

Phonological processing in Chinese–English bilingual biscriptals: An fMRI study

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Different activation loci have been reported for language processing in unilingual Chinese and unilingual English participants, as well as in bilingual readers of English and French, two alphabetic languages. Nevertheless, the extant imaging work on Mandarin–English bilinguals favors *common* neural substrates for English and Chinese, languages with contrasting oral and written forms. We investigated the phonological processes in reading for English–Chinese biscriptals using a homophone matching task with parallel behavioral ($n = 28$) and fMRI ($n = 6$) experiments. Unlike previous reports, we observed distinct regions of activation for Mandarin in the left and right frontal lobes, the left temporal lobe, and the right occipital lobe, plus distinct regions of activation for English bilaterally in both the frontal and parietal lobes. The implications of these novel findings are discussed with reference to language representation in bilinguals.

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Introduction

Imaging research with healthy bilinguals has focused on trying to elucidate whether similar, or spatially segregated, neural substrates subservise two languages (see Vaid and Hull, 2002 for a review). While some studies provide evidence for anatomically separate mental lexicons (e.g., Dehaene et al., 1997, on English–French bilinguals; Kim et al., 1997, on English–French bilinguals; Yetkin et al., 1996, on a variety of English-knowing bilinguals), others have shown common regions of activation for both languages (e.g., Illes et al., 1999, on English–French bilinguals). To date, neuroimaging experiments involving *English–Chinese bilinguals* favor the view that English and Mandarin have common neural substrates (Chee et al., 1999a,b, 2000; Klein et al., 1999; Lee et al., 2004). This is rather surprising because English and Mandarin differ markedly in at least two levels of language processing. First, at the orthographic level, the scripts of English and Mandarin are visually

distinct and derive from different types of writing systems, alphabetic and logographic, respectively. Second, at the phonological level, Mandarin is a morpho-syllabic *tonal* language while English is not. This means that, when readers are asked to match pairs of stimuli for phonology, lexical tone as well as syllable phonology must be addressed or computed for Chinese characters.

In this paper, we describe parallel behavioral and fMRI experiments with skilled bilingual biscriptals, designed to investigate whether this expected disparity for phonological processing in English and Mandarin results in differential activation at the neural level.

Neuroanatomical representation of English phonology

Phonological processing has been studied with tasks that require the perception and evaluation of the sound structure of words and letters (Joseph et al., 2001). These have included rhyme judgements (e.g., Paulesu et al., 1996; Petersen et al., 1989; Pugh et al., 1996; Sergent et al., 1992), passive word listening (e.g., Binder et al., 1994; Price et al., 1996; Warburton et al., 1996), phonological monitoring (e.g., Demonet et al., 1992, 1994), and nonword reading (e.g., Herbster et al., 1997; Rumsey et al., 1997). The activation loci observed when unilinguals perform these phonological tasks vary considerably because a wide range of experimental paradigms have been employed. Nevertheless, the brain regions frequently reported include the left inferior frontal gyrus (BA 44, 45) (e.g., Herbster et al., 1997; Paulesu et al., 1993; Rumsey et al., 1997; Sergent et al., 1992; Zatorre et al., 1992), the inferior parietal regions, such as the supramarginal gyrus (BA 40) and the angular gyrus (BA 39), (e.g., Demonet et al., 1994; Paulesu et al., 1993; Petersen et al., 1988; Rumsey et al., 1997; Zatorre et al., 1992), as well as the left superior temporal lobe (e.g., Demonet et al., 1992; Fiez et al., 1995; Paulesu et al., 1996; Pugh et al., 1996; Sergent et al., 1992).

Neuroanatomical representation of Mandarin phonology

There is much less work on the neuroanatomical representation of Mandarin phonology, but two papers are relevant. First, Tan et al.

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(2001) used a homophone decision task to investigate the neural correlates of Mandarin phonology in unilinguals. Relative to fixation, the investigators reported peak activation in the left middle frontal gyrus (BA 9) but other brain regions activated included the bilateral infero-middle prefrontal cortex (BAs 44/45 and 47/10), left medial prefrontal lobe (BA 11), bilateral precentral (motor) gyri (BAs 4 and 6), bilateral superior parietal lobule (BA 7), left post-central gyrus (BA 3), bilateral middle temporal lobes (BAs 21 and 22), and right precuneus (BA 39). In the occipital–temporal regions, significant activations were observed bilaterally in the cuneus (BA 17/18), the extrastriate cortex covering the left inferior gyrus (BA 18), and the right fusiform and lingual gyri (BAs 18 and 19).

Second, Klein et al. (2001) compared tone perception in native Mandarin speakers with that of native English speakers by using PET. Participants were scanned under two conditions: a silent resting baseline and a tonal task involving discrimination of pitch patterns in Mandarin. Although both groups showed common regions of cerebral blood flow (CBF) increase, there were hemispheric differences between the two groups: CBF changes observed *only* for the Mandarin speakers were all in the *left* hemisphere (ventromedial orbital frontal cortex, frontopolar cortex, pre- and postcentral gyri, inferior and superior parietal cortex, and in the lateral occipital–temporal and middle occipital gyri), whereas CBF changes observed *only* for the English speakers were in the *right* hemisphere (ventrolateral frontal cortex, anterior orbitofrontal gyrus, lateral orbital gyrus, cingulate region, and the superior temporal gyrus). Furthermore, only the native English speakers showed activity in the right inferior frontal cortex. Klein et al. suggested that the left lateralization for Mandarin might be explained by the fact that tones were meaningful only to the Mandarin speakers (see Hsieh et al., 2001; Van Lancker and Fromkin, 1973 for similar results).

Neuroanatomical representation of English vs. Mandarin phonology

Previous research suggests that the brain regions activated by the phonological processing of English words are located mainly in the *left* hemisphere. More specifically, the *left* superior temporal regions have been identified as subserving fine-grained phonemic analysis (i.e., letter-to-sound conversion, see Simos et al., 2000; 2002). By contrast, Tan et al. (2001) found bilateral activations in the Mandarin homophone decision task. The most notable difference was that a set of right hemisphere cortical regions (i.e., the frontal pole (BA 10/11), frontal operculum (BA 45/47), dorsolateral frontal gyrus (BA 9/44), and the superior and inferior parietal lobules (BA 7, 39/40)) was observed to mediate homophonic judgments. Tan et al. attributed their results to memory processes. More specifically, they suggested that the right prefrontal regions subserve episodic memory processes whereby the spatial features of perceived objects are retrieved (see also Haxby et al., 1996; Kapur, et al., 1995; Lepage et al., 2000; Nyberg et al., 1996), while the right superior and inferior parietal lobes subserve spatial working memory tasks (e.g., Courtney et al., 1998; Haxby et al., 1995; Jonides et al., 1993; McCarthy et al., 1994). Given that episodic memory retrieval refers to the “search, access, and monitoring of stored information about experienced past events, as well as to the sustained mental set underlying these processes” (Cabeza and Nyberg, 2000, p. 26), Tan et al. went on to argue that the right prefrontal and parietal regions might be involved in perceiving the spatial locations of strokes in Chinese characters, but for lexical tone, Mandarin readers recruit the left cortical areas, while English readers recruit the right cortical regions for suprasegmental (tone) information.

We expected differences in fMRI activation for English words and Chinese characters related to phonological processing because the oral and written forms of these two languages are well-contrasted. The phonology for English words can be accessed lexically or assembled non-lexically from the constituent graphemes (letters and letter combinations), but, for Chinese characters, the orthography–phonology relationship is at the morpheme level, and lexical–semantic access is obligatory for correct tone identification. Like Tan et al. (2001), we used a homophone matching task to investigate aspects of phoneme/syllable and tone processing. This task requires participants to judge if character pairs presented in Mandarin have exactly the same phonology (same syllable/same tone). As reading in Mandarin requires the additional processing of tonal information, the Mandarin task might elicit more distinct and/or greater cortical activation in some brain regions than English.

Methods

Participants

Volunteers were first screened behaviorally for language abilities using the Language Background Questionnaire (Rickard Liow and Poon, 1998) and a battery of paper and pencil language proficiency tests. There were three criteria for inclusion in this study: (a) minimum of 70% accuracy for language screening tests such as pinyin transcription with tone assignment and lexical decision; (b) right-handedness based on self-report; and (c) no known history of neurological impairment. A total of 28 right-handed early bilinguals (three males) aged 18 to 23 years, with exposure to Mandarin and English before 5 years of age, met these criteria and took part in the behavioral experiment. A subset of six (three males) of these participants subsequently took part in the fMRI experiment.

Materials

It is virtually impossible to equate Chinese characters and English words fully. Regional differences in pronunciation and pedagogical methods also preclude an objective categorization of Chinese characters (see Rickard Liow et al., 1999 for further details). We decided to sample relatively high frequency stimuli for each language and ensure a representative mix of words/characters.

English homophone matching (HM) task

The stimuli were selected from the PALPA battery (Kay et al., 1992) and consisted of pairs of regular words (e.g., weigh–way), exception words (e.g., bury–berry), and nonwords (e.g., zole–zoal). The use of these three different pair types makes it more likely that both the lexical route (exception and regular words) and the non-lexical route (nonwords and regular words) would be activated during processing. The ‘no’ trials comprised of distractor pairs that are not homophonic but matched closely to the target pairs.

Mandarin homophone matching (HM) task

We expected regularity to affect Chinese reading so the phonology participants required for the experimental trials (24 same pairs and 24 different pairs) was only predictable for a few of the 96 characters (3%). All the characters were relative high

frequency (Loo, 1989 for local norms), making lexical–semantic processing more likely. (See Appendix A for character pairs with hanyu pinyin and phonetic radical phonology.)

Procedures

The procedures for the behavioral and fMRI experiments were kept as similar as possible. Each participant gave informed consent and received token payment upon completion of each experiment.

Behavioral experiment

The fMRI participants were a subset of the participants for the behavioral experiment, so we ensured a minimum gap of 2 weeks between the two phases to limit practice effects. In both the behavioral and fMRI experiments, trials were blocked by language, but order of language (Mandarin or English) was counterbalanced across participants. All stimuli were typed in black (words in lower case) and centrally presented on a white screen (subtended angle: 2° at 40 cm). For both experiments and both languages, a practice block of 10 stimulus trials was followed by 4 blocks of 15 trials with each stimulus lasting 1975 ms. For each language, half the trials were “yes”, and no performance feedback was given.

fMRI experiment

Imaging was performed on a 1.5 T whole-body magnetic resonance imaging (MRI) scanner (Siemens Vision; Erlangen, Germany). Prior to imaging, participants were briefed on the scanning procedures and experimental conditions so as to minimize anxiety and enhance performance. Participants were asked to lie supine inside the MRI scanner with their heads inside a standard head coil. Head movement was minimized within the coil using foam wedges, and a restraining band was placed across the forehead. Participants were also fitted with headphones (MSI™, Tampa, Florida) that attenuated ambient scanner noise by 30 dB and provided a means of conveying the experimenter’s instructions.

The presentation of written words and characters was controlled by Eprime software running on an IBM-compatible computer located outside the scanning room. Using a block design, each run consisted of four periods of the same language task (i.e., activation condition with homophone task), interleaved with four periods of fixation (i.e., baseline condition with fixation “+”, presented for 30 s (see Fig. 1).

All stimuli were back-projected via a high-resolution LCD projector (MSI™, Tampa, Florida) onto an opaque screen positioned at the head end of the bore, with an especially designed mirror mounted on the head coil for viewing. For the activation periods, participants were asked to respond to the words and characters by pressing “yes” (right hand) if the stimuli sound alike or “no” (left hand) if the stimuli sound different. For the fixation (baseline) periods, participants were instructed to focus their entire attention on a fixation point (“+” sign) shown on the middle of the screen.

MRI image acquisition

Tri-planar scout images in the sagittal plane and T1-weighted 3D coronal anatomical images (MPRAGE sequence) were acquired (TR = 9.7 ms, TE = 4.0 ms, FOV = 240 × 240 mm, matrix = 256 × 256, thickness = 1.0 mm, voxel size = 0.94 × 0.94 × 1.00 mm).

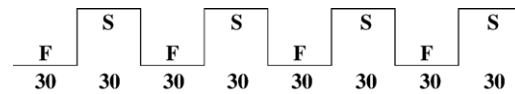


Fig. 1. Diagrammatic representation of the experimental paradigm in each run. Alternating blocks of fixation (F) and stimuli (S), each lasting 30 s, were presented.

These high-resolution images of the entire brain served as structural scans for Talairach transformation. Functional images were then obtained with a T2*-weighted gradient echo, echo planar imaging (EPI) sequence, 10 contiguous oblique axial 8 mm slices, TR/TE/θ = 3000 ms/66 ms/90°, FOV = 190 × 190 mm and acquisition matrix = 128 × 128, voxel size = 1.5 × 1.5 × 8.0 mm) with blood oxygen level-dependent (BOLD) contrast. For each of 10 slices, 800 images were acquired in 237 s with a 1 s cue, i.e., “!”, prior to the first trial.

fMRI and statistical analyses

The fMRI data were analyzed using the Statistical Parametric Mapping (SPM2) software developed by Friston et al., (1995a). The first five scans (15 s) in each session (during which magnetization steady state was being reached) were excluded from the data analysis. All functional images were first corrected for movement using least-squares minimization (Friston et al., 1995b) and then co-registered to the subjects 3D T1-weighted image. Using the 3D image as a guide, the functional images were subsequently spatially normalized into the SPM standard space. Images were then re-sampled every 2 mm using sinc interpolation and smoothed with a FWHM 10 mm, 3D Gaussian kernel to decrease spatial noise.

Changes in blood oxygenation level-dependent (BOLD) contrast associated with the performance of the reading tasks were assessed on a pixel-by-pixel basis, using the general linear model (Friston et al., 1995a,b) and the theory of Gaussian fields (Worsley and Friston, 1995) as implemented in SPM2. This method takes advantage of multivariate regression analysis and corrects for temporal and spatial autocorrelations in the fMRI data. Group analyses were investigated using fixed-effect analysis (FFX) (recommended by Friston et al., 1999a), which infers “typical” characteristics about the sample of participants. Each language effect was tested by applying appropriate linear contrast, and significant hemodynamic changes for each contrast were assessed using the *t* statistical parametric maps. We report activations below a threshold of $P < 0.05$ corrected for multiple comparison using false discovery rate (FDR) (Genovese et al., 2002).

To identify the locations of the significant activations, we referred to the single-subject MRI anatomical atlas developed by the ICBM consortium (see <http://www.loni.ucla.edu/ICBM>). We normalized the pre-labeled high-resolution (0.5 mm isotropic) atlas using the same transformation as our MR images and from this we inferred the MNI coordinates and the region labels. Talairach coordinates are not given, but interested readers can estimate these using routines developed by Matthew Brett (<http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml>).

Results

Behavioral experiment

The reaction times (RTs) for correct responses and the error rates (%) for the main behavioral experiment ($N = 28$),

including the subset of 6 fMRI participants, were English: $M = 1308.66$ ms (SD = 105.5), 15.12% (SD = 5.27); Mandarin: $M = 1589.76$ ms, SD = 193.08, 21.28%. The equivalent mean values for the subset of fMRI ($n = 6$) participants were comparable, English: $M = 1259.24$ ms, 13.61%; Mandarin: $M = 1644.35$ ms, 24.65%, and well above chance. Response times for the Mandarin task were significantly longer than those for the English homophone judgment [$t_{27} = 7.94$, $P_{\text{adjusted}} < 0.05$], and participants also made more errors for Mandarin [$t_{27} = 3.58$, $P_{\text{adjusted}} < 0.05$].

fMRI experiment

As predicted, distinct and common brain regions were activated during the English and Mandarin HM tasks (see Table 1 and Figs. 2–5).

Note that the common brain regions activated by both tasks included the left inferior frontal gyrus (BA 46) and left inferior occipital gyrus (BAs 17 and 18). However, in view of the previous work suggesting no differences between Chinese and English, the aim of our study was to identify any distinct areas of activation. For the Mandarin task, distinct brain regions were observed in the medial frontal gyrus, anterior cingulate cortex (BA 32), fusiform gyrus (BA 37), and lateral cerebellum in the *left* hemisphere, and the superior frontal gyrus (BA 8), anterior cingulate cortex (BA 32), inferior occipital gyrus (BA 19), and cuneus (BA 17) in the *right* hemisphere. For the English task, distinct brain regions were observed in the primary motor cortex (BA 4) and supramarginal gyrus (BA 40) of the *left* hemisphere, and in the primary motor cortex (BA 4), middle frontal gyrus (BA 9), supramarginal gyrus (BA 40) and medial cerebellum of the *right* hemisphere.

Discussion

Although the oral and written forms of English and Mandarin differ markedly, previous imaging research involving English–Chinese bilinguals suggests that common brain areas subserve the two languages. We investigated the phonological processing of skilled English–Chinese bilingual biscriptals by using a homophone matching task and equivalent behavioral ($N = 28$) and fMRI ($n = 6$) experiments. Like Chee et al. (1999a,b), we found evidence of common brain regions for Mandarin and English in our bilingual participants but only in the *left* hemisphere—inferior frontal gyrus (BA 46) and left inferior occipital gyrus (BAs 17 and 18). More importantly, we found several *distinct* areas of activation for *both* languages in *both* hemispheres that have not been reported previously. Brain regions activated *only* during the Mandarin homophone matching task were found bilaterally in the frontal and occipital lobes, and in the left temporal lobe, while those activated *only* during the English homophone matching were found bilaterally in the frontal and parietal lobes.

There are at least two explanations for our novel findings, and they are not mutually exclusive. First, our task required a time-paced overt manual response and may be more suitable for eliciting language-specific activation for phonology. Chee et al.'s (1999b) use of a covert stem completion task probably involved more language-neutral attention or memory systems. Second, and more importantly, our participants were all early bilinguals, who had been carefully screened with objective measures of language proficiency in Mandarin and English.

In our fMRI experiment, averaging over a small homogenous group of participants seems to have resulted in greater sensitivity and hence new evidence of several *distinct* regions of activation related to language-specific processes. To make correct homo-

Table 1
Brain regions showing a significant BOLD signal for English and Mandarin HM tasks relative to fixation (language-specific distinct regions in bold)

Brain region	English		Mandarin	
	MNI coordinates	<i>P</i> value	MNI coordinates	<i>P</i> value
Frontal lobe				
Left hemi	PMC (BA 4)	(−48,8,34)	<0.001	(−44,10,36) 0.023*
	IFG (BA 46)	(−40,28,24)	<0.001	(−30,40,8) <0.001
	MedFG	(−40,28,24)	0.010*	(−42,32,38) <0.001
	ACC (BA 32)	–	–	(−4,16,40) 0.007
Right hemi	PMC (BA 4)	(44,8,30)	<0.001	(44,4,34) 0.019*
	SFG (BA 8)	–	–	(12,10,50) 0.001
	MFG (BA 9)	(40,32,28)	0.001	(36,38,12) 0.026*
	ACC (BA 32)	–	–	(12,18,38) 0.001
Parietal lobe				
Left hemi	SMG(BA 40)	(−30,−62,44)	<0.001	(−46,−38,32) 0.026*
Right hemi	SMG (BA 40)	(42,−54,44)	0.001	(40,−40,28) 0.025*
Temporal lobe				
Left hemi	FG (BA 37)	(−28,−82,−14)	0.010*	(−44,−62,−14) <0.001
Occipital lobe				
Left hemi	IOG (BA 17 and 18)	(−30,−90,−4)	<0.001	(−42,−84,2) <0.001
Right hemi	Cuneus (BA 17)	(14,−76,14)	0.040*	(22,−92,−6) <0.001
	IOG (BA 19)	(26,−88,−4)	0.010*	(48,−70,−8) 0.001

Note. (1) Numbers in parentheses refer to approximate Brodmann's areas. Brain regions showing peak activations from clusters of ≥ 15 voxels ($P < 0.05$, uncorrected) are expressed in millimeters as MNI coordinates. (2) Brain regions—primary motor cortex (PMC); superior frontal gyrus (SFG); middle frontal gyrus (MFG); medial frontal gyrus (MedFG); inferior frontal gyrus (IFG); anterior cingulate gyrus (ACC); superior parietal gyrus (SPG); inferior parietal gyrus (IPG); supramarginal gyrus (SMG); fusiform gyrus (FG); middle occipital gyrus (MOG); inferior occipital gyrus (IOG). (3) * denotes values that did not pass the FDR correction for multiple comparisons at a significance level of $P < 0.05$.

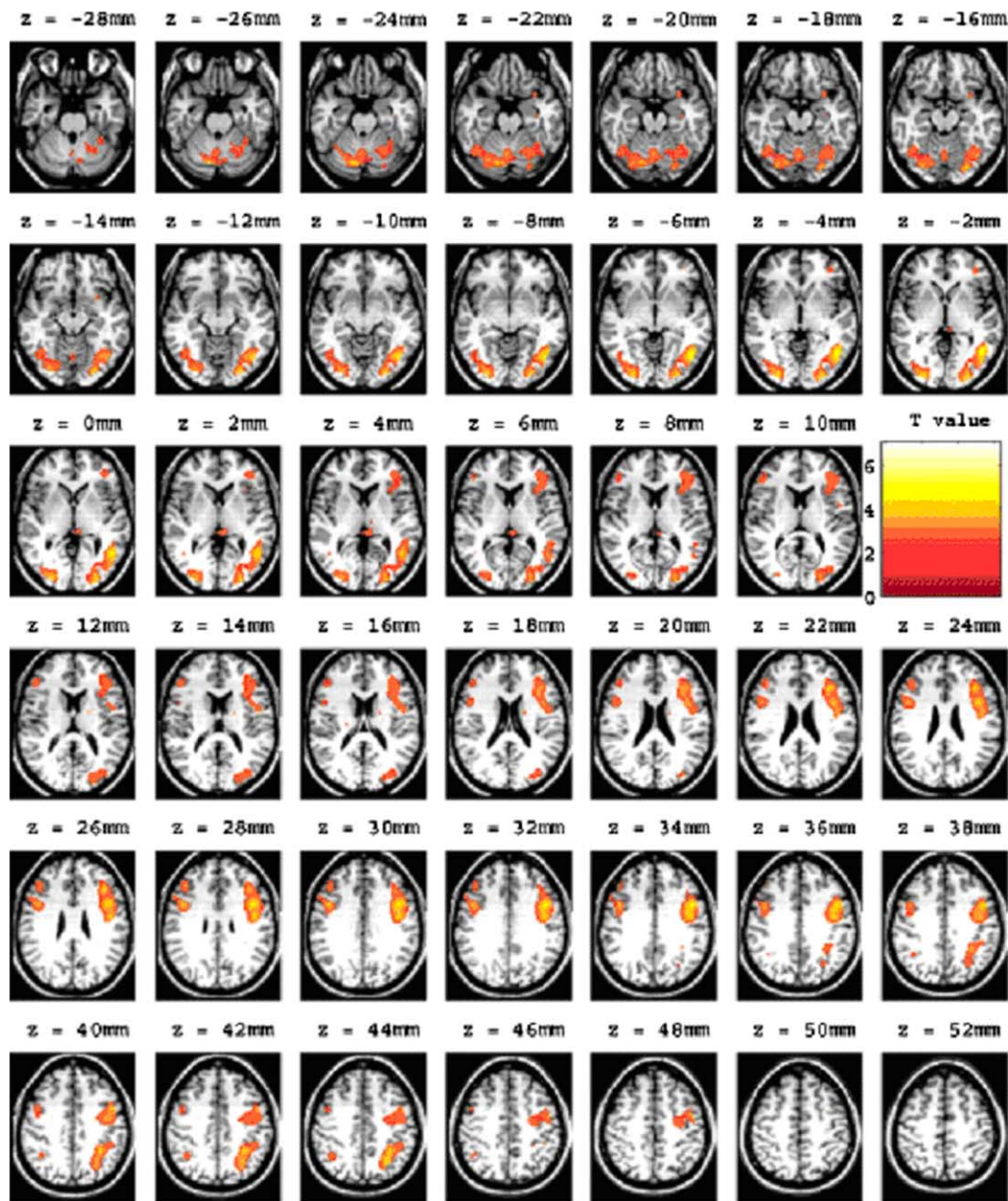


Fig. 2. Group level activation maps for the English homophone task relative to fixation.

phone judgments in Mandarin, participants must match syllable *and* lexical tone. The results of the behavioral experiment confirmed that the Mandarin version of the task is more cognitively demanding than the English version, that is, there were significantly longer response times and more errors. One plausible explanation for the extra processing load is that matching lexical tone in working memory involves semantic access for Chinese characters, but not for English words. However, from Table 1, it seems clear that there are several candidate loci for lexical tone representation: left or right frontal lobes or the left temporal lobe. In other words, we did not find unequivocal support for left lateralization of lexical tone reported in earlier PET studies (Hsieh et al., 2001; Klein et al., 2001) because two of the distinct loci for Mandarin are within the *right* frontal lobe. To be more exact, our results suggest that the match/no match decision for both languages

is based on a range of cognitive processes subserved by both hemispheres, many of which do not overlap even in skilled bicultural bilinguals.

Given that our results are not consistent with earlier work on comparable Mandarin–English bilinguals (i.e., Chee et al., 1999a,b), we re-consider previous reports on both types of unilinguals. For unilingual English readers, the pattern of activation we observed for the English homophone task is broadly consistent except that we did not find the typical left superior temporal gyrus activation. We also observed three additional loci in the *right* hemisphere that are not usually reported for unilinguals: middle frontal gyrus (BA 9), pre-motor cortex (BA 4), and supramarginal gyrus (BA 40). These differences provide tentative support for the view that English is less left-lateralized for these bilinguals compared to unilinguals.

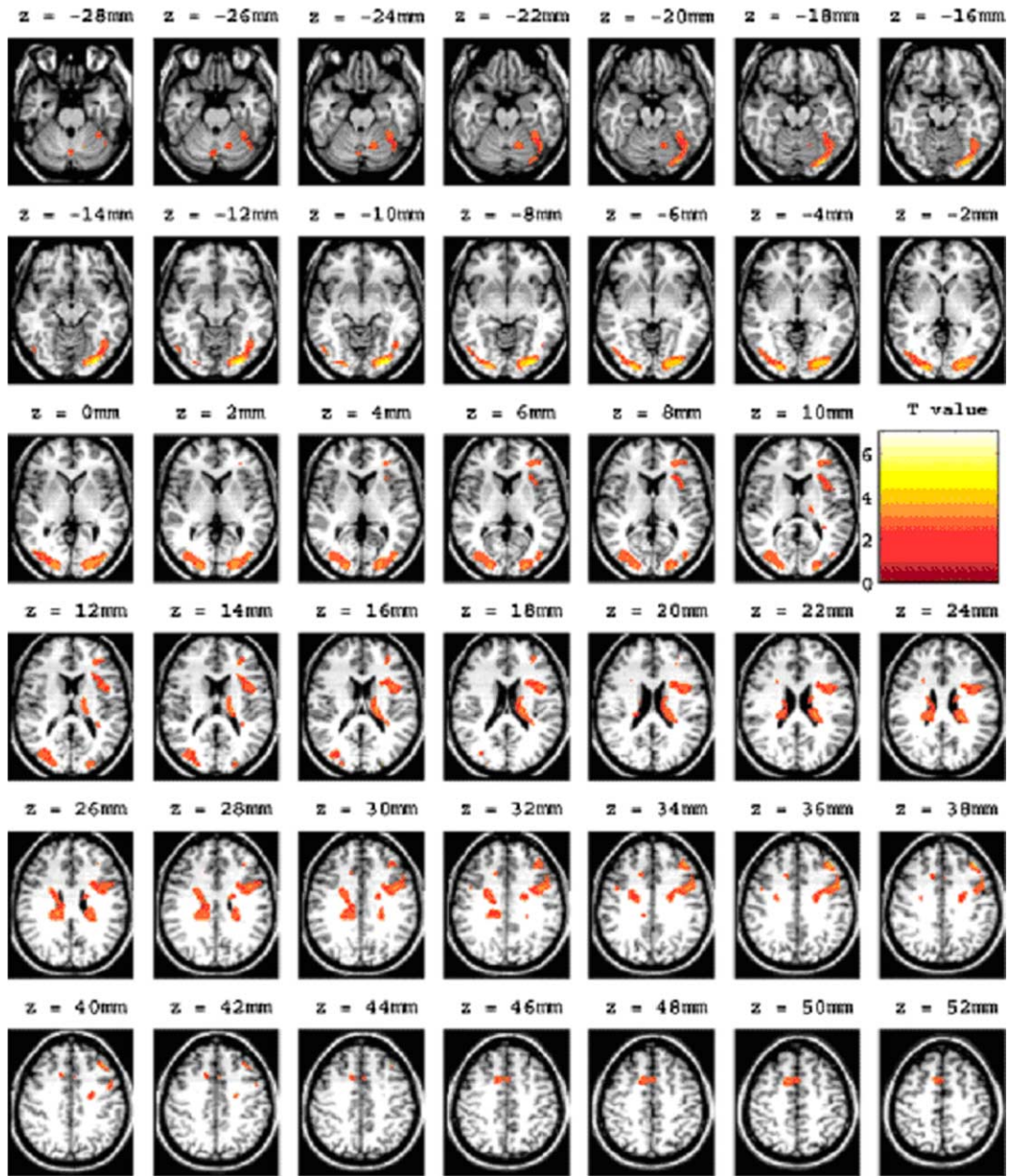


Fig. 3. Group level activation maps for the Mandarin homophone task relative to fixation.

For unilingual Mandarin readers, Tan et al. (2001) used a similar experimental paradigm (homophone judgement relative to fixation) and found peak activations in the *left* middle frontal gyrus

(BA 9). For our bilingual participants, in the *left* hemisphere, distinct activation was found in the medial frontal gyrus, the anterior cingulate cortex (BA 32), the fusiform gyrus (BA 37), and lateral cerebellum, and in the *right* hemisphere, distinct activation

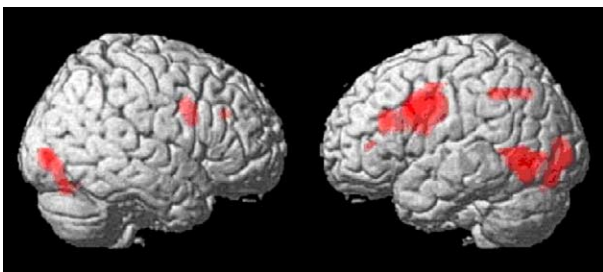


Fig. 4. Significant group activation patterns of the English HM task rendered on the 3D model of a volunteer's brain.

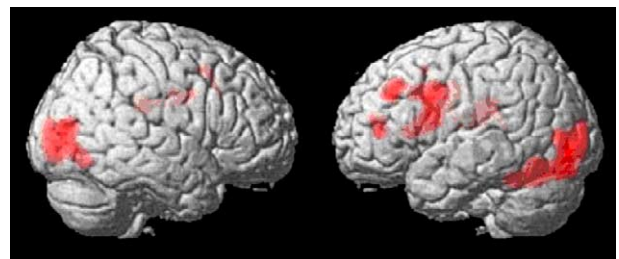


Fig. 5. Significant group activation patterns of the Chinese HM task rendered on the 3D model of a volunteer's brain.

was found in the superior frontal gyrus (BAs 8 and 32), the anterior cingulate cortex (BA 32), the inferior occipital gyrus (BA 19), and the cuneus (BA 17). Unlike Tan et al., we found *no* evidence of activation in the middle frontal gyrus (BA 9), right infero-middle prefrontal cortex, bilateral pre-motor cortex, left medial prefrontal lobe (BA 11), bilateral middle and superior temporal gyri (BA 21 and 22), bilateral superior parietal gyrus, right angular gyrus (BA 39), left postcentral gyrus (BA 3), or left cuneus. Although the activation patterns for our early English–Chinese bilinguals show some overlap with earlier work on respective unilinguals, there are also some notable differences. At this stage, it seems premature to speculate further about neural substrates for specific processes, but for both languages, participants appear to recruit a range of distinct cognitive components for phonological matching. Instead, we will conclude by drawing attention to three methodological caveats that should be addressed in future work with Chinese–English biscriptals. First, the inclusion of unilingual controls alongside early bilinguals would facilitate better understanding of any differences in their language representation, especially with respect to lateralization. Second, the results of our behavioral experiment revealed significant differences in performance across the two languages in terms of response latencies and error rates. Mandarin homophone matching takes longer than English homophone matching and is more prone to errors. The direction of the difference is consistent with the idea that our biscriptal readers found that phonological processing in Mandarin is more cognitively demanding than in English (see also Perfetti and Tan, 1998). Neural activation is modulated by task demands (Raichle, 1987), but these could not be equated at the design stage because the

languages are so different. Finally, although our sample size of six fMRI participants was small, we were able to find significant differences in activation loci for the two languages. It seems that a small homogenous group can suffice, provided it is truly representative of the population and an overt response is required. We ensured this by conducting a parallel behavioral experiment and carefully screening all participants for language proficiency.

In conclusion, a number of distinct brain regions were activated by both English words and Chinese characters when early bilingual biscriptal readers performed a homophone matching task with concurrent fMRI. Phonological processing in English and Mandarin requires the interaction and collaboration of a number of brain regions in both hemispheres, many of which do not overlap even in skilled bilinguals.

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Appendix A. Mandarin homophone matching task

NP = no identifiable phonetic radical therefore phonology is unpredictable.

Homophone Matching: “Yes” Trials

	No.	Same Tone Same Syllable	Phonetic Radical
Practice Trials	1	楚 (chu3) - 储 (chu3)	疋 (shu1) - 诸 (zhu1)
	2	游 (you2) - 邮 (you2)	NP - 由 (you2)
	3	持 (chi2) - 池 (chi2)	寺 (si4) - 也 (ye3)
	4	指 (zhi3) - 纸 (zhi3)	旨 (zhi3) - 氏 (shi4)
Block1	5	还 (huan2) - 环 (huan2)	不 (bu4) - 不 (bu4)
	1	倾 (qing1) - 轻 (qing1)	顷 (qing3) - NP
	2	舵 (duo4) - 惰 (duo4)	它 (ta1) - NP
	3	颞 (ke1) - 科 (ke1)	果 (guo3) - NP
	4	毁 (hui3) - 悔 (hui3)	爻 (shu1) - 每 (mei3)
	5	住 (zhu4) - 助 (zhu4)	主 (zhu3) - 且 (zu3)
Block2	6	接 (jie1) - 街 (jie1)	姜 (jie4) - 圭 (gui1)
	7	仇 (chou2) - 愁 (chou2)	九 (jiu3) - 秋 (qiu1)
	8	献 [献] (xian4) - 羨 (xian4)	虞 (yan4) - NP
	9	毯 (tan3) - 坦 (tan3)	炎 (yan2) - 旦 (dan4)
	10	怦 (peng1) - 烹 (peng1)	平 (ping2) - 亨 (heng1)
	11	矩 (ju3) - 举 (ju3)	巨 (ju4) - NP
Block3	12	犯 (fan4) - 饭 (fan4)	NP - 反 (fan3)
	13	刘 [刘] (liu2) - 流 (liu2)	邝 (you3) - NP
	14	瞧 (qiao2) - 桥 (qiao2)	焦 (jiao1) - 乔 (qiao2)
	15	引 (yin3) - 饮 (yin3)	NP - NP
	16	设 (she4) - 社 (she4)	爻 (shu1) - 土 (tu3)
	17	啼 (ti2) - 提 (ti2)	帝 (di4) - 是 (shi4)
Block4	18	斋 [斋] (zhai1) - 摘 (zhai1)	齐 (qi2) - 萑 (chi4)
	19	裁 (cai2) - 财 (cai2)	?(zai1) - 才 (cai2)
	20	辞 (ci2) - 词 (ci2)	辛 (xin1) - 司 (si1)
	21	悬 (xuan2) - 玄 (xuan2)	县 (xian4) - 玄 (xuan2)
	22	倘 (tang3) - 躺 (tang3)	尚 (shang4) - 尚 (shang4)
	23	频 (pin2) - 贫 (pin2)	NP - 分 (fen1)
	24	妒 (du4) - 度 (du4)	户 (hu4) - 庶 (shu4)

Homophone Matching: “No” Trials

	No.	Different Tone Different Syllable	Phonetic Radicals
Practice Trials	1	楚(chu3) - 厨(chu2)	疋(shu1) - 討(shu4)
	2	游(you2) - 诱(you4)	NP - 秀(xiu4)
	3	持(chi2) - 翅(chi4)	寺(si4) - 支(zhi1)
	4	指(zhi3) - 制(zhi4)	旨(zhi3) - NP
Block1	5	还(huan2) - 缓(huan3)	不(bu4) - 爰(yuan2)
	1	刘(liu2) - 溜(liu1)	乖(you3) - 留(liu2)
	2	瞧(qiao2) - 俏(qiao4)	焦(jiao1) - 肖(xiao1)
	3	引(yin3) - 银(yin2)	NP - 艮(gen4)
	4	设(she4) - 奢(she1)	爻(shu1) - 者(zhe3)
Block2	5	啼(ti2) - 梯(ti1)	帝(di4) - 弟(di4)
	6	斋(zhai1) - 债(zhai4)	齐(qi2) - 责(ze2)
	7	裁(cai2) - 彩(cai3)	NP - 采(cai3)
	8	辞(ci2) - 疵(ci1)	辛(xin1) - 此(chi3)
	9	悬(xuan2) - 眩(xuan4)	县(xian4) - 玄(xuan2)
	10	倘(tang3) - 趟(tang4)	尚(shang4) - 尚(shang4)
Block3	11	频(pin2) - 拼(pin1)	NP - 并(bing4)
	12	妒(du4) - 赌(du3)	户(hu4) - 者(zhe3)
	13	倾(qing1) - 情(qing2)	顷(qing3) - 青(qing1)
	14	舵(duo4) - 躲(duo3)	它(ta1) - 朵(duo3)
	15	颀(ke1) - 渴(ke3)	果(guo3) - 曷(he2)
	16	毁(hui3) - 挥(hui1)	爻(shu1) - 军(jun1)
	17	住(zhu4) - 猪(zhu1)	主(zhu3) - 者(zhe3)
Block4	18	接(jie1) - 解(jie3)	妾(qie4) - NP
	19	仇(chou2) - 抽(chou1)	九(jiu3) - 由(you3)
	20	献(xian4) - 贤(xian2)	廡(yan4) - NP
	21	毯(tan3) - 谈(tan2)	炎(yan2) - 炎(yan2)
	22	怦(peng1) - 捧(peng3)	平(ping2) - 奉(feng4)
	23	矩(gui1) - 局(ju2)	巨(ju4) - NP
	24	犯(fan4) - 返(fan3)	NP - 反(fan3)

References

- Binder, J.R., Rao, S.M., Hammeke, T.A., Yetkin, F.Z., Jesmanowicz, A., Bandettini, P.A., Wong, E.C., Estkowski, L.D., Goldstein, M.D., Haughton, V.M., Hyde, J.S., 1994. Functional magnetic resonance imaging of human auditory cortex. *Ann. Neurol.* 35 (6), 662–672.
- Cabeza, R., Nyberg, L., 2000. Imaging cognition II: an empirical review of 275 PET and fMRI studies. *J. Cogn. Neurosci.* 12 (1), 1–47.
- Chee, M.W.L., Caplan, D., Soon, C.S., Sriram, N., Tan, E.W.L., Thiel, T., Weekes, B., 1999a. Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron* 23, 127–137.
- Chee, M.W.L., Tan, E.W.L., Thiel, T., 1999b. Mandarin and English single word processing studied with functional magnetic resonance imaging. *J. Neurosci.* 19 (8), 3050–3056.
- Chee, M.W., Weekes, B., Lee, K.M., Soon, C.S., Schreiber, A., Hoon, J.J., Chee, M., 2000. Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from fMRI. *NeuroImage* 12 (4), 392–403.
- Courtney, S.M., Petit, L., Maisog, J.M., Ungerleider, L.G., Haxby, J.V., 1998. An area specialized for spatial working memory in human frontal cortex. *Science* 279, 1347–1351.
- Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., Van De Moortele, P.-F., Lehericy, S., Le Bihan, D., 1997. Anatomical variability in the cortical representation of first and second language. *NeuroReport* 8, 3809–3815.
- Demonet, J.F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.-L., Wise, R., Rascol, A., Frackowiak, R., 1992. The anatomy of phonological and semantic processing in normal subjects. *Brain* 115, 1753–1768.
- Demonet, J.-F., Price, C., Wise, R., Frackowiak, R.S.J., 1994. Differential activation of right and left posterior sylvian regions by semantic and phonological tasks: a positron-emission tomography study in normal human subjects. *Neurosci. Lett.* 182, 25–28.
- Fiez, J.A., Raichle, M.E., Miezin, F.M., Petersen, S.E., Tallal, P., Katz, W.F., 1995. PET studies of auditory and phonological processing: effects of stimulus characteristics and task design. *J. Cogn. Neurosci.* 7, 357–375.
- Friston, K.J., Holmes, A.P., Worsley, K.J., 1999. How many subjects constitute a study? *NeuroImage* 10, 1–5.
- Friston, K.J., Ashburner, J., Poline, J.B., Frith, C.D., Heather, J.D., Frackowiak, R.S.J., 1995a. Spatial registration and normalization of images. *Hum. Brain Mapp.* 2, 165–189.
- Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.P., Frith, C.D., Frackowiak, R.S.J., 1995b. Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain Mapp.* 2, 189–210.
- Genovese, C.R., Lazar, N.A., Nichols, T., 2002. Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *NeuroImage* 15, 870–878.
- Haxby, J.V., Ungerleider, L.G., Horwitz, B., Rapoport, S.I., Grady, C.L., 1995. Hemispheric difference in neural systems for face working memory: a PET-rCBF study. *Hum. Brain Mapp.* 3, 68–82.
- Haxby, J.V., Ungerleider, L.G., Horwitz, B., Maisog, J.M., Rapoport, S.I., Grady, C.L., 1996. Face encoding and recognition in the human brain. *Proc. Natl. Acad. Sci. U. S. A.* 93, 922–927.
- Herbster, A.N., Mintun, M.A., Nebes, R.D., Becker, J.T., 1997. Regional cerebral flow during word and nonword reading. *Hum. Brain Mapp.* 5, 84–92.
- Hsieh, L., Gandour, J., Wong, D., Hutchins, G.D., 2001. Functional heterogeneity of inferior frontal gyrus is shaped by linguistic experience. *Brain Lang.* 76, 227–252.
- Illes, J., Francis, W.S., Desmond, J.E., Gabrieli, J.D.E., Glover, G.H.,

- Poldrack, R., Lee, C.J., Wagner, A.D., 1999. Convergent cortical representation of semantic processing in bilinguals. *Brain Lang.* 70, 347–363.
- Jonides, J., Smith, E.E., Poeppel, R.A., Awh, E., Minoshima, S., Mintun, M.A., 1993. Spatial working memory in humans as revealed by PET. *Nature* 363, 623–625.
- Joseph, J., Noble, K., Eden, G., 2001. The neurobiological basis of reading. *J. Learn. Disabil.* 34 (6), 566–579.
- Kapur, N., Friston, K.J., Yong, A., Frith, C.D., 1995. Activation of human hippocampal formation during memory for faces: a PET study. *Cortex* 31, 99–108.
- Kay, J., Lesser, R., Coltheart, M., 1992. PALPA—Psycholinguistic Assessments of Language Processing in Aphasia. Lawrence Erlbaum Associates, East Sussex, England.
- Kim, K.H.S., Relkin, N.R., Lee, K.-M., Hirsch, J., 1997. Distinct cortical areas associated with native and second languages. *Nature* 388, 171–174.
- Klein, D., Milner, B., Zatorre, R.J., Zhao, V., Nikelski, J., 1999. Cerebral organization in bilinguals: a PET study of Chinese–English verb generation. *NeuroReport* 10, 2841–2846.
- Klein, D., Zatorre, R.J., Milner, B., Zhao, V., 2001. A cross-linguistic PET study of tone perception in Mandarin Chinese and English speakers. *NeuroImage* 13, 646–653.
- Lee, C.-Y., Tsai, J.-L., Kuo, W.-J., Yeh, T.-C., Wu, Y.-T., Ho, L.-T., Hung, D.L., Tzeng, O.J.L., Hsieh, J.-C., 2004. Neuronal correlates of consistency and frequency effects on Chinese character naming: an event related fMRI study. *NeuroImage* 23, 1235–1245.
- Lepage, M., Ghaffar, O., Nyberg, L., Tulving, E., 2000. Prefrontal cortex and episodic memory retrieval mode. *Proc. Natl. Acad. Sci. U. S. A.* 97, 506–511.
- Loo, S.C., 1989. Frequency Dictionary of Chinese Characters, Words, and Phrases Used in Singapore Primary School Textbooks. Chinese Language and Research Centre, National University of Singapore, Singapore.
- McCarthy, G., Blamire, A.M., Puce, A., Nobre, A., Bloch, G., Hyder, F., Goldman-Rakic, P., Shulman, R.G., 1994. Functional MR imaging of human prefrontal cortex activation during a spatial working memory task. *Proc. Natl. Acad. Sci. U. S. A.* 91, 8690–8694.
- Nyberg, L., McIntosh, A.R., Cabeza, R., Habib, R., Houle, S., Tulving, E., 1996. General and specific brain regions involved in encoding and retrieval of events: what, where, and when. *Proc. Natl. Acad. Sci. U. S. A.* 93, 11280–11285.
- Paulesu, E., Frith, C.D., Frackowiak, R.S.J., 1993. The neural correlates of the verbal component of working memory. *Nature* 362, 342–345.
- Paulesu, E., Frith, C., Snowling, M., Gallagher, A., Morton, J., Frackowiak, R.S.J., Frith, C., 1996. Is developmental dyslexia a disconnection syndrome? Evidence from PET scanning. *Brain* 119, 143–157.
- Perfetti, C., Tan, L.H., 1998. The time course of graphic, phonological, and semantic activation in Chinese character identification. *J. Exp. Psychol.: Learn. Mem. Cogn.* 24, 101–118.
- Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M., Raichle, M.E., 1988. Positron emission tomographic studies of cortical anatomy of single-word processing. *Nature* 331, 585–589.
- Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M., Raichle, M.E., 1989. Positron emission tomographic studies of the processing of single words. *J. Cogn. Neurosci.* 1, 153–170.
- Price, C.J., Wise, R.J.S., Warburton, E.A., Moore, C.J., Howard, D., Patterson, K., Frackowiak, R.S.J., Friston, K.J., 1996. Hearing and saying: the functional neuro-anatomy of auditory word processing. *Brain* 119, 919–931.
- Pugh, K.R., Shaywitz, B.A., Shaywitz, S.E., Constable, R.T., Skudlarski, P., Fullbright, R.K., Bronen, R.A., Shankweiler, D.P., Katz, L., Fletcher, J.M., Gore, J.C., 1996. Cerebral organization of component processes in reading. *Brain* 119, 1221–1238.
- Raichle, M.E., 1987. Circulatory and metabolic correlates of brain function in normal humans. In: Plum, F., Mountcastle, V. (Eds.), *Handb. Physiol.*, vol. 5. American Physiological Association, Bethesda, MD, pp. 643–674.
- Rickard Liow, S.J., Poon, K.K.L., 1998. Phonological awareness in multilingual Chinese children. *Appl. Psycholinguist.* 19, 339–362.
- Rickard Liow, S.J., Tng, S.K., Lee, C.L., 1999. Chinese characters: semantic and phonetic regularity norms for China, Taiwan and Singapore. *Behav. Res. Methods Instrum. Comput.* 31, 155–177.
- Rumsey, J.M., Horwitz, B., Donohue, B.C., Nace, K., Maisog, J.M., Andreason, P., 1997. Phonologic and orthographic components of word recognition: a PET-rCBF study. *Brain* 120, 739–759.
- Sergent, J., Zuck, E., Levesque, M., MacDonald, B., 1992. Positron emission tomography study of letter and object processing: empirical findings and methodological considerations. *Cereb. Cortex* 2, 68–80.
- Simos, P.G., Breier, J.I., Wheless, J.W., Maggio, W.W., Fletcher, J.M., Castillo, E.M., Papanicolaou, A.C., 2000. Brain mechanisms for reading: the role of the superior temporal gyrus in word and pseudowords naming. *NeuroReport* 11, 2443–2447.
- Simos, P.G., Breier, J.I., Fletcher, J.M., Foorman, B.R., Castillo, E.M., Andrew, C., Papanicolaou, A.C., 2002. Brain mechanisms for reading words and pseudowords: an integrated approach. *Cereb. Cortex* 12, 297–305.
- Tan, L.H., Liu, H.-L., Perfetti, C.A., Spinks, J.A., Fox, P.T., Gao, J.-H., 2001. The neural system underlying Chinese logograph reading. *NeuroImage* 13, 836–846.
- Vaid, J., Hull, R., 2002. Re-envisioning the bilingual brain using functional neuroimaging: methodological and interpretive issues. In: Fabbro, F. (Ed.), *Advances in the Neurolinguistics of Bilingualism: Essays in Honor of Michel Paradis*. Udine Univ. Press, Udine Forum, pp. 315–355.
- Van Lancker, D., Fromkin, V., 1973. Hemispheric specialization for pitch and ‘tone’: evidence from Thai. *J. Phon.* 1, 101–109.
- Warburton, E., Wise, R.J., Price, C.J., Weiller, C., Hadar, U., Ramsay, S., Frackowiak, R.S., 1996. Noun and verb retrieval by normal subjects. Studies with PET. *Brain* 119, 159–179.
- Worsley, K.J., Friston, K.J., 1995. Analysis of fmri time-series revisited—again. *NeuroImage* 2, 173–181.
- Yetkin, O., Yetkin, F.Z., Houghton, V.M., Cox, R.W., 1996. Use of functional MR to map language in multilingual volunteers. *Am. J. Neuroradiol.* 17, 473–477.
- Zatorre, R.J., Evans, A.C., Meyer, E., Gjedde, A., 1992. Lateralization of phonetic and pitch discrimination in speech processing. *Science* 256, 846–849.