An fMRI study with semantic access in low proficiency second language learners

Gui Xue, Qi Dong,[CA] Zhen Jin,[1] Lei Zhang[1] and Yue Wang[2]

Institute of Brain and Cognitive Sciences, School of Psychology, Beijing Normal University, Beijing 100875; [1]MRI Center, Beijing 306 Hospital, Beijing, China; [2]Department of Linguistics, Simon Fraser University, Burnaby, BC, Canada

[CA]Corresponding Author: dongqi@bnu.edu.cn

Received 17 November 2003; accepted 22 December

DOI: 10.1097/01.wnr.0000122484.43641.02

Brain activity was measured with fMRI in twelve 10- to 12-year-old Chinese children who began learning English when they were 8 years old in order to find out whether there is a common or a distinct neural semantic system for native language (L1) and second language (L2) in low proficiency bilingual subjects. Although they performed less well in L2 in the semantic decision task administered during fMRI measurement, these subjects showed similar robust activation, for both languages, in brain areas involved in semantic processing (e.g. the left inferior frontal cortex). Within-subject and group analyses revealed no significant difference in the activation patterns for L1 and L2 in these regions. These results suggest that at least at single-word level, there are shared neural substrates for semantic processing of L1 and L2 even when one is at a very low L2 proficiency level. *NeuroReport* 15:791–796 © 2004 Lippincott Williams & Wilkins.

Key words: Bilingualism; Chinese characters; fMRI; Language proficiency; Semantic; Task difficulty

INTRODUCTION

A fundamental question on bilingualism is whether the two languages are represented as overlapped or separate systems in the brain. Using neural imaging technology, current research has suggested that attained second language proficiency may be an important factor that influences the cognitive and neural organization of a bilingual individuals's two languages [1–3]. For proficient or relatively proficient bilinguals, spatially overlapping regions are activated when a bilingual individual performs linguistic task in the two languages [4–8]. This is true even when the two languages are of very different surface structure, such as Chinese and English [4,5,7,8]. However, for less proficient bilinguals, existing studies have provided a mixed picture [1–3,9,10].

There is evidence that the processing of one's less proficient second language (L2) would be largely implemented by the same neural substrates as those of the native language (L1). For example, by examining two groups of English–Chinese bilinguals with one group being more proficient in English and the other more in Chinese, Chee *et al.* [1] found significant activation in the left frontal area for both groups. Similarly, Hasegawa *et al.* [2] found a significant degree of overlapping activation in most of the cortical regions on their moderately proficient Japanese–English bilinguals. In these studies, greater and more extensive activation was found for participants' less proficient second language, and further analysis indicated that the volume of activation or amplitude of BOLD signal change were commensurate with reaction time [1,2]. It could be assumed that this difference in the magnitude of activation is due to a greater degree of task difficulty or complexity in processing L2 compared with L1. Recently, cumulative functional imaging evidence has suggested a workload or task difficulty effect in brain responses to a wide range of cognitive tasks, including sentence comprehension [11], semantic decision making [12] and working memory [13]. For example, Just *et al.* [11] found that compared to that of simple sentences, the processing of complex sentences caused more extensive activation in Broca's area and its right hemisphere homologue. Thus, it is possible that L1 and L2 are implemented by the same neural substrates in the brain of less proficient bilinguals, and this neural network is modulated by computational load [2].

On the other hand, several studies on less proficient bilinguals found significant neural dissociation between L1 and L2 [3,9,10]. Perani *et al.* [10] found that when low proficiency Italian–English bilinguals were listening to stories in their two languages, some brain areas, such as the left inferior parieto-occipital area, the left and right temporal poles, and the left inferior frontal gyrus, were activated only for the native language. Using a similar paradigm, Dahaene *et al.* [9] obtained resembled results in non-fluent French–English bilinguals and revealed significant individual difference in neural activation pattern while processing L2. These results are taken as evidence supporting the neural specialization for native language shaped by early and extensive exposure [10]. In a follow-up study, Perani *et al.* [3] found that the amount of exposure rather than the age of acquisition may be the critical factor that affects the formation of the neural representation of a second language. Alternatively, Hasegawa *et al.* suggested that the less extensive activation observed for participants' second language in the above mentioned studies could be attributed to the lower comprehension level of L2 [2].

It should be noted that, in these studies, the degree of L2 proficiency was highly varied. Behavioral studies have indicated a developmental shift of semantic process as a function of second language proficiency [14–16]. That is, novice learners would rely more exclusively on lexical links when processing in their second language, and the connection between L2 and concepts would gradually be developed as they become more proficient. As a result, low proficiency learners will first translate L2 word into L1 at the lexical level to access the meaning of the second language, while advanced bilinguals may access the semantics of two languages both via the direct semantic link to concepts [15,16]. Thus, it is hypothesized that as a second language learner becomes more proficient in L2, the neural network underlying L2 processing would become increasingly like that of L1 [5].

Results from proficient bilinguals with a semantic decision task at single-word level appear to be consistent with the above postulation [4–8]. However, the validation of this hypothesis has not been well examined on low proficiency bilinguals. At present, studies showing significant spatial dissociation on less fluent bilinguals usually used whole-language comprehension tasks. Thus, it is very difficult to determine whether non-fluent bilinguals' different processing patterns between L1 and L2 are due to semantic processing, or other linguistic processes, such as phonological and syntactic processes.

The present study aimed at testing this hypothesis on low proficiency L2 learners, or low proficiency bilinguals, according to the broad definition of bilingual (i.e. a person who knows two languages, but not necessarily with equal proficiency). Previous studies with native English speakers [12,17] and proficient bilinguals [4–8] have demonstrated that the left inferior prefrontal cortex (LIPC) is involved in semantic processing of single words. Based on these findings, we adopted a similar procedure to study the semantic processing on low proficiency bilinguals. The focus of the present study was whether the LIPC activation in Chinese and English tasks differed from each other both at the individual level and group level. If we found different activation patterns in this region, we could infer that non-overlapping neural correlates represent the semantic processing of L1 and L2 in very low proficient bilinguals. Otherwise, we could determine that low proficiency L2 learners share the same neural representation of L1 and L2.

In this study, primary school students who had been learning English at school were recruited, consisting of a homogeneous group of subjects in terms of L2 experience (e.g. learning method, age and time of L2 exposure) and proficiency. This helps to minimize the individual difference in neural organization of L2 processing potentially influenced by these factors [10,18]. As previous studies were mainly on adults, this study may further our understanding of the neural mechanism of bilingual processing in children.

MATERIALS AND METHODS

Subjects: Twelve right-handed children (six male) aged between 10 and 12 years (mean 11.6) were included in this experiment. Informed consent was obtained from both the children and their parents in accordance with guidelines set by the MRI center at the Beijing 306 Hospital. All subjects were students from a local elementary school in Beijing. A brief survey on their English learning experience indicated that all these students began to learn English at about 8 years old at school for about 2 h each week, and none had received special training in English outside of school setting. They could recognize only about 300 English words, and their ability to communicate in English was very limited.

Material and behavioral performance: Figure 1 presents examples of the Chinese and English materials used in this study. Eighty Chinese words and 80 English words were adopted from the subjects' textbook to ensure their familiarity with the stimuli. All Chinese stimuli were single-character words and all English materials were monosyllabic words with a length of 3–5 letters. For both English and Chinese words, several grammatical categories were selected, including nouns, adjectives and verbs. The number of words from each category is matched between the two languages. For both languages, 40 pairs of items were divided into four blocks of 10 pairs each, with half being semantically related words and half semantically unrelated (Fig. 1).

All Chinese and English blocks were organized into one fMRI scan and the sequence of them was counter-balanced. Each experimental block lasted 30 s and was preceded by a control block of fixation lasted 21 s. The stimuli were programmed with DMDX (http://www.u.arizona.edu/~kforster/dmdx/dmdx.htm) on an IBM compatible notebook computer and presented by a projector onto a translucent screen. Subjects viewed the stimuli through a mirror attached to the head coil. During the experimental condition, each pair of stimuli was presented for 2500 ms, followed by a blank screen for 500 ms. Subjects were asked to judge whether the two words were semantically related or not. A positive response was indicated by pressing the key corresponding to the index finger of their right hand

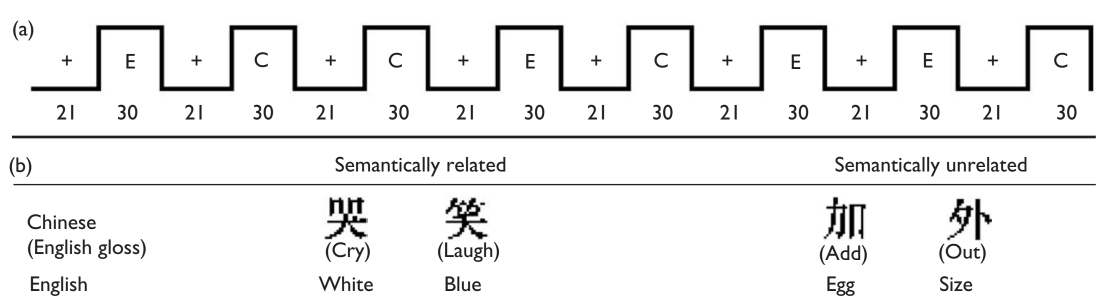

Fig. 1. (**a**) Block timing of stimulus presentation. E, English; C, Chinese; +, Baseline. The durations for the experiment block and control block are 30 s and 21 s, respectively. (**b**) Examples of the stimuli for Chinese and English tasks used in the present experiment.

Table I. Foci of significant activation in the Chinese and English semantic decision tasks relative to fixation (baseline), and the direct comparison between the two languages.

Brain region (BA)	Chinese minus baseline					English minus baseline				
	x	*y*	*z*	Z	*p*	*x*	*y*	*z*	Z	*p*
L inferior frontal gyrus (45)	−42	21	18	5.06	< 0.0001	−39	15	19	4.93	< 0.0001
	−45	24	10	5.01	< 0.0001	−45	32	7	4.25	< 0.0001
L precentral gyrus (4)	−24	−12	42	3.74	< 0.0001	−36	5	36	3.65	< 0.0001
R precentral gyrus (4)	27	−12	42	3.85	< 0.0001	33	−6	50	2.79	0.003*
L superior parietal lobule (7)	−27	−53	42	3.60	< 0.0001	−27	−53	44	4.40	< 0.0001
L inferior parietal lobule (40)	−39	−33	35	3.37	< 0.0001	−36	−33	32	4.56	< 0.0001
L fusiform gyrus (37)	−39	−56	−10	4.95	< 0.0001	−36	−50	−10	4.00	< 0.0001
L fusiform gyrus (19)	−36	−65	−12	5.47	< 0.0001	−35	−68	−12	4.76	< 0.0001
R fusiform gyrus (37)	36	−56	−17	4.91	< 0.0001	39	−59	−12	4.27	< 0.0001
L inferior occipital gyrus (18)	−15	−91	−8	5.54	< 0.0001	−21	−88	−8	5.12	< 0.0001
R middle occipital gyrus (19)	33	−79	−8	4.82	< 0.0001	33	−82	−9	4.42	< 0.0001
L anterior cingulate (32)	−6	28	26	5.19	< 0.0001	−6	28	26	5.21	< 0.0001
R cingulate gyrus (32)	9	22	35	4.66	< 0.0001	9	33	26	5.21	< 0.0001
R insula (13)	45	−16	20	3.22	< 0.0001	33	27	12	3.36	< 0.0001
L lentiform nucleus	−18	−9	−2	5.07	< 0.0001	−21	6	−3	4.46	< 0.0001
R lentiform nucleus	21	−6	−2	4.37	< 0.0001	21	3	5	3.53	< 0.0001
L thalamus	−15	−15	1	4.7	< 0.0001	−12	−14	3	4.23	< 0.0001
R thalamus	18	−15	−2	4.67	< 0.0001	15	−15	−2	3.74	< 0.0001
	Chinese minus English					English minus Chinese				
L cingulate gyrus (32)	–	–	–	–	–	−9	30	26	3.59	< .0001
L posterior cingulate (29)	–	–	–	–	–	−3	−40	19	3.44	< 0.0001
L inferior parietal lobule (40)	–	–	–	–	–	−27	−50	41	3.37	< 0.0001

BA: Brodmann area; L=Left, R=right; Z=z-score.
*Not significant at $p < 0.0001$.

and a negative response by pressing the key corresponding to the index finger of the left hand. In the control block, fixation cross was presented and subjects were asked to only silently fixate on the crosshair.

Apparatus and procedure: Scans were performed on a 2.0 T GE/Elscint Prestige whole-body MRI scanner (Elscint Ltd., Haifa, Israel) at the MRI center of Beijing 306 Hospital. A single-shot T2*-weighted gradient-echo, EPI sequence was used for functional imaging scan with the following parameters: TR/TE/θ=3000 ms/60 ms/90°, FOV=375 × 210 mm, matrix=128 × 72, slice thickness=6 mm. Twenty contiguous axial slices were acquired to cover the whole brain at 136 time points during the total imaging time of 6 min, 48 s. The anatomical MRI was acquired using a T1-weighted, 3D gradient-echo pulse-sequence. The parameters for this sequence was: TR/TE/θ=25 ms/6 ms/28°, FOV=220 × 220 mm, matrix=220 × 220, slice thickness=2 mm. This provided high-resolution (1 × 1 × 2 mm) anatomic imaging of the entire brain.

Data analysis: Statistical parametric mapping (SPM99, Wellcome Department of Cognitive Neurology, London, UK) was used in the imaging preprocessing and the statistical analysis. This software is implemented in Matlab (Mathworks Inc. Sherborn, MA, USA). The main steps of imaging preprocessing included realignment, anatomic-functional image co-registration, normalization and spatial smoothing (8 mm FWHM Gaussian filter).

The general linear model was used to estimate the condition effect of individual subject. Boxcar convolved with HRF was selected as reference function. Individual results were acquired by defining four effects of interests (L1 minus baseline, L2 minus baseline, L1 minus L2, and L2 minus L1) for each subject with the relevant parameter estimates. The threshold for significant activation was $p < 0.05$ (multiple comparison corrected). The group averaging effects were computed with a random-effects model, a cluster with > 5 voxels activated above a threshold of $p < 0.0001$ (uncorrected) were considered as significant.

RESULTS

Behavior data: Correct ratio (CR) and reaction time (RT) were recorded while the children were performing the task. The participants were significantly more correct and faster at semantic decision in Chinese than in English (CR/RT: Chinese 0.89/1452 ms; English 0.71/1897 ms). Paired *t*-test revealed significant difference in the Chinese and English tasks for both CR ($t(11)=7.58$, $p < 0.0001$) and RT ($t(11)=-8.23$, $p < 0.0001$).

Imaging data: Group average data revealed a very similar neural network for Chinese and English semantic tasks (Table 1, Fig. 2). Most salient activation was found in the left inferior frontal gyrus (LIPC) (BA45). Other regions showing significant activation included bilateral fusiform gyrus (BA37/19), bilateral middle/inferior occipital gyrus (BA19/18), bilateral cingulate area (BA32) and several subcortical regions. In addition, there was significant activation in the left parietal lobule (BA7/40) in the English task.

A paired-sample *t*-test between Chinese and English tasks revealed no significant difference in the LIPC, or the fusiform cortex, the occipital cortex, and the subcortical region. Nevertheless, English tasks showed more activation in the anterior cingulate area (BA32), posterior cingulated area (BA29), and the left inferior parietal lobule (BA40). No single area was more intensively activated for L1 tasks compared to L2 tasks.

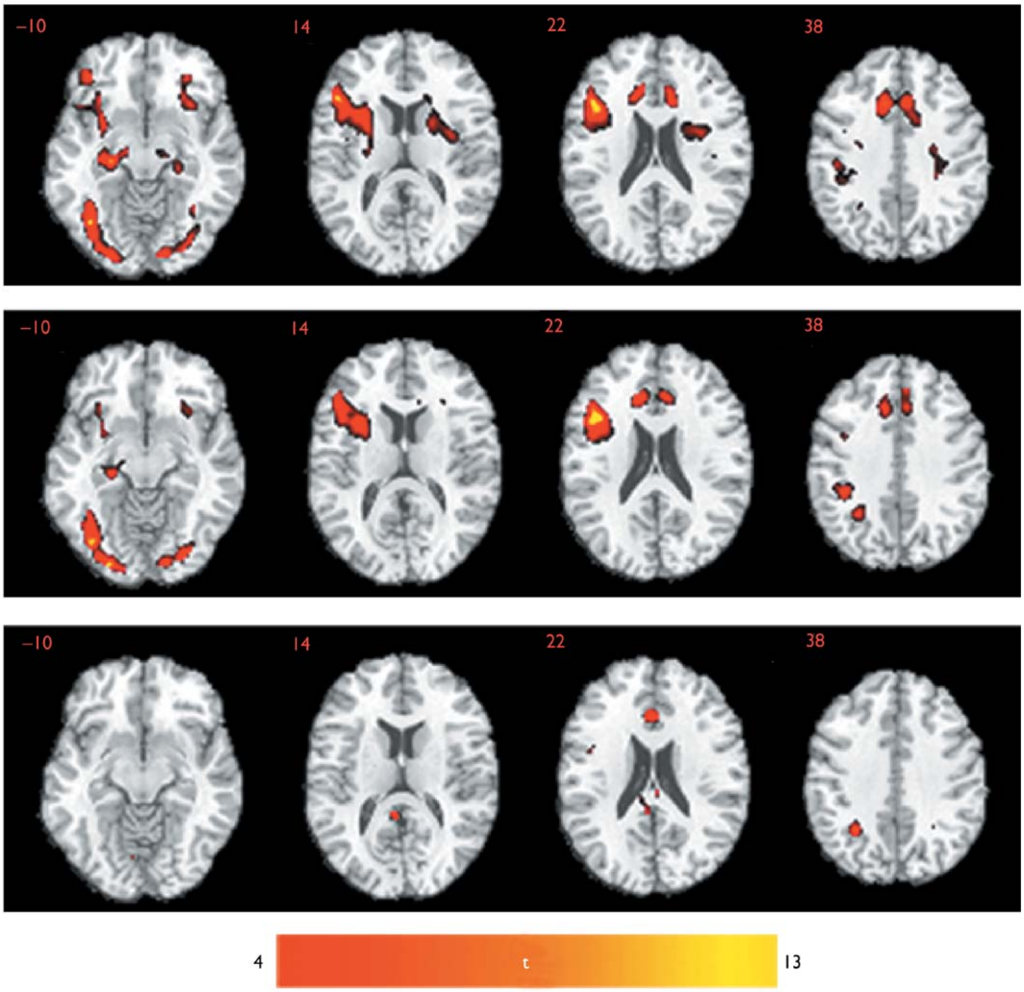

Fig. 2. Group averaged results for the semantic judgment of Chinese characters minus fixation (upper row), English words minus fixation (middle row) and English minus Chinese (bottom row). The activations are overlain on to difference slices of a single-subject template from the Montreal Neurological Institution, with the number on each slice indicating its distance (in mm) to origin according to MNI coordinate system.

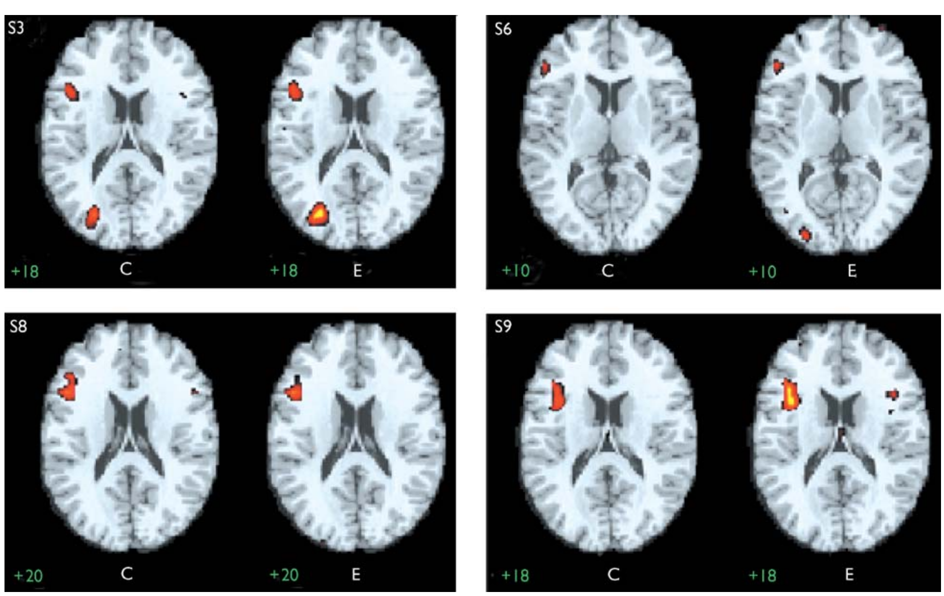

Fig. 3. Representative results from four subjects showing consistent and similar activation in the left prefrontal gyrus for semantic judgment task in Chinese and English. The images with a C or E in the bottom represent the result of Chinese task *vs* baseline and English *vs* baseline, respectively. See the legend of Fig. 2 for details on the template and slices number.

Individual results of the contrasts between the semantic task and baseline in Chinese and English are illustrated in Fig. 3. Among all the 12 subjects, 10 showed significant activation in LIPC for both Chinese and English. Direct comparison between Chinese and English indicated that only two subjects showed significant difference between the processing of the two languages in LIPC. These results are consistent with the group patterns.

DISCUSSION

The present fMRI study explored whether there was common and differential semantic processing in low proficiency Chinese learners of English. We found significant activation in the left inferior prefrontal cortex, the left parietal lobule, and the left fusiform cortex for both Chinese and English tasks. These results are consistent with the previous studies on visually-presented semantic decision tasks [1,4–8,12,17]. Specifically, the most robust activation was found in the LIPC both for Chinese and English semantic tasks. Direct comparison between the activation patterns of the two languages revealed no significant difference of cortical location in this region. This highly similar activation for L1 and L2 strongly suggests that there are shared neural substrates for semantic access in very low proficiency bilinguals.

Previous studies on proficient bilinguals have consistently indicated that the LIPC is commonly activated for L1 and L2 [4–8]. In Chee *et al.*'s study on relatively proficient bilinguals, the LIPC is also commonly activated for both L1 and L2, with no spatial distinction between the two languages [1]. The present results extend this finding to very low proficiency young second language learners, demonstrating that even when one is at a very low L2 proficiency level, the neural representation of the two languages does not differ from each other. Taken together, these brain imaging results provide converging evidence that a bilingual's two languages share a common semantic network [19].

Our results are consistent with the previous findings that L2 learners would rely on the existing conceptual system to construct the semantic representation of L2, and they use the same conceptual link from L1 to concepts to access the meaning of the two languages [14–16]. The present findings on low proficiency bilinguals, together with that on fluent bilinguals [1,4–8], suggest that there is only one conceptual system for bilinguals, irrespective of their proficiency levels in L2. Furthermore, it appears that the semantic processing of L1 and L2 is implemented by largely identical neural networks, although there may be different routes of semantic access in high and low proficiency bilinguals [15,16], which may cause differences in computation requirement.

Our findings are not consistent with two prior studies which found regions that were activated specifically for L1 [9,10]. This might be due to the fact that different aspects of bilingual process were examined in our study and those other studies, that is, semantic decision and auditor story comprehension, respectively. It is possible that the neural implementation of these processes is differentially affected by L2 proficiency and age of acquisition. For example, while it is indicated that when performing the inner story telling task, the age at which learners were first exposed to a second language would affect the cortical representation of the L2 [18], studies with semantic task revealed common activation for both early and late bilinguals [4,5,8]. The differential effect of age of acquisition on bilingual processing was clearly manifested in a direct examination on semantic and syntactic processing with early and late bilinguals [20,21]. Taken together, these studies suggest a divergent mechanism underlying L2 semantic, phonological, and syntactic processing, which are differentially affected by L2 proficiency and age of acquisition.

It is notable that in Chee *et al.*'s study [1], the intensity of LIPC activation is increased on tasks that required more reaction time. However, in the present study, though RT was also longer for L2 tasks, no significant difference was found in the activation in LIPC between L1 and L2. To address this discrepancy, we may refer to the theoretical framework developed by Kroll and Stewart [16], which suggests a direct conceptual link for high proficiency bilinguals, whereas a word-mediated, indirect link for low proficiency bilinguals (see Introduction). In Chee *et al.*'s study, the subjects were fluent bilinguals, though they showed relative different language proficiency in the two languages. Thus it is assumed that the semantic processing of the two languages could both be via a semantic link to concepts. As the link from concepts to the less proficient language is weaker than that to the more proficient one, it will increase the difficulty of semantic retrieve, and thus the increased activation in the LIPC. However, in the present study, since the subjects were very unskillful in L2, presumably they could only access the meaning of L2 by firstly translating it into the L1 equivalents via a lexical link. This inserted process, though it increased the reaction time, did not add any cognitive demand on semantic retrieve. Therefore, there was no difference between L1 and L2 in the activation of the left inferior frontal lobe.

This raises an important question to further clarify the role of task difficulty in modulating the neural activity in a given brain region. For example, it is indicated that the increase of task difficulty would not necessarily change the neural activation in the LIPC if it were caused by non-semantic task [17]. Our results, together with that of Chee *et al.* [1], demonstrate the dissociation of cognitive load (e.g. increased requirement on semantic retrieval) and task-specific process (e.g. insertion of non-semantic process) in regulating the LIPC activation, though both of them can be attributed to the increase of task difficulty, and thus the delay of reaction time. As task difficulty should be taken into consideration in research on less proficient bilinguals, a careful examination on the specific cognitive process may be of specific importance to explain the correlation of reaction time and neural activation in a given brain region.

The present study found greater activation in the left inferior parietal lobule and cingulate cortex for the English than for the Chinese tasks, which may be attributed to the generally increased computation requirement. More intensive parietal activation in participants' less proficient language is also found in Chee *et al.*'s study [1]. However, its involvement in semantic processing is less consistent and its exact role is still very obscure. By now, parietal activation has been found in some verbal tasks that may be relevant to semantic processing, such as verbal working memory [22], orthography to sound conversion [23], as well as many non-verbal tasks, including visual-spatial attention, grasping, and saccades [23,24]. Possibly, the parietal lobe is in charge of a variety of tasks that shared an abstract component of attention orienting [24]. Thus, the difference in parietal activation may lie in the fact that L2 needs more attention resource. This explanation may also apply to the difference in anterior cingulate cortex, which is more strongly activated in more difficult tasks [25].

Two main differences should be noted while comparing the present results to other studies on low proficient bilinguals. First, all participants in the present study were young children before puberty. The difference between adults and children in the cognitive and neural mechanism of semantic learning and process needs to be further addressed. Second, our participants are less skilled in L2 compared to those from most previous studies on less proficient bilinguals. Our results, together with previous studies with a similar paradigm on high and relative high proficient bilinguals, are likely to suggest that the neural contrast between L1 and L2 may not decrease in a linear fashion as the L2 learner become increasingly proficient. Therefore, a comprehensive examination on the cognitive change during L2 learning, as well as its impacts on the neural representation of bilinguals' two languages seems to be important. Furthermore, integrated information is needed to understand the mechanism of bilingual processing in the brain, including the exactly stage of second language learning (i.e. proficiency), age of acquisition, workload, performance, cognitive task, and the specific cognitive process under given second language developmental stage.

CONCLUSION

The present fMRI study aimed to examine the neural integration and/or separation of semantic access of poorly proficient bilinguals' two languages. The non-fluent Chinese learners of English, though performed slower and less accurate in the semantic decision task in English than in Chinese, showed very similar activation in the left prefrontal cortex for L1 (Chinese) and L2 (English). These results extend the body of evidence in the bilingual literature that, even for low proficiency bilinguals, there is a shared semantic system for L1 and L2 at single word level.

REFERENCES

1. Chee M, Hon N, Lee HL and Soon CS. Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *Neuroimage* **13**, 1155–1163 (2001).
2. Hasegawa M, Carpenter PA and Just MA. An fMRI study of bilingual sentence comprehension and workload. *Neuroimage* **15**, 647–660 (2002).
3. Perani D, Paulesu E, Sebastian Galles N, Dupoux E, Dehaene D, Bettinardi V *et al*. The bilingual brain: proficiency and age of acquisition of the second language. *Brain* **121**, 1841–1852 (1998).
4. Chee MW, Tan EW and Thiel T. Mandarin and English single word processing studied with functional magnetic resonance imaging. *J Neurosci* **19**, 3050–3056 (1999).
5. Illes J, Francis W, Desmond J, Gabrieli J, Glover G *et al*. Convergent cortical representation of semantic processing in bilinguals. *Brain Lang* **70**, 347–363 (1999).
6. Klein D, Miller B, Zatorre RJ, Meyer E and Evans AC. The neural substrates underlying word generation: a bilingual functional imaging study. *Proc Natl Acad Sci USA* **92**, 2899–2903 (1995).
7. Klein D, Milner B, Zatorre R, Zhao V and Nikelski J. Cerebral organization in bilinguals: a PET study of Chinese-English verb generation. *Neuroreport* **10**, 2841–2846 (1999).
8. Pu YL, Liu HL, Spinks JA, Mahankali S, Xiong JH, Feng CM *et al*. Cerebral hemodynamic response in Chinese (first) and English (second) language processing revealed by event-related functional MRI. *Magn Reson Imaging* **19**, 643–647 (2001).
9. Perani D, Dehaene S, Grassi F, Cohen L, Cappa S, Paulesu E *et al*. Brain processing of native and foreign languages. *Neuroreport* **7**, 2439–2444 (1996).
10. Dehaene S, Dupoux E, Mehler J, Cohen L, Paulescu E, Perani D *et al*. Anatomical variability in the cortical representation of first and second language. *Neuroreport* **8**, 3809–3815 (1997).
11. Just MA, Carpenter PA, Keller TA, Eddy WF and Thulborn KR. Brain activation modulated by sentence comprehension. *Science* **274**, 114–116 (1996).
12. Thompson-Schill SL, D'Esposito M, Aguirre GK and Farah MJ. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proc Natl Acad Sci USA* **94**, 14792–14797 (1997).
13. Rypma B, Prabhakaran V, Desmond JE, Glover GH and Gabrieli JD. Load-dependent roles of frontal brain regions in the maintenance of working memory. *Neuroimage* **9**, 216–226 (1999).
14. Chen HC. Lexical processing in a non-native language: effects of language proficiency and learning strategy. *Mem Cogn* **18**, 279–288 (1990).
15. Kroll JF and Sholl A. Lexical and conceptual memory in fluent and nonfluent bilinguals. In: Harris RJ (ed.). *Cognitive Processing in Bilinguals*. Amsterdam: Elsevier; 1992, pp. 191–203.
16. Kroll JF and Stewart E. Category interference in translation and picture naming: evidence for asymmetric connections between bilingual memory representations. *J Mem Lang* **33**, 149–174 (1994).
17. Demb JB, Desmond JE, Wagner AD, Vaidya CJ, Glover GH and Gabrieli JD. Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. *J Neurosci* **15**, 5870–5878 (1995).
18. Kim KH, Relkin NR, Lee KM and Hirsch J. Distinct cortical areas associated with native and second languages. *Nature* **388**, 171–174 (1997).
19. Francis WS. Cognitive integration of language and memory in bilinguals: semantic representation. *Psychol Bull* **125**, 193-222 (1999).
20. Weber-Fox C and Neville HJ. Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *J Cogn Neurosci* **8**, 231–256 (1996).
21. Wartenburger I, Heekeren HR, Abutalebi J, Cappa SF, Villringer A and Perani D. Early setting of grammatical processing in the bilingual brain. *Neuron* **37**, 159–170 (2003).
22. Jonides J, Schumacher EH, Smith EE, Koeppe RA, Awh E, Reuter-Lorenz PA *et al*. The role of parietal cortex in verbal working memory. *J Neurosci* **18**, 5026–5034 (1998).
23. Simon O, Mangin JF, Cohen L, Bihan DL and Dehaene S. Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. *Neuron* **33**, 475–487 (2002).
24. Wojciulik E and Kanwisher N. The generality of parietal involvement in visual attention. *Neuron* **23**, 747–764 (1999).
25. Carter CS, Braver TS, Barch DM, Botvinick MM, Noll D and Cohen JD. Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science* **280**, 747–749 (1998).

Acknowledgements: We greatly appreciate the helpful comments from the editor and anonymous reviewers on the earlier version of this paper. Also, we thank Professor Kewei Chen for his help in data analysis and draft preparation. This research is supported by the National Pan Deng Project (95-special-09).