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Cerebral organization in bilinguals: A PET study of Chinese-English verb generation

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POSITRON emission tomography (PET) was used to investigate cerebral organization in seven subjects who had Mandarin Chinese as their native language (L1), and learned English (L2) later in life. When activation from word repetition was subtracted from verb generation in L1 and L2, CBF increases were observed for both languages in left inferior frontal, dorsolateral frontal, temporal and parietal cortices, and right cerebellum. Direct comparison of the difference between verb generation and word repetition in L1 and L2 revealed no significant differences. Within-subject analysis of verb generation minus word repetition yielded CBF increases in left frontal cortex for all individuals for L1 and L2, and a comparison of differences yielded no spatial separation in frontal peaks. We argue for shared neural substrates even for such contrasting languages as Mandarin and English. *NeuroReport* 10:2841–2846 © 1999 Lippincott Williams & Wilkins.

Key words: Bilingualism; Cerebral blood flow; Language; PET; Speech

Introduction

The precise factors that may influence cerebral organization in bilingual individuals have still to be elucidated. A strong body of evidence exists to suggest a common cortical representation for native and second languages (L1 and L2, respectively) [1,2], but interhemispheric [3] and intrahemispheric [4] differences have also been reported. In recent years, functional neuroimaging has been applied to the study of bilingual individuals with a view to finding the factors that may influence cerebral organization in the two languages. In a PET study of word generation in native speakers of English who were also proficient in French, Klein *et al.* [5] observed overlap between L1 and L2 in the left inferior frontal cortex. Using fMRI, Kim *et al.* [6] argued for spatial separation of L1 and L2 within area 44 of the left frontal cortex when the second language is acquired in adulthood, but not when both languages are acquired early. Other neuroimaging studies have failed to find this difference [7,8], and some have suggested that attained proficiency and fluency may be more important than age of acquisition as determinants of the cortical representation of L2 [9,10].

Thus far, the debate has focused mainly on comparisons of bilingual subjects who speak Indo-European languages, where one might argue that the observed overlap between L1 and L2 is due to the fact that the languages sampled have similar structural properties. It seems reasonable to suppose that, the greater the differences between first and second languages, the more likely it is that the cerebral representation of the second language may differ from that of the native language [11]. From this standpoint, the cerebral representation of Chinese may be different from that of English, because these two languages differ completely in syntax, morphology and phonology [12]. In support of this notion, differential localization has been found when Oriental languages have been compared with English in intraoperative cortical stimulation mapping studies [13]. However, even in speakers of tone languages recent neuroimaging experiments have demonstrated CBF increases in regions that would be predicted on the basis of work with Indo-European languages. For example, CBF increases were observed in the left frontal operculum in a study of linguistic tone in Thai and Chinese speakers [14]. More recently, an fMRI study of early and late Mandarin-English bilinguals, using a visually cued word-generation task, showed similar patterns of cortical activation in the left prefrontal region for Mandarin and English, irrespective of age of acquisition of either language [8].

In the present study, we examined performance in bilingual Mandarin-English speakers to test the hypothesis that even such a distinct language as Chinese would recruit areas similar to those found with non-tonal Indo-European languages. We examined the patterns of CBF change using a lexical search and retrieval paradigm, with auditory input of stimuli and spoken output. Although a visual presentation of stimuli might have obviated processing differences arising from language-specific auditory segmentation of spoken words [8], Mandarin differs from English in its specified use of pitch and tone. Since there is evidence that segmentation of speech sounds occurs according to templates built during initial exposure to spoken words [15], it was hypothesized that our choice of the auditory modality would maximize the possibility of observing CBF differences between L1 and L2.

If language diversity has no influence on language organization in the brain, then even in languages that are acoustically as different as Mandarin and English, both L1 and L2 should be mediated by the same brain regions, and we should observe similar CBF patterns for tasks requiring lexical search and retrieval in Chinese as have been observed for other languages. If cerebral organization is influenced by language specificity, then we should see differences between patterns of CBF activation for L1 and L2. Furthermore, one might expect that bilingual subjects who acquire their L2 in early adulthood, should show a greater likelihood for differential organization for the two languages if any are indeed to be observed.

Materials and Methods

Subjects: After a proficiency interview and several prescreening tests, four subjects were rejected and seven right-handed volunteers (four male; three female) between the ages of 19 and 45 (mean age 29 years) who were in good health, under no medication, and who had no history of neurological disorder were chosen for the study. All were native speakers of Chinese (Mandarin) who had acquired their L2 (English) in adolescence (mean age at first exposure 12.1 years; range 10–14 years). All subjects first learned English in school with a formal method of instruction and consequently the acquisition conditions for L2 were clearly distinct from those for L1. They were currently students at an English-speaking university and prescreening required them to be relatively fluent in both languages. They were asked to describe different pictures in L1 and L2, and their fluency (number of sentences produced and errors per sentence) was rated by a linguist. On the WAIS-R vocabulary subtest (administered in English), the subjects' scaled scores ranged from 6 to 11, but all subjects chosen scored $\geqslant 90\%$ correct on four different tasks requiring verb generation in L1 and L2 and translation from L1 to L2, and *vice versa*. The subjects gave informed consent to undergo PET scanning, which was performed according to institution-reviewed medico-ethical guidelines.

Procedure: In our previous bilingual study [5], synonym generation tasks in both L1 and L2 were found to activate left ventrolateral frontal cortex. However, careful analysis of the linguistic structure of Mandarin Chinese led us to conclude that the use of synonyms would be inappropriate in this case. Most Mandarin words are compounds, and synonyms usually share aspects of the target word. Moreover, in a pilot study, which evaluated accuracy and latency of responses when Mandarin speakers generated synonyms in Mandarin and in English, it took even longer for these L1 Mandarin speakers to generate synonyms in their L1 than in their L2. In contrast, it became apparent that we could make use of a noun–verb generation task for both languages because the lists could easily be matched for difficulty and latency in producing the responses. Data from published studies of noun–verb generation [16] indicate that similar patterns of CBF increase are to be predicted for the noun–verb generation task as we have previously observed for synonym generation [5]. Thus, the task conditions consisted of repeating words in Mandarin (L1 REP); repeating words in English (L2 REP); generating a verb for a noun in Mandarin (L1 GEN); and generating a verb for a noun in English (L2 GEN). In each 60 s PET scan, subjects were presented with 22 different stimulus items at the rate of one word every 4.2 s. The task was initiated 10 s in advance of each scan, and continued until after the scan had finished. Each condition was repeated twice, but with different stimuli. The stimuli were matched item by item across each of seven lists on a range of psycholinguistic variables (length, syllable number, frequency and part of speech). The same number of compound words were chosen for the English and Mandarin lists.

In each experimental task, the input was presented binaurally through insert earphones (Eartone 3A), and the subject was required to produce a spoken response. Sensory input and motor output were similar in all conditions, since they involved listening to a single word and producing a single spoken response. To familiarize subjects with each task, subjects were presented with 10 practice items before each scan. A new stimulus list was used for each scan. Stimulus order was fixed, but the order of presentation of the conditions was counterbalanced across subjects. The lights were dimmed for the duration of the scan and subjects were instructed to keep their eyes closed. Latency and accuracy of response were recorded.

PET scanning: PET scans were obtained with a Siemens Exact HR+ tomograph operating in three-dimensional acquisition mode. The distribution of CBF was measured during each 60 s scan using the H_2O^{15} water bolus method. T1-weighted structural MRI scans (160 1 mm slices) were also obtained for each subject with a 1.5 T Phillips ACS system to provide anatomical detail. CBF images were reconstructed using a 14 mm Hanning filter, normalized for differences in global CBF, and co-registered with the individual MRI data [17]. Each matched MRI/PET data set was then linearly resampled into the standardized stereotaxic coordinate system of Talairach and Tournoux [18] via an automated feature-matching algorithm [19].

Statistical analyses: PET images were averaged across subjects for each condition and the mean change image-volume obtained for each comparison; this volume was converted to a t-statistic map, and the significance of focal CBF changes was assessed by a method based on three-dimensional Gaussian random-field theory [20]. The presence of significant changes in CBF was first established on the basis of an exploratory search, for which the t-value criterion was set at $\geqslant 3.53$. This value corresponds to an uncorrected p value of 0.0004 (two-tailed), and results in an average of 0.58 false positives per search volume of 182 resolution elements (dimensions of $14 \times 14 \times 14$ mm), corresponding approximately to the volume of gray matter scanned. For the left inferior frontal region, where activity had been predicted based on previous findings, the threshold was lowered to $t = 3.0$.

For the group analyses, the mean of 14 scans was used for each subtraction, except for noun–verb generation in L2 where one subject was excluded from the analysis because of computer registration failure in the scanner. We were unable to repeat this scan owing to radiation safety limitations for the volunteer. In order to study the activation patterns in individuals we used intra-subject averaging by taking the average of the two repetition conditions and subtracting it from the average of the two generation conditions, and then the subtractions for each language were directly compared to each other.

Results

Performance measures: There were no differences in accuracy or latency of response to the two language lists for repetition (percentage correct/ms: Mandarin 99.5/1162; English 96.8/1229), but subjects were significantly slower and less accurate at generating verbs in L2 than in L1 (percentage correct/ms: Mandarin 92.3/1724; English 80.9/1836; $p < 0.01$).

PET findings: Regions of significant CBF increase are shown in Table 1. Overall there were similar configurations of CBF visible across tasks (Fig. 1). We observed a series of distinct foci in the left ventrolateral frontal cortex, and in the immediately adjacent posterior dorsolateral and medial frontal cortex in each of the word generation tasks, compared with the appropriate baseline repetition task (foci A, Table 1). There was considerable overlap in the frontal activations observed, irrespective of whether the generation involved L1 or L2. The peak locations are somewhat different, but to test the hypothesis that the areas active represented different anatomical substrates we compared the two languages directly against one another. Direct comparison of L1 and L2 [(L1 verb generation−L1 repeat)−(L2 verb generation−L2 repeat)] ruled out any apparent differences in blood flow in the regions observed in Table 1.

For both L1 and L2, when word repetition was subtracted from verb generation, CBF increases were also observed in the left medial temporal region, left parietal cortex and right cerebellum (foci B, C and E, Table 1).

Patterns of CBF changes were also examined for each subject within the group in order to determine to what extent between-language differences were manifest in the individual activation patterns. We focused our attention on the left frontal region because this is where the most robust activations have been observed in the group data for several studies, using either synonym generation or verb generation tasks [5,16]. Moreover, differences in the cortical organization of early and late bilinguals have been reported in the frontal but not in the temporal region [6]. In the present study, intra-subject analyses consistently yielded CBF increases in the left frontal cortex in L1 and L2 for all individuals, when word repetition was subtracted from verb generation. The individual analyses pointed to considerable inter-subject variability, but certain commonalities emerged. In all subjects, several increases in the left frontal cortex (ventrolateral, dorsolateral and medial) were observed in both L1 and L2, suggesting the strong participatory role of these left frontal regions in word generation in both English and Chinese, in accord with the group data. When the t-value criterion was set at $\geqslant 3.53$ direct comparison of the subtractions for L1 and L2 in each individual failed to reveal any spatial separation of L1 and L2 within the left frontal cortex. Furthermore, even with a lowering of the threshold to a value of $t = 2.0$, only a single instance of CBF change could be observed

Table 1. Blood flow increases: verb generation minus word repetition

Region	Subtraction	Coordinates (mm)			t-value
		X	Y	Z	
A: Left frontal					
Ventrolateral	L1 GEN–L1 REP	–46	34	8	7.96
	L2 GEN–L2 REP	–40	49	0	5.51
Dorsolateral	L1 GEN–L1 REP	–46	27	23	7.83
	L1 GEN–L1 REP	–44	18	33	7.51
	L2 GEN–L2 REP	–38	17	38	6.22
	L2 GEN–L2 REP	–33	6	59	5.99
Medial	L1 GEN–L1 REP	0	24	47	8.63
	L2 GEN–L2 REP	–1	12	59	6.25
	L2 GEN–L2 REP	–4	25	47	5.72
B: Left temporal					
Medial	L1 GEN–L1 REP	–52	–40	–2	5.27
	L2 GEN–L2 REP	–59	–49	–8	3.84
C: Left parietal					
Superior	L1 GEN–L1 REP	–27	–62	47	4.92
	L2 GEN–L2 REP	–35	–64	48	4.00
D: Right occipital					
	L1 GEN–L1 REP	4	–87	11	4.61
E: Right cerebellum					
	L1 GEN–L1 REP	36	–69	–23	4.05
	L2 GEN–L2 REP	29	–73	–24	3.61
	L1 GEN–L1 REP	7	–83	–21	4.83
	L2 GEN–L2 REP	7	–78	–23	5.68
F: Right cingulate					
	L1 GEN–L1 REP	9	30	27	4.45
G: Brain stem					
	L2 GEN–L2 REP	–3	–35	–20	3.71

Activation foci in this table represent peaks of statistically significant increases in normalized CBF (see Materials and Methods). The stereotaxic coordinates are expressed in mm: X, medial to lateral distance relative to the midline (positive = right); Y, anterior–posterior distance relative to the anterior commissure (positive = anterior); Z, superior–inferior distance relative to the anterior commissure line (positive = superior).

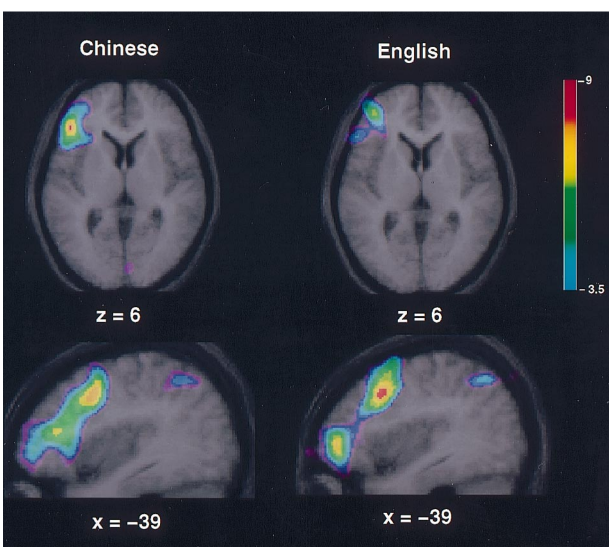

FIG. 1. Averaged PET subtraction image of CBF increases in the left frontal cortex for seven subjects, superimposed upon the seven averaged MRI volumes for the subtraction of word repetition from verb generation for L1 and L2 respectively. In general, similar regions are active for the two languages. The horizontal slices (above) show the left ventrolateral frontal peaks and the sagittal images (below) illustrate the left ventrolateral, dorsolateral and medial frontal peaks. Images were chosen at the same level across the two languages for comparison (See Table 1 for coordinates and t-values).

in the left inferior frontal cortex (x,y,z: –42,17,6; t = 2.5) when L2 was subtracted from L1. The likelihood that this change is in fact a false positive cannot be ruled out owing to the low t-value.

Discussion

In this study, which examined the influence of linguistic structure on CBF patterns in Mandarin-English bilingual volunteers when they performed a word generation task, overall the pattern of CBF increases seen in response to L1 (Mandarin) was strikingly similar to that seen for L2 (English). Moreover, these CBF patterns of activation for both Mandarin and English were similar to what we have observed for English and French [5] and what has been observed by others for a visual stem completion task in Mandarin-English bilinguals [8]. This similarity for L1 and L2 was noted in spite of differences in success in word generation or latency to respond, supporting our predictions for similar cerebral representation in the two languages. It should be emphasized, however, that spatially overlapping networks to process L1 and L2 should not be equated with degree of competence or performance skills. In our data we do obtain significantly different behavioural scores for performance accuracy and latency in generating words in L1 relative to L2, despite the observation of overlapping brain regions for L1 and L2.

Our data find support from all the neuroimaging studies that addressed the question of bilingual cerebral representation using a single word paradigm and that required a measurable behavioural response [5,7,8]. Moreover, in all of these studies, homogeneous groups of bilinguals were tested, even though across studies the languages sampled were diverse (English, French, Italian, Spanish, Mandarin). Looking at both the group and the individual data, we failed to find support for the notion that languages acquired later in life are represented differently from languages acquired in infancy [6]. Although the intrinsic resolution of fMRI may be higher than that of PET, with current methods available, it is possible with PET to detect functional zones separated by < 3 mm (centre to centre) even with a spatial resolution of 18 mm [21]. Moreover, in the study of Kim *et al.* [6] subjects were engaged in a covert descriptive language task, making it difficult to know whether the CBF increases observed were indeed directly related to the processing demands of the task.

It has often been postulated that there is a critical period for normal language acquisition [22]. Several behavioural studies examining the effects of delays in primary and secondary language acquisition have lent support to the idea that the ultimate proficiency attained for various linguistic skills depends in part on the age of first exposure to the language [23]. It has also been suggested that functional specialization for grammatical processing may be more sensitive to the timing of exposure to a language than is semantic processing [23]. Since the acquisition of vocabulary appears to be least vulnerable to delays in exposure, it may be that this distinction is reflected in our findings, since we addressed the issue of CBF differences between L1 and L2 at the single word level. However, strikingly similar patterns of activation have been shown for L1 and L2 in English-Italian and in Catalan-Spanish high proficiency bilinguals in a PET study requiring the auditory processing of stories [9].

Aside from the frontal activations, several other brain regions similar to those reported previously [5] were observed for both languages (left temporal and parietal regions as well as right cerebellum), suggesting that these regions contribute to the cognitive processes associated with verb generation and are implicated in both L1 and L2 processing in a similar manner. Our results confirm and extend the body of literature suggesting that the left inferior frontal cortex acts in conjunction with multiple distributed regions to accomplish the processing demands required by lexical search and retrieval. The findings also suggest that this constellation of regions predicted from previous studies can now be extended to non-Indo-European languages, and points to the existence of a common network of brain regions involved in lexical search and retrieval, at least at the single word level.

In our previous study a strong CBF increase was noted in the left putamen whenever the subjects were required to produce a spoken response in their L2 [5,24]. In the present investigation no increase in CBF in the left putamen was noted, even though subjects had strong foreign accents in their L2. We are thus unable to tease apart the putative role of left putaminal involvement in articulatory processing. One possibility for the absence of an effect here may simply be that this difference is due to language-specific effects; but the difference might also be attributed to the fact that the majority of responses required in this study were mono- or bi-syllabic, whereas in our previous study [24], the majority of responses were bi- or multi-syllabic, and therefore made greater demands on articulatory control. For example, in our previous study of English-French bilinguals, the list of L2 (French) words for repetition had 1.4 times more syllables than the list of L2 (English) words for repetition in the present study. In the study by Klein *et al.* [5,24], out of a list of 22 words, there were a total of 54 syllables to be repeated, whereas in the present study, out of the list of 22 words, there were only 39 syllables. Future research will be needed to examine the effect of number of syllables on motor timing for speech output and on the corresponding brain regions implicated in such processes.

Conclusion

Our findings support the hypothesis that common cortical areas are activated during a lexical search task involving single words in Mandarin and English, in fluent bilinguals who use both languages in daily life. We do show that lexical search utilizes common cortical areas within the left frontal, parietal and temporal cortex for L1 and L2, consistent with the prediction that similar brain regions are active even when languages are distinct, and even when the L2 is acquired later in life.

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