which related to the "language control" from the general task switching areas, two studies have directly compared linguistic and nonlinguistic switching tasks and made a similar conclusion (de Bruin et al., 2013; Xue et al., 2008). There seem no language control specific areas.

Interestingly, fMRI evidence in our study demonstrated more brain regions activated during backward switching relative to forward switching (i.e., L2-to-L1>L1-to-L2), in an opposite pattern of neural activities to word-level language switching with production tasks (Guo et al., 2011a; Wang et al., 2007, 2009). Notably, the frontal-parietal network activated during backward switching relative to forward switching suggests more cognitive/language control during backward switching. According to Task Set Inertia hypothesis (Meuter and Allport, 1999), on a switch trial from the weaker to the stronger task, the inhibition of the stronger task set must be overcome before the task can be performed. In the following, borrowing the view from Task Set Inertia hypothesis, we attempt to interpret our fMRI results in light of context effect.

Context offers a rich ecology in which language control occurs. Context affects lexical selection via semantic, syntactic and grammatical information it provides (Tabossi, 1991). Conceivably, it is harder for unbalanced Chinese–English bilinguals to process English contexts than Chinese contexts. There is evidence that unbalanced bilinguals would experience unconscious translation into native language during tasks involving only foreign language stimuli (Thierry and Wu, 2007). Thereby, English contexts take up more cognitive resources during English-to-Chinese switching conditions than Chinese contexts during Chinese-to-English switching conditions. This context effect leads to the dominance (or harder-to-process task) of English contexts. This may be the reason why more cognitive control is called for to inhibit the dominant English contexts before the occurrence of switching during English-to-Chinese than Chinese-to-English switching conditions in the present study.

An alternative interpretation of the discrepancy between our study and word-level studies concerns the difference in choice of contrasts. While forward (L1-to-L2) switching was contrasted with L1 (L1-to-L1) non-switching in our study, forward (L1-to-L2) switching was contrasted with L2 (L2–L2) non-switching in most word-level studies (de Bruin et al., 2013; Wang et al., 2007, 2009). In their studies, they could directly influence the effect of the previous language while the actual naming language remained the same. This excluded potential confounds of naming latency differences in different languages and words. They could then compare the effects of switching from L1 versus L2 non-switching. However, in our study, this contrasting way might cause context-induced confounds. For example in L1–L2 vs. L2–L2, we had different contexts (Chinese context in L1–L2 and English context in L2–L2). The difference between processing the Chinese context in Ch–En and processing the English

context in En–En is obvious. This difference can have different brain activations. Then the results would be confounded by context-induced activation and switching-induced activation. So we contrasted L1–L2 to L1–L1. In this way we could keep the context the same and examine the sentence-end switching. We could then compare the effects of switching into English in Chinese context versus non-switching in Chinese context.

What's more, the only fMRI study of in-context language switching with auditory comprehension paradigm further complicated the issue, finding that switching into less exposed L1 called for more cognitive control in early bilinguals. Abutalebi et al. (2007) explained that comprehension was a more passive task in comparison with production tasks. Additional controlled investigations are needed to clarify the issue of asymmetric switching with varying paradigms.

Although context poses such confounding factors as preparation effects and linguistic constraints in our study, we scrupulously speculate that both switching and non-switching conditions called for comparable preparation. Likewise, the semantic, syntactic and grammatical constraints were comparable during both switching and non-switching conditions with the exception of sentence-end variation. If this speculation holds true, those activated brain regions during switching conditions relative to non-switching conditions were switching-specific rather than preparation-elicited. Some brain-imaging studies reported that preparation-related activation was found in the prefrontal cortex (specifically DLPFC) (MacDonald et al., 2000; Sohn et al., 2000).

3.3.2. *Behavioral accounts of in-context language control in bilinguals*

Behaviorally, we found symmetric switching cost during switching relative to non-switching conditions. The issue of asymmetric switching costs has remained a debate. While some studies of word-level language switching with production tasks showed greater costs during the backward switching than during the forward switching (i.e., L2-to-L1 > L1-to-L2) (Meuter and Allport, 1999; Wang et al., 2007, 2009), others reported symmetric switching costs for highly proficient bilinguals as well as for unbalanced bilinguals (Christoffels et al., 2007; Costa and Santesteban, 2004; Jackson et al., 2001).

Monsell (2003) assumed that the switching cost might be reduced, but not eliminated by an opportunity of preparation. In the present study, the context-induced preparation effects, the block design, and familiarity with the experimental contexts and practice prior to the experiment leave the subjects much preparation for production. Thus, the switching cost might be defused ahead of the occurrence of switching during switching conditions. Sufficient preparation might be a good reason to account for symmetric switching costs in our study. In fact, a previous study with sentence priming paradigm also did not find language asymmetries (Hernandez et al., 1996), which might be attributable to sentential context effects (Hernández, 2002).

3.3.3. *Interpretations for remaining issues*

The first issue is about two apparent discrepancies among studies of language switching. For one thing, the issue of asymmetric switching may be confounded by modality (auditory/visual comprehension vs. verbal production), language proficiency (highly proficient bilinguals vs. unbalanced bilinguals), or context (in-context vs. out-of-context), and above all, the variation in experimental design. For the other, there seem no correlations, even negative correlations between the switching costs and the number of activated voxels, as shown in the present study and some other studies (Wang et al., 2007, 2009). Thus, language switching costs should be distinguished from switching effects (Alvarez et al., 2003).

Second, it is here inappropriate to ascribe the switching effects only to the inhibitory control mechanism though inhibitory control might play an important role in language switching. For instance, unconscious translation into native language may be omnipresent when foreign language is being processed in unbalanced bilinguals (Thierry and Wu, 2007). Thus, backward switching and forward switching call for differential degrees of cognitive control for unbalanced bilinguals.

Lastly, a concession to language specific vs. non-specific lexical access in bilinguals, as mentioned in Introduction, concerns language types and language contexts. Lexical access in unbalanced bilinguals exhibits language specificity only when the target language is strong language, but not when it is weak language (Kroll et al., 2006, 2008). Moreover, lexical access in bilinguals can be language-specific when it is in monolingual context. For instance, bilinguals demonstrated a very efficient blocking of the non-target language (Rodriguez-Fornells et al., 2002) with GO/NOT GO tasks, which exert a mandatory monolingual context on bilinguals. Admittedly, some more confounding factors are involved in language specificity of lexical access in bilinguals, awaiting clarification.

4. fMRI data acquisition

Functional MRI scans were performed with a Siemens 3.0 T Trio scanner at HuaXi MR Research Center of West China Hospital in Chengdu, China. Stimuli, programmed with E-prime software 2.0 (Psychology Software Tools) were projected onto a translucent screen via a projector. The subjects viewed the stimuli through a mirror attached to the head coil. Head motion was minimized by placing pillows and cushions around the head. Ear plugs were used to reduce noise in the scanner. Functional imaging consisted of an echo planner imaging with gradient echo (EPI GRE) sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 240 × 240 mm^2, 30 interleaved descending slices, voxel size = 3.8 × 3.8 × 5.0 mm^3). The five initial scans of each session were dummy scans that were used to equilibrate the state of magnetization and were excluded from the analysis. Anatomical reference images, acquired after the functional imaging, consisted of a 3-D GRE T1-weighted sequence (TR = 1900 ms, TE = 2.26 ms, flip angle = 9°, FOV = 256 × 256 mm^2, voxel size = 1 × 1 × 1 mm^3). A total of 772 whole brain volumes were collected from each subject. Head motions were evaluated on a workstation of the MRI machine as soon as the scans ended.

4.1. Image processing and statistical analysis

Data processing and statistical analyses were analyzed using spm8 implemented on MATLAB (Wellcome Trust Centre for Neuroimaging, London, UK, http://www.fil.ion.ucl.ac.uk/spm/). All functional volumes were corrected for slice timing with the middle slice as reference, realigned to remove head motion, normalized onto the EPI template image provided by spm8, and then smoothed using an 8 mm FWHM Gaussian kernel (Friston et al., 1994). The resulting voxel size after normalization was $3 \times 3 \times 3\ mm^3$. Time-series from each voxel were high-pass filtered (1/128 Hz cutoff) to remove low-frequency noise and signal drift. At the first level, the preprocessed functional volumes were submitted to fixed-effects analyses for each subject, with the general linear model applied at each voxel across the whole brain. Significant changes in hemodynamic response for each subject and condition were assessed using t-statistics. The group-averaged effects and the direct comparisons between the conditions were performed on a second level analysis (random effects) at $P<0.001$ (uncorrected) in order to generalize the results from our sample to the population (Friston et al., 1999). An extent threshold of 10 contiguous voxels was applied to all contrasts. A gray matter brain mask was used during statistical analysis.

5. Conclusion

In general, the inhibitory control mechanism is at work during in-context language control in bilinguals. But differential degrees of cognitive control are needed depending on the switching direction. This might be the reflection of differential degrees of interference from the non-target language in unbalanced ¥ bilinguals, in favor of the IC model. In fact, the inhibitory control mechanism has also been proposed in language-specific lexical access model, even to an extreme extent. The prefrontal cortex may serve this function: complete inhibition or blocking of the non-target language (Rodriguez-Fornells et al., 2002). Behaviorally, context-induced preparation effects seem to defuse switching costs ahead of the occurrence of language switching, leaving undifferentiated response latencies between switching and non-switching conditions. This might be well the case that a bilingual speaker switches languages in volition during a real-life conversation. One limitation in the present study is that it is still far away from simulating the real-life language control. One key direction for future research will be to examine directly the neural bases of volitional language control. Another limitation is that we did not include early bilinguals as the subjects. Studies found that an increase in L2 proficiency is accompanied by a reduction in prefrontal activity (Abutalebi and Green, 2008, 2007). Moreover, a recent study reported reorganization of the neural substrates responding to linguistic experiences, especially in the right hemisphere (Hosoda et al., 2013). Thus, early bilinguals may exhibit similar as well as different patterns of language switching as compared to late bilinguals. Such findings would carry more weight to understanding language switching if both early and late bilinguals were included in the present study.

6. Experimental procedures

6.1. Subjects

Twenty-one healthy Chinese–English bilingual students (12/9 M/F, aged 23–27, mean age=24.38) from Graduate School of West China Hospital were recruited in the experiment. All subjects were native Chinese speakers and were right-handed. All subjects had normal or corrected-to-normal vision. None of them displayed any signs, or had any previous history of, medical or neurological diseases. We obtained written informed consent from each subject in accordance with the guidelines approved by the research ethical committee of West China Hospital in Chengdu, China.

6.2. Language proficiency assessment

All subjects followed school in China since their early childhood and started learning English as their second language at junior high school. The mean age and length of acquisition of English for these subjects were 12.4 and 11.8 years, respectively. We assessed the subjects' English proficiency on the basis of College English Test Band 6 (CET 6). All subjects passed CET 6 (mean percentage=68%) with writing 63%, reading 73%, and listening 67% (3.13, 3.65 and 3.35 respectively when converted into 5-point scale). The spoken English proficiency was assessed by means of a self-rated questionnaire on a 5-point scale (very fluent, fluent, moderately fluent, non-fluent, and very non-fluent). The subjects rated themselves as moderately fluent English speakers (mean=3.24). The Chinese proficiency was also assessed by means of a self-rated questionnaire on a 5-point scale from very good to very bad. The mean scores of their ratings in Chinese were speaking 4.42, reading 4.61, writing 4.17, and listening 4.53.

6.3. Materials

Thirty frequently-used candidate English adjectives which we chose from junior high school English textbooks were used to make up daily-encountered contexts. The make-up of a context consists of three parts (Table 2): The first part serves as contextual primer (e.g., 8848 m), and the second part as contextual booster, a person or a thing which is closely related to the first part (e.g., The Mount Everest is). The third

Table 2 – Examples of stimuli in the present experiment (E=English; C=Chinese).

Contextual conditions	Contextual primer	Contextual booster	Articulation task with a prior cue
E–E non-switching	8848 m	The Mount Everest is	very _____
E–C switching	8848 m	The Mount Everest is	很 _____
C–C non-switching	8848米	珠穆朗玛峰	很 _____
C–E switching	8848米	珠穆朗玛峰	very _____

part is a speech production task with a prior cue "very" or "很" ("很"means "very") immediately followed by a blank (e.g., very __). One example of three-part scenarios will be illustrative: "8848 m/The Mount Everest is/very __". Altogether thirty candidate contexts were created. These contexts were balanced for sentence length. To match the sentence length, we used some abbreviations such as "m" for "meter" in "8848 m".

Prior to fMRI experiment, we recruited twenty healthy graduate bilingual students (10/10 M/F, aged 22–24, mean age=23.1. All passed CET 6) to participate a context screening test, which was conducted to exclude contexts with difficult tasks. The remaining sixteen contexts (Appendix A) were highly context-constrained with very easy tasks (mean=1.21) by means of a self-rated questionnaire on a 5-point scale from very difficult to very easy.

To examine the language switching, we created two switching conditions (C–E or Chinese-to-English switching, and E–C or English-to-Chinese switching) and two non-switching conditions (C–C or Chinese non-switching, and E–E or English non-switching) from a single context (see Table 2). In the same language context, a switching condition differed from a non-switching condition at the sentence end (e.g., "8848 m/The Mount Everest is/很 __" vs. "8848 m/The Mount Everest is/very __"). Altogether sixty-four contextual trials were generated out of sixteen contexts.

6.4. *Task procedures*

We conducted two identical runs with 128 contextual trials altogether (32 trials for each condition). In a run, sixteen mini-blocks were regularly alternated in the present study (i.e., C–C, C–E, E–E, E–C, C–C, C–E, E–E, E–C, C–C, C–E, E–E, E–C, C–C, C–E, E–E, and E–C). A mini-block contained 4 contextual trials with the condition held constant. The experimental stimuli in an experiment session were 64 contextual trials which were pseudo-randomized and counterbalanced across subjects.

All the production tasks were highly context-constrained. Fig. 2 illustrated the procedure. The trials were presented in mini-blocks lasting 32 s (4 trials × 8 s), followed by a 12-s resting period (blank screen), in which no trial was presented and the BOLD response was allowed to return to a baseline state. The experiment started with an initial 10-s welcome addressing. All trials lasted 8 s: Each trial was introduced by a fixation cross, which was presented in the center of the screen for 1 s. Following this, a contextual trial was presented visually in a phrase-by-phrase fashion (i.e., three parts): the contextual primer was presented for 1 s (e.g., 8848 m); the contextual booster was presented for 2 s (e.g., The Mount Everest is); a cue followed by a blank was presented for 4 s (e.g., very __). The subjects were required to view the contextual trial, and then covertly articulate a Chinese or an English word according to the contextual constraint as soon as the presence of the cue "很" or "very".

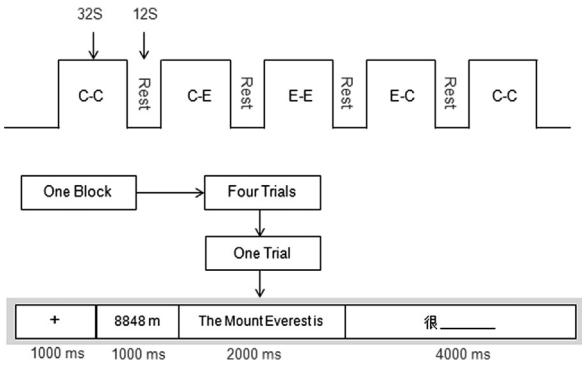

Fig. 2 – Procedure followed in the present experiment.

Due to technical limitations of recording the verbal responses, a separate behavioral session was conducted outside of the scanner after the fMRI sessions (Abutalebi et al., 2008; Guo et al., 2011b; Wang et al., 2007, 2009). The subjects' actual responses and the time of voice onset were collected with a SRBOX (Psychology Software Tools) and E-Prime 2.0, and analyzed with SPSS 17.0. Prior to fMRI experiment, we (1) provided the sixteen contexts (including the target words) used in the experiment for the subjects to familiarize those contexts; (2) conducted a practice session in order to acquaint the subjects with the task involved and the order (i.e., C–C, C–E, E–E, E–C) of mini-blocks presented in the experiment.

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Appendix A

See Table A1.

Table A1 – The complete list of the sixteen contexts. A context generates four contextual conditions. A contextual trial is a three-part scenario.

8848 m	The Mount Everest is	Very____ (high)
12′88″	Liu Xiang is	Very____ (fast)
6671 km	The Nile is	Very____ (long)
400 kg	This pig is	Very____ (fat)
$10 million	The car is	Very____ (expensive)
160 cm	Hitler is	Very____ (short)
38.5°C	Today it is	Very____ (hot)
3 years old	His brother is	Very____ (young)
¥500	The computer is	Very____ (cheap)
1.35 billion	China's population is	Very____ (large)
$50 billion	Bill Gates is	Very____ (rich)
4896 pages	The dictionary is	Very____ (thick)
−3 °C	Today it is	Very____ (cold)
¥100/month	His salary is	Very____ (low)
5:00 a.m.	Tom gets up	Very____ (early)
2.26 m	Yao Ming is	Very____ (tall)

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