NEUROANATOMICAL REPRESENTATION OF LANGUAGE IN ENGLISH-CHINESE BILINGUAL BISCRIPTALS: AN FMRI STUDY

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"If we knew what it was we were doing, it would not be called research, would it?"

~ Albert Einstein ~

SUMMARY

The advent of modern neuroimaging techniques such as Functional Magnetic Resonance Imaging (fMRI) provided an impetus for investigating language representation in the healthy bilingual brain. To date, neuroimaging experiments involving English-Chinese bilinguals suggest that common brain areas subserve the two languages. Given that the oral and written forms of English and Mandarin differ so markedly, and differences have been reported for bi-alphabetic readers, the null findings for English-Chinese bilinguals warrant a systematic investigation.

In this thesis, the language representation of skilled English-Chinese bilingual biscriptals was investigated at the orthographic, phonological and semantic levels at both the cognitive and neuroanatomical levels, using equivalent behavioural ($N = 28$) and fMRI ($n = 6$) experiments. The three experimental tasks (lexical decision, homophone matching and synonym judgement) employed in this study were developed from a cognitive model of skilled reading with the additional assumption of modularity in language processing. The behavioural data (reaction times and error rates) were used to gauge task demands across the two languages, and the neuroanatomical correlates for English and Mandarin were compared.

The results of the behavioural experiment showed that for reaction times, processing Chinese characters took significantly longer than English words for the homophone matching and synonym judgement tasks but task demands were similar for lexical decision. For error rates, significant differences between Chinese characters and English words were found for all three tasks: performance in English was significantly better than Mandarin despite attempts to equate for frequency across languages and a

reduction in trials for Mandarin. For this reason, it is argued that greater task demands for Mandarin may be unavoidable in some tasks because of the nature of the two languages.

The pattern of activations observed for the English-Chinese bilingual biscriptals showed strong consistencies with past neuroimaging studies that investigated the neural correlates of language processing in English and Mandarin unilinguals, although the bilinguals showed less left lateralization. The fMRI data for English and Mandarin confirmed that many common brain regions were found to subserve both languages. However, for some of these common brain areas, greater activation was observed for Mandarin than English. More importantly, and contrary to previous fMRI studies, a number of different brain regions were activated for English and Mandarin at the level of orthography, phonology and semantics. Across all tasks, brain regions activated *only* during the English tasks were generally observed to be located in the *parietal* and *temporal* lobes, whereas those areas activated *only* during the Mandarin tasks were generally observed to be located in the *frontal* and *parietal* lobes. The theoretical implications of these results are discussed in detail.

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CHAPTER 1

INTRODUCTION

Bilingualism is becoming more the norm than the exception worldwide (De Groot, & Kroll, 1997; Grosjean, 1982; Harris & Nelson, 1992), yet our understanding of how the bilingual brain learns, stores and processes language is relatively fragmented. Published research on the representation of language in the brain has centred on unilingual populations but the advent of modern and noninvasive neuroimaging techniques such as Positron Emission Tomography (PET), Functional Magnetic Resonance Imaging (fMRI), and Event-Related Brain Potentials (ERP) in the last decade has provided an impetus for investigating language representation in the bilingual brain.

Research that involves imaging the healthy bilingual brain has focused on trying to elucidate whether similar, or spatially segregated, neural substrates subserve two languages (see Vaid & Hull, 2002, for a review). Whilst some studies have provided evidence in support of anatomically separate mental lexicons (e.g., Dehaene *et al.*, 1997, on English- French bilinguals; Kim, Relkin, Lee, & Hirsch, 1997, on English-French bilinguals; O. Yetkin, F. Z. Yetkin, Haughton, & Cox, 1996, on a variety of English-knowing bilinguals), others have shown a common neural substrate for both languages (e.g., Illes *et al.*, 1999, on English-French bilinguals; Klein, Milner, Zatorre, Meyer, & Evans, 1995, on English-Chinese bilinguals). To date, neuroimaging experiments involving *English-Chinese bilinguals* favour the view that English and Mandarin[1] have shared neural substrates (Chee *et al.*, 1999a; Chee, Tan, &

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[1] The term 'Chinese' is used for ethnicity and writing script, whereas 'Mandarin' refers to a particular spoken form of Chinese, the language used for this study.

Thiel, 1999b; Chee *et al.*, 2000; Klein, Milner, Zatorre, Zhao, & Nikelski, 1999). This is a rather surprising finding as English and Mandarin differ markedly in at least three levels of language processing: (a) 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; (b) at the phonological level, Mandarin is a tonal language whilst English is not; and (c) at the semantic level, English letters need to be combined in a sequence to represent meaning whilst a single character in Mandarin represents a unit of meaning (see pp. 8-11 for details on differences between English and Mandarin writing systems). If the languages in bilinguals are differentially represented, one might expect that the neuroanatomical representation of English and Mandarin would be more likely to show differences in orthography and phonology, if not semantics. This thesis describes a systematic fMRI study of language processing at these three levels for six English-Chinese bilingual biscriptals with behavioural benchmarking. The specific aims of this study are to: (a) investigate the cognitive processes underlying English-Chinese bilingual biscriptal reading; and (b) examine differences in neural activation related to English and Mandarin language processing.

Functional Imaging of English – Chinese Bilinguals: A Literature Review

It is worth noting that the investigation of the cerebral organization of the bilingual brain has involved a wide variety of experimental paradigms ranging from single word production to sentence comprehension, different imaging techniques (PET, fMRI, ERP), and participants from diverse language backgrounds (English, Spanish, French, German, Mandarin). As the generality of findings across different kinds of bilinguals is unclear, the focus of the following review will be on *English-Chinese bilinguals*, and the methodological issues in these studies will be considered for the

design of this thesis. To date, there are four main studies that have shown common neuroanatomical representation of English and Mandarin in *English-Chinese bilinguals* using three main paradigms: (a) word generation; (b) semantic judgement; and (c) sentence comprehension.

Word Generation

Using PET, Klein *et al.* (1999) employed the noun-verb generation task (see Petersen, Fox, Posner, Mintun, & Raichle, 1988) with Mandarin-English speakers whose native language was Mandarin (L1) but all had acquired English (L2) in adolescence. The seven participants were screened for language abilities prior to the experiment and all were found to be relatively fluent in both languages. During the scanning procedure, English or Mandarin nouns were presented binaurally through earphones, and participants were required to produce a spoken response (i.e., generate a verb). In the control task, participants performed a word repetition task – English or Mandarin words were presented binaurally, and participants were instructed to repeat what they heard. For the word repetition task, no differences in accuracy or latency of responses for English and Mandarin were noted. However, performance for generating verbs in English L2 was significantly slower, and less accurate, than in Mandarin L1. When activation for word repetition was subtracted from verb generation in L1 and L2, there were regional cerebral blood flow (rCBF) increases in the left inferior frontal, dorsolateral frontal, left medial temporal, left superior parietal cortices and right cerebellum for both languages. Despite this, a direct comparison of the difference between verb generation and word repetition in L1 and L2 showed no significant differences in activation.

Then, on the basis of the findings from previous studies, the investigators focused on a region of interest (ROI) in the left frontal region for the within-participant

analyses. When activation for the word repetition task was subtracted from the verb generation task, within-participant analyses consistently revealed rCBF increases in the left frontal cortex for all six participants for both languages. (Note that for the noun-verb generation task in L2, one participant was excluded from the analysis because of computer registration failure in the scanner. The investigators were unable to repeat this scan owing to radiation safety limitations for the participant). This led the investigators to suggest that the left frontal cortex (i.e., ventrolateral, dorsolateral and medial) played a strong role in word generation in both English and Mandarin. They concluded that even when languages are distinct, and despite the late acquisition of L2, common neural substrates are activated during a lexical search task involving single word production for highly fluent and proficient English-Chinese bilinguals.

In another experiment based on word generation, Chee *et al.* (1999b) used fMRI to study the cortical representation of single word processing in fluent English-Chinese bilinguals. In this study, fifteen early bilinguals (i.e., both English and Mandarin were acquired by the age of six years) were compared to nine late bilinguals (i.e., English L2 acquired after twelve years of age). Participants were instructed to covertly produce words when cued by a word stem presented visually on a screen (e.g., "cou" for "couple"). Compared to the control task (in this case fixation), the cued word generation task revealed the most robust foci of brain activation in the left prefrontal cortex, involving both the middle and inferior frontal gyri (BA 9/46, 44/45) [2], the left pre-motor cortex (BA 6), bilateral superior parietal (BA 7) and bilateral occipital gyri in both languages.

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[2] The term 'BA' refers to Brodmann areas. Brodmann (1909) divided the cerebral cortex into numbered subdivisions (see Figure 1) based on cell arrangements, types and staining properties. Brodmann's anatomical maps are commonly used as the reference system for discussion of neuroimaging findings (Buckner & Wheeler, 2001). Details of Brodmann's cytoarchitectonic map are discussed on pp. 35.

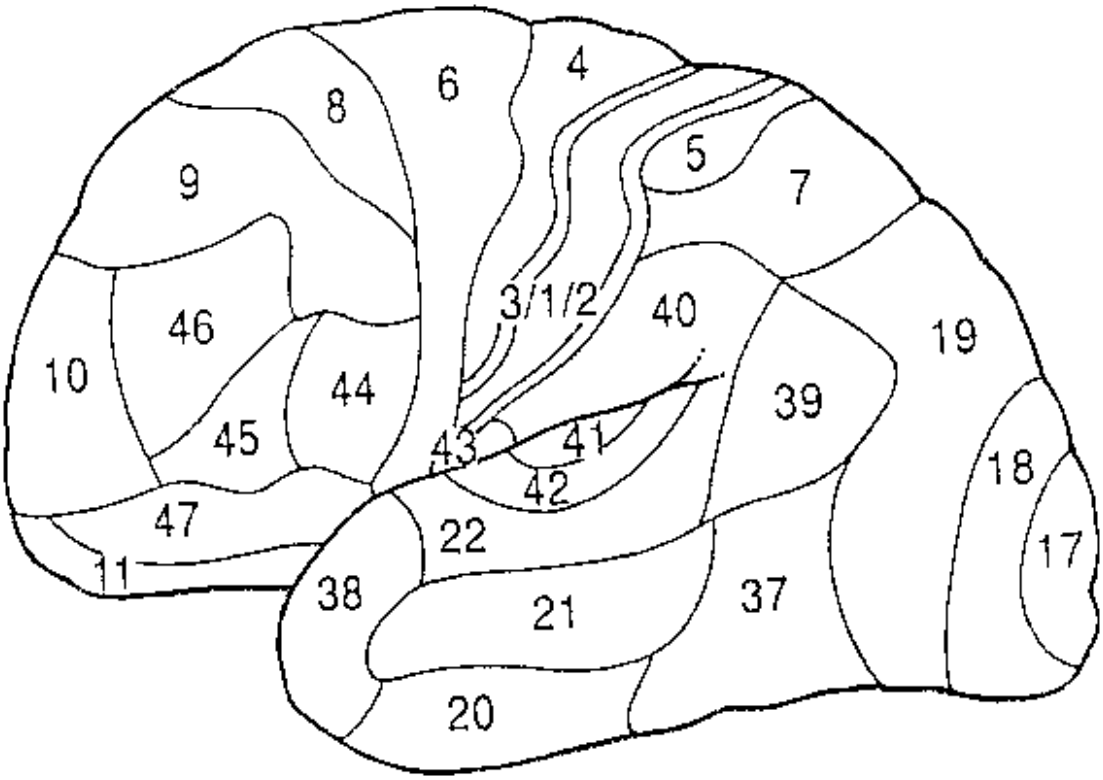

Figure 1. Brodmann's cytoarchitectonic map.

Again, the investigators found no significant differences in the locus of neural activation for Mandarin and English, and the pattern of brain activation was also similar for the early and late bilinguals. However, it is worth noting that although the participants in this study were reported to be fluent in both languages, it appears that a language prescreening procedure was not conducted to determine proficiency in both languages. Also, due to the nature of the task employed (i.e., covert word generation), no behavioural data such as accuracy scores or response latencies, were available to ascertain task demands.

Semantic Judgement

In a second experiment, Chee and colleagues (2000) used a semantic judgement task (Pyramids and Palm Trees task, Howard & Patterson, 1992) to evaluate differential cerebral organization of English-Chinese bilinguals. The aim of the study was to investigate if Chinese character semantic processing was more similar to

English word processing or picture processing. Stimulus triplets were presented during scanning and participants were asked to choose the stimulus (i.e., English word, Chinese character or picture) closest in meaning to the target. For example, in the English semantic association task, "comb" was presented as the target whilst "broom" (fail) and "brush" (correct choice) were presented as the stimuli. For the control task, participants were required to perform a size judgement task. In this task, one of the stimuli was 6% smaller or larger than the target whilst the other stimulus was 12% smaller or larger than the target. Participants were required to choose the stimulus that was closer in size to the target.

For the word and character semantic judgement, relative to the size judgement task, common brain regions activated included the left prefrontal (BA 9, 44, 45), left posterior temporal (BA 21, 22), left fusiform gyrus (BA 37) and left parietal region (BA 7). Overall, more activation was observed for character semantic processing. Within-group analyses of time courses (fMRI time course reflects the signal change that occurs in response to brain activity) also showed greater BOLD signal change in the left prefrontal areas for character semantic processing. Nevertheless, the investigators concluded that lexico-semantic processing might be independent of the type of script processed in fluent bilinguals.

Sentence Comprehension

Chee and colleagues (1999a) also used fMRI to investigate sentence comprehension in English-Chinese bilinguals. Unlike the other studies, this experiment examined sentence level processing, rather than single word processing. Two important variables, namely, the age of acquisition of L2 and language proficiency, were controlled for in this study. During the scanning procedure, participants were presented with written sentences in English (e.g., "The speech that

the minister gave angered the reporter") or Mandarin and asked to respond to a probe question (e.g., "The minister angered the reporter?") that followed each sentence by manually indicating a "true" or "false" response with a two-button mouse. Two types of control tasks were used in this study. In the first experiment, sentence comprehension in each language was compared to fixation so that the entire set of cognitive processes related to sentence comprehension would be engaged. In the second experiment, a control task involving Tamil-like pseudo-characters was used to control for any activity resulting from low-level perceptual processing (i.e., motor activity and early visual processing). The results of the two experiments were somewhat similar except that less occipital activation was associated with the Tamil control stimuli. Brain regions activated included the left inferior (BA 44, 45, 47) and middle frontal gyri (BA 9, part of BA 8, BA 6), left superior and middle temporal gyri (BA 22, BA 21), left temporal pole (BA 38), left angular gyrus (BA39), the anterior supplementary motor area (BA 8), bilateral superior parietal gyrus (BA 7) and bilateral occipital regions. Again, at the individual and group levels of analyses, no significant differences were found when comparing the brain regions activated by each language.

In summary, so far the neuroimaging studies involving English-Chinese bilinguals have failed to demonstrate differences in neuroanatomical representations that might be expected for two such contrasting languages, alphabetic English and morpho-syllabic Mandarin. One possible explanation is that the experimental paradigms employed so far were limited in their ability to tease apart the salient differences of English and Mandarin at the neuroanatomical level. Second, the choice of experimental paradigm is not well linked to a theoretical framework. A within-participant investigation of two or more language processing components would allow the experimenter to make stronger links with cognitive models. Finally, the use of an

experimental paradigm such as covert word generation, together with the lack of on-line behavioural data, as was the case with Chee *et al.*, 1999b, raises the question of whether participants were complying with task instructions, or even performing the task at all whilst in the scanner (see Binder, 1995). Behavioural data provide an opportunity to assess relative task demands across languages even if they cannot be fully equated.

Given the limitations of previous studies, there is reason to think that differences in the neuroanatomical representation of English and Mandarin in English-Chinese bilingual biscriptals can be identified. In fact, existing behavioural and neuroimaging studies on unilingual English and unilingual Mandarin support the view that differences in processing and representation are likely. In what follows, I will review these reported differences and briefly describe a cognitive model of reading.

Differences between English and Mandarin writing systems

Before discussing the evidence for differential processing of English and Mandarin, it is worthwhile examining the attributes that distinguish the two languages at the orthographic, phonological and semantic levels.

Orthographic Level

Mandarin and English are based on completely different writing systems. Written Mandarin is based on the morpho-syllabic system whilst written English is based on the alphabetic system. Unlike English words, which typically consist of a string of letters, concepts in Mandarin are usually represented by two or more characters (Shu & Anderson, 1999). Each Chinese character is made up of a configuration of strokes that are packed into a square shape (Tan *et al.*, 2000; Yang & McConkie, 1999). Most Chinese characters are compound characters consisting of two parts, a component called a semantic radical, which often provides information

associated with the meaning of the character, and a component called a phonetic radical, which often provides information associated with the pronunciation of the character (Hoosain, 1991).

Visually, the features of English and Mandarin are distinct (Lin & Akamatsu, 1997). Letters are placed in horizontal linear sequences of different lengths whereas characters always form a same-size square frame, which is a more compact visual representation. Chinese characters also appear more visually complex than English text.

Finally, English graphemes (i.e., letters or combinations of letters) correspond to phonemes (i.e., basic units in speech) but, as Chen (1999) notes, a single Chinese character corresponds to a single syllable, and each of these represents a morpheme, which is the basic unit of meaning.

Phonological Level

Another important difference to note is that Mandarin is a tonal language. In sentence-level English, intonation is used either to convey an attitude, or to change a statement into a question, but the use of tone alone does not change the meaning of words. In tonal languages, the meaning of a word can change dramatically with the use of different tones (Stafford, 2003). Spoken Mandarin has four contrasting tones which are used to distinguish otherwise identical syllables. For example, 妈 /ma/ with Tone 1 means 'mother'; 麻 /ma/ with Tone 2 means 'hemp'; 马 /ma/ with Tone 3 means 'horse' and 骂 /ma/ with Tone 4 means 'scold' (Klein, Zatorre, Milner & Zhao, 2001).

Another salient characteristic of Mandarin phonology is its extensive homophony, i.e., many Chinese characters share the same pronunciation including tone (Tan & Perfetti, 1998). In visual recognition, characters with the same sound are

disambiguated by their graphic forms, and in the auditory perception of Mandarin words, context cues and tonal phonology play an important role in disambiguating homographs (Li & Yip, 1996).

Semantic Level

In English, letters need to be combined in a sequence to represent meaning, but in Mandarin, a single character represents a unit of meaning (Ho & Hoosain, 1989). Another important distinction is morphological category. In English, two types of morphology exist: (a) inflectional morphology, where changes to a word usually do not alter its underlying meaning or syntactic category; and (b) derivational morphology, where bound morphemes can alter the meaning, and often the syntactic category, of the base word to which they are attached (Harley, 1995). In Mandarin, however, there is no inflectional morphology (i.e., no plural inflections on nouns or tense inflections on verbs) and very little derivational morphology (Bates, Devescovi & Wulfeck, 2001).

In most languages, there is an imperfect mapping between words and their exact meanings, but there are cross-linguistic differences in lexical ambiguity. In English, lexical ambiguity, such as the use of synonyms and homonyms, can be reduced by context (e.g., *the* brush versus *to* brush), or by prosodic cues (e.g., to re*cord* versus the *re*cord) (Bates *et al.*, 2001). In Mandarin, lexical ambiguity can be reduced by the use of contrasting tones in the auditory modality (Bates *et al.*, 2001) and context cues (in written form) in the visual modality.

The language-specific differences at the levels of orthography, phonology and semantics (as reviewed above) suggest that the underlying cognitive processes that mediate reading in English and Mandarin may be different. Localist dual-route theories of reading seem able to accommodate these differences. In what follows, I will use an example.

Dual-Route Model: Modularity and Reading

Cognitive theorists do not make explicit assumptions about the relationship between modules and neuroanatomy but the modularity hypothesis (Fodor, 1983) is implicit in fMRI research. A module consists of a self-contained set of processes (Harley, 1995). Modules can interact in at least two ways: (a) the output of one module may serve as the input of another module; and (b) two modules may act in parallel, either processing different aspects of the same stimulus or processing the same stimulus differently to produce an output based on the outcome of both modules. Even though modules interact with one another, they are conceptualized as autonomous and they can operate in isolation (Paradis, 1997). Thus, if the two languages of a bilingual are separable neuroanatomically, we may expect some differences in the modular system underpinning processing.

The dual-route model of reading (see Figure 2) is based on behavioural data from uniscriptal readers of English (Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001). Central to this framework is the concept of the mental lexicon, and each word's spelling (orthography), sound (phonology) and meaning (semantics) is stored in separate modules. The model asserts that two distinct routes exist for translating print to sound: a lexical (visual) route and a non-lexical (phonological) route.

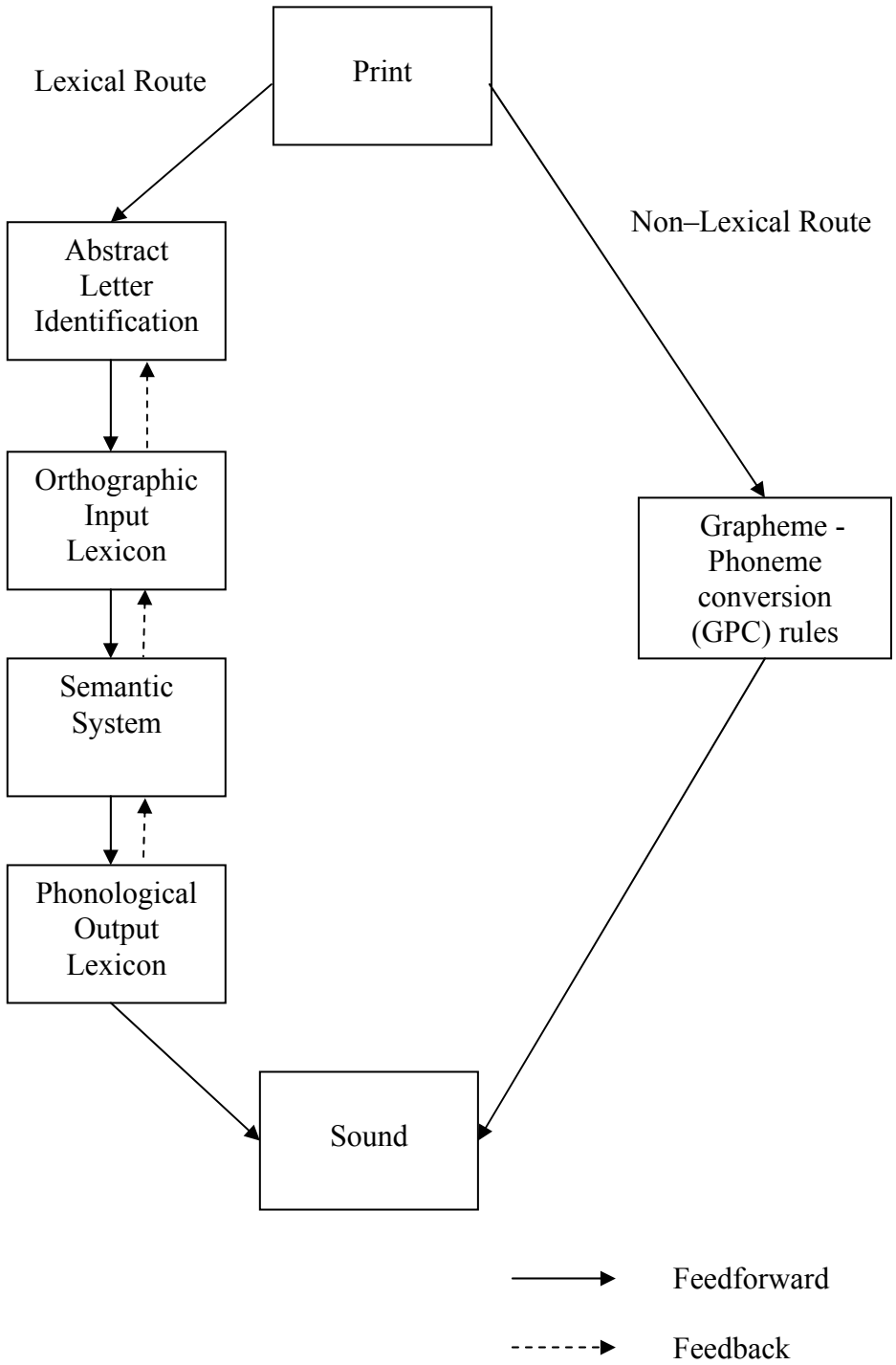

Figure 2. Basic architecture of the dual-route model of reading, adapted from Coltheart *et al.*, 1993, 2001; Kay, Lesser & Coltheart, 1992.

Lexical Route

The modules in the lexical route include an abstract letter identification system, an orthographic input lexicon, a semantic system and a phonological output lexicon (see Kay *et al.*, 1992 for details). The abstract letter identification module is a system

for recognizing the letters of a word, the orthographic input lexicon is a mental dictionary containing spellings of words known to the reader, the semantic system contains information about the meanings of words and the phonological output lexicon contains the sound representation of all the words known to the reader. Thus, when a printed word is matched with an entry in the orthographic input lexicon, the reader will be able to recognize, understand and read the word aloud. The lexical route is also called the visual route since it involves the direct 'look-up' of a word in the mental lexicon.

Non-lexical Route

The non-lexical route involves the 'grapheme to phoneme conversion (GPC) rules' module, which allows the word to be 'sounded out' by translating letter units (graphemes) into corresponding sound units (phonemes) by using a rule-based process (Fiez & Peterson, 1998). Thus, the non-lexical route allows the correct reading of pronounceable nonwords (e.g., 'meach') and regular words (i.e., words that obey the GPC rules). Exception or irregular words (i.e., words that violate the rules such as 'pint' or 'colonel') can only be read by using the lexical route (Coltheart *et al.*, 2001). The meaning of a word is irrelevant in the non-lexical route.

Evidence for Dual-Route Model

Evidence in support of the dual-route model comes from both brain-damaged patients and skilled readers. Patients with phonological dyslexia are able to read regular words but are unable to read pronounceable nonwords or pseudowords (e.g., 'sleeb'), suggesting that the lexical route is intact whereas the non-lexical route is impaired (Funnell, 1983; Lesch & Martin, 1998). In contrast, patients with surface dyslexia can often decode nonwords and regular words, but fail to read exception

words, indicating that the lexical route is impaired (Bub, Cancelliere, & Kertesz, 1985; McCarthy & Warrington, 1986).

For skilled readers, the word frequency by word regularity interaction was found in naming tasks (Paap, Chen & Noel, 1987; Paap & Noel, 1991). For high frequency words, whether the spelling to sound correspondence was regular did not affect naming latencies. For low frequency words, naming latencies for exception words were longer than naming latencies for regular words. It appears that regularity affects the naming of low frequency words more than high frequency words. In addition, the results indicate that both routes are activated in parallel and that the lexical route is faster than the non-lexical route. Thus, for high frequency words, the lexical route is often activated, even for regular words. For low frequency words, the non-lexical route takes precedence over the lexical route, thus requiring phonological mediation (Perfetti, 1999). Another robust finding is the *lexicality effect*, where readers name regular words faster than nonwords (McCann & Besner, 1987; Rastle & Coltheart, 1999). The explanation for this effect is that the non-lexical route can only process nonwords whilst both routes can process words. Since the lexical route is faster than the non-lexical route, the naming of words will be faster than nonwords.

Many of the assumptions held by the dual-route model have not gone unchallenged. Alternative models have been proposed to account for word reading (e.g., see Glushko, 1979; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989, etc. for alternative models), but fMRI research necessarily assumes a modular rather than a connectionist account, so these connectionist accounts will not be discussed further.

Language Representation in English and Chinese Unilinguals

The null findings for English-Chinese bilinguals were evaluated earlier so I will now review existing behavioural and neuroimaging studies that have investigated the orthographic, phonological and semantic processing in English and Chinese unilinguals.

Cognitive Processing of English and Mandarin Orthography

Given that the orthographic features of English and Mandarin are vastly different, and given the visual complexity of the basic graphemes in Mandarin, differences in the nature of processing might be expected. More specifically, Chinese characters may involve more visuo-spatial processing. Consistent with this, some studies (see Hasuike, Tzeng & Hung, 1986) have revealed that experience of reading Mandarin may confer an advantage on certain nonverbal tasks requiring visuo-spatial processing. Also, Huang and Hanley (1995) showed that performance on a test of visual memory (visual paired associate learning) was significantly related to the reading ability of the children in Hong Kong and Taiwan, but not to the reading of the British children reading English. Apart from suggesting processing differences, these results also imply that learning Mandarin may make greater memory demands on the learner than English. Studies of skilled adult readers suggest that Mandarin readers performed better in memory tasks under the visual presentation condition whilst English readers performed better under the auditory presentation condition (Fang, Tzeng & Alva, 1981; Turnage & McGinnies, 1973).

Cognitive Processing of English and Mandarin Phonology

Phonological processing refers to operations that involve the perception or production of speech sounds, i.e., phonemes, syllables, rhymes (see Rayner, Foorman, Perfetti, Pesetsky & Seidenberg, 2001, for review). According to Coltheart *et al.*'s

(2001) dual-route model, phonology can be assembled by the non-lexical route for reading in English. This process involves transforming printed graphemes into phonemes using a series of rules. In Mandarin, however, a single character maps onto a morpheme, not a phoneme. Although a phonetic component in the Chinese character may provide some clues about pronunciation, the components cannot be 'sounded out' in the same way they can in English (Bookheimer, 2001). Hence, the grapheme-to-phoneme rules for English have no equivalent in Mandarin. Of the 85% of compound characters that contain a valid phonetic component, it is estimated that only 38% of phonetic components actually provide the correct pronunciation to the character (Perfetti & Tan, 1999; Zhou, 1978; Zhu, 1988). Thus, the phonetic cueing value of the phonetic component is low and its relation to whole character phonology is not very systematic (Feldman & Siok, 1999).

The idea that character identification is not mediated by pre-lexical phonological recoding has also received support from studies of skilled Mandarin readers (Biederman & Tsao, 1979; Hoosain & Osgood, 1983; Leck, Weekes & Chen, 1995). Thus, pronouncing Mandarin involves making reference to stored representations of each character and its associated sound (Bookheimer, 2001). In fact, during the first six years of school, Mandarin-speaking children rote learn about 500 to 600 characters per year. By adulthood, they would have acquired a vocabulary of 5000 to 7000 characters (Rayner *et al.*, 2001). This further suggests that reading Mandarin may require more intensive memory resources than English.

The unique characteristics of written Chinese, and evidence from empirical studies, have led some researchers to conclude that lexical access for Chinese characters is via the direct visual route, unmediated by phonology (Shen & Forster, 1999; Tzeng & Hung, 1978; Wong & Chen, 1999). However, Perfetti, Tan and

colleagues (Perfetti & Tan, 1998, 1999; Perfetti & Zhang, 1995a, b; Tan, Hoosain & Peng, 1995; Tan, Hoosain & Siok, 1996; Tan & Perfetti, 1997) propose the 'identification-with-phonology' hypothesis, which posits that phonology is central to word recognition in Mandarin. Based on a series of priming experiments, the authors suggest that the phonological information of a character is activated very early in the course of character identification (e.g., Perfetti & Tan, 1998; Perfetti & Zhang, 1991; Perfetti, Zhang, & Berent, 1992; Tan & Perfetti, 1997).

Other studies have also provided support for the hypothesis that phonological processing does occur in Mandarin reading. For instance, the same interaction effect between frequency and regularity that was obtained for English words has been observed in the naming of low-frequency Chinese characters (Hue, 1992; Liu, Wu & Chou, 1996; Seidenberg, 1985). Seidenberg found that low-frequency regular characters (i.e., compound characters having the same pronunciations as their phonetic radicals) were named faster than low-frequency irregular characters. He hypothesized that in recognizing the low-frequency regular characters, pre-lexical phonological information provided by the phonetic component was activated and, thus, the phonological information facilitated the recognition speed of the character. This led him to assume that pre-lexical phonological processing played a role in Chinese character recognition as well. Likewise, Fang, Horng and Tzeng (1986) showed that the degree of consistency of a phonetic component could influence character naming. The consistency effect was also found in pseudo-characters. Other investigators, using a variety of experimental paradigms such as backward masking (Tan *et al.*, 1996), eye movements (Pollatsek, Tan, & Rayner, 2000), semantic categorization (Xu, Pollatsek, & Potter, 1999) and primed character decision (Weekes, Chen, & Lin, 1998) have also found support for the 'identification-with-phonology' hypothesis. These findings have

led to the suggestion that, in terms of phonological processing, reading in Mandarin may have more in common with English than previously assumed (Perfetti, Liu, & Tan, 2002; Seidenberg, 1985)

Despite this evidence in support of phonological activation in the reading of Mandarin, there is good reason to treat such findings with caution. A recent study by Chen and Shu (2001) questioned the reliability and validity of Perfetti and Tan's (1998) study. Using the same stimuli and procedure as Perfetti and Tan, they were unable to replicate the significant homophone priming effect in naming. Instead, they found that semantic, rather than phonological activation appeared early in the course of lexical access in Chinese character recognition. Chen (1996) had previously pointed out that the phonological effect observed in many of the studies could be due to the type of experimental paradigms employed, some of which (e.g., the naming or the rhyming judgement task used by Tzeng & Hung, 1980) specifically required the activation of the phonological code in the character. When non-phonological tasks were used (e.g., the semantic categorization task), phonological effects were not observed (Chen, Flores d'Arcais, & Cheung, 1995; Leck *et al.*, 1995).

Thus, it seems that phonological activation in Mandarin reading is not a very robust phenomenon and that further research would have to be carried out before a consensus is reached. Even if Mandarin reading does involve phonological activation, it seems unlikely that it will be founded on the same processes that are invoked for English. Bertelson, Chen and Gelder (1997) pointed out that the phonological information carried by Chinese characters is *holistic* at the level of the syllable. In the case of English, phonological processing involves the *assembling* of multi-letter units. The process of assembly (i.e., a function of the non-lexical route) is simply not possible in Chinese characters. Furthermore, given the extensive number of compound

characters in existence, the number of pronunciation rules (i.e., such as grapheme to phoneme rules) would be unwieldy at the sub-character level for Mandarin (Liu, 1997). Even with a fully regular phonetic component, nothing in the pattern of strokes will help readers infer pronunciation unless they have encountered the component before and have committed it to memory.

Another important consideration is the processing of tonal information in Mandarin, which has no equivalent in English. The nature of tonal processing was investigated by Spinks, Liu, Perfetti, and Tan (2000). Using a Stroop color-word task, participants were required to name the ink colour of characters or colour patches. The key stimuli were colour characters, their homophones with the same tone, homophones with different tones, and semantic associates. The authors found that homophones produced significant interference in the incongruent condition, provided that they had the same tone as the colour characters. These findings suggested that a Chinese character's phonological code included both the segmental (consonants and vowels) and suprasegmental (tone) information.

In light of the existing findings, it is reasonable to assume that English word recognition involves both the lexical and non-lexical routes, whilst the recognition of Chinese characters relies more on the direct lexical route. Furthermore, the cognitive processing of Chinese characters involves the additional processing of tonal phonology and the utilization of extra memory resources as compared to English.

Cognitive Processing of English and Mandarin Semantics

Semantic processing refers to the encoding or analysis of word meaning (Demb, Poldrack, & Gabrieli, 1999). As a Chinese character maps onto a morpheme, it has often been assumed that the correspondence between its graphemes and meaning is more direct than other writing systems (Tan & Perfetti, 1998). Fan (1986) estimates

that as many as 80% of compound characters have semantic radicals that provide useful cues to the meaning of the whole character. This indicates that the orthography-to-meaning relationship is more transparent for readers of Mandarin than readers of English. The meaning of English words is not only more opaque, there are no physical boundaries separating morphemes as there are in Chinese characters.

Several studies have provided support for the hypothesis that Chinese characters invoke meaning much faster than do words in an alphabetic language (Biederman & Tsao, 1979; Hoosain & Osgood, 1983; Treiman, Baron, & Luk, 1981). However, others suggest that access to semantics in Mandarin may not be that direct (Tan *et al.*, 1996). As mentioned earlier, although Chinese characters can exist alone as single-character words, they are often used with others to form multiple-character words with distinctively different meanings. Thus, the activation of meaning for some Chinese characters is difficult when the characters appear out of context (Tan & Perfetti, 1998). For example, the character 服 /fu2/ is defined as follows in the dictionary: (a) clothes or dress; (b) take (medicine); (c) serve; (d) be convinced, obey; (e) be accustomed to; (f) dose; and (g) surname. The first four meanings are more frequently used but none can be taken to be the dominant meaning. Tan *et al.* (1996) found that participants had difficulty expressing this character's meaning: they either reported different meanings or were unable to define its meaning. This simple phenomenon was referred to as the semantic uncertainty effect.

Despite the controversy concerning semantic activation in reading Mandarin, Zhou, Shu, Bi and Shi (1999) proposed that the direct visual route is still the predominant way to access lexical semantics, and that phonology has a limited effect on semantic activation in the time course of processing Chinese characters. However, in English, because the mapping from orthography to phonology is much more

systematic than the mapping from orthography to semantics, phonology could be activated much earlier than semantics. Thus, phonological mediation is often considered the predominant process in lexical access (Lukatela & Turvey, 1994a, 1994b; van Orden, 1987; van Orden, Pennington, & Stone, 1990) and direct visual access plays a relatively minor role.

Comparing the Neuroanatomical Representation of English and Mandarin Orthography

Neuroanatomical Representation of English Orthography

The proliferation of neuroimaging studies of orthographic processing in English unilinguals makes a summary difficult. Researchers have used a variety of tasks and found activations in many different brain regions. Experimental paradigms that have been developed to tap orthographic processing include single word reading (e.g., Howard *et al.*, 1992; Petersen, Fox, Posner, Mintun, & Raichle, 1988,1989; Petersen, Fox, Snyder & Raichle, 1990; Small *et al.*, 1996), verbal fluency or word generation (e.g., Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995; Friedman *et al.*, 1998; Paulesu *et al.*, 1997; Rueckert *et al.*, 1994), and case judgement on letter strings (e.g., Pugh *et al.*, 1996; Shaywitz *et al.*, 1995). These tasks were all designed to examine access to and the functioning of the orthographic lexicon (Joseph, Noble & Eden, 2001), yet the specific brain regions related to orthographic processing vary considerably. The disparity in the findings might be attributable to differences in experimental design, stimuli (words, pseudowords, letter strings, etc.), baseline tasks (fixation, line orientation judgement, etc.), and imaging method (PET, fMRI, etc.) across studies. Nevertheless, the common brain regions associated with orthographic processing of English words are: (a) the bilateral extrastriate cortices, BAs 18 and 19, (e.g., Petersen *et al.*, 1988, 1989, 1990; Pugh *et al.*, 1996); (b) the left medial extrastriate cortex, (e.g., Menard, Kosslyn, Thompson, Alpert, & Rauch, 1996;

Petersen *et al.*, 1990; Price *et al.*, 1994; Pugh *et al.*, 1996); (c) the ventral occipital-temporal areas, such as the lingual and fusiform gyri, BAs 18, 19, 37, (e.g., Kuriki, Takeuchi, & Hirata, 1998; Petersen *et al.*, 1990; Polk & Farah, 1998; Pugh *et al.*, 1996); and (d) the left inferior frontal cortex, BAs 44, 45 (Friedman *et al.*, 1998; Paulesu *et al.*, 1997; Rueckert *et al.*, 1994). See Table 1 in Appendix A for a summary of the neuroimaging studies related to orthographic processing in English unilinguals.

Joseph *et al.* (2001) noted that many of the tasks that have presumed to tap orthographic processing might also involve phonological decoding and even automatic activation of semantic processing. For example, in the word generation task, participants are presented with a single letter and instructed to generate a word that begins with the given letter. Although access to the orthographic lexicon is required in order to generate a word, participants may use phonological strategies by converting the given visual letter into a corresponding sound before retrieving words from the phonological lexicon (see Friedman *et al.*, 1998). Also, other neuroimaging studies have suggested that the left frontal gyri (BAs 44, 45) contribute to the semantic rather than orthographic processing of words (e.g., Buckner & Petersen, 1996; Buckner, Petersen, & Raichle, 1995; Demb *et al.*, 1995; Gabrieli *et al.*, 1996). Thus, Joseph *et al.* concluded that there might be a great deal of overlap in terms of brain activation for both orthographic and phonological processing even though the tasks sought to tap only orthographic processing.

Neuroanatomical Representation of Mandarin Orthography

Compared to the neuroimaging studies on English reading, there have been relatively few studies looking at the neural correlates of reading in Mandarin. Tan *et al.* (2000) employed the word generation task to investigate the neural correlates of Chinese character and word reading. The task used was similar to the verb generation

task developed by Petersen *et al.* (1988) to investigate the orthographic processing of English words. During the scanning procedure, participants were instructed to covertly generate a word that was semantically related to a visually presented stimulus. Three types of stimuli were used in the study: (a) semantically vague Chinese single characters (i.e., single characters having vague and several frequently used meanings); (b) semantically precise Chinese single characters (i.e., single characters having precise and dominant meanings); and (c) two-character Chinese words. When compared with the control conditions (i.e., fixation task), the investigators found peak activations in the left middle frontal gyrus (BA 9, 46), left temporal fusiform gyrus (BA 37), right postcentral parietal gyrus, and right occipital lingual gyrus or cuneus (BA 17, 18) for all three types of stimuli. Significant activations were also found in the left supplementary motor area (BA 6), left superior parietal lobule (BA 7), and left middle occipital gyrus (BA 18), but activations in these areas were much weaker compared to the activations in the middle frontal gyrus (BAs 9, 46). Generally, brain activations were strongly left lateralized in the frontal and temporal (BA 37) cortices but right lateralized in the occipital cortex (BAs 17-19) and parietal lobe (BA 3). However, the overall brain activations for both single and two-character words showed strong left lateralization, without dissociation in laterality pattern. See Table 2 in Appendix A for a summary of the neuroimaging studies related to orthographic processing in Chinese unilinguals.

Again, the word generation task is likely to involve both orthographic and semantic processing and thus, the pattern of activation observed may not be due to orthographic processing alone. Also, due to the nature of the task (i.e., covert word generation), participants' responses were not monitored during the fMRI study. Thus,

as Tan *et al.* (2001) acknowledged, it was not entirely clear which cognitive processes were engaged in this experiment.

Differences in the Neuroanatomical Representation of English and Mandarin Orthography

The neural correlates of orthographic processing in English appear to be characterized more by activations in the occipital lobes. Specifically, several studies have suggested that the left medial extrastriate cortex in the occipital lobe is involved in the recognition of word forms that obey English spelling rules (e.g., Petersen *et al.*, 1988, 1989, 1990; Pugh *et al.*, 1996). For example, Petersen *et al.* (1990) found that the left medial extrastriate cortex was activated by words and pseudowords (e.g., 'tweal'), but not by illegal consonant strings (e.g., 'ntwxz'). However, other studies (e.g., Howard *et al.*, 1992; Menard *et al.*, 1996) did not support this proposal. A recent fMRI study conducted by Indefrey *et al.* (1997) failed to find any significant activation in the medial extrastriate region for pseudoword strings compared to false font strings (i.e., the false font strings were created by recombining character elements, such as ascending, descending, horizontal, and curved lines, of the font type, *Arial*). Bookheimer *et al.* (1995) reported activations in the left medial extrastriate region for both word reading and object naming. Despite the inconsistencies reported, Demb *et al.* (1999) note that the majority of evidence from neuroimaging studies suggests that the medial extrastriate cortex is activated by English word forms.

By contrast, the processing of Mandarin orthography is characterized by peak activations in the left middle frontal cortex (BAs 9 and 46), located in the frontal lobes. Note that BAs 9 and 46 are also collectively referred to as the dorso-lateral prefrontal cortex (DLPFC) in the literature. The peak activations observed in the DLPFC led Tan (unpublished) to suggest that this brain region is the "center" of Mandarin reading.

Tan *et al.* (2001) noted that the DLPFC is not commonly reported in past investigations with English word recognition and reading. Even for studies that report activations in this region, a much weaker activation is noted for native English readers (Poldrack *et al.*, 1999; Price, Moore, Humphreys, & Wise, 1997; Warburton *et al.*, 1996; Wise *et al.*, 1991).

Many neuroimaging studies have consistently demonstrated that the prefrontal cortex is involved in working memory and memory retrieval; both episodic and semantic (see Cabeza & Nyberg, 2000, 2002; Fletcher & Henson, 2001 for review). Working memory (WM) generally refers to the collection of mental processes that permit the temporary storage and manipulation of information during the performance of some complex cognitive task like language, planning and spatial processing (Baddeley, 1986). According to Baddeley's (1986, 1998) theoretical model of WM, there are three main components in WM: a phonological loop for the maintenance of verbal information, a visuo-spatial sketchpad for the maintenance of visuo-spatial information, and a central executive for attentional control and manipulation of the information that is being maintained (Cabeza & Nyberg, 2000).

Neuroimaging studies involving WM have provided considerable evidence that there are anatomical divisions within the prefrontal cortex that subserve different functions. It has been suggested that the DLPFC (BAs 9 and 46) and anterior frontal cortex (AFC, BAs 8 and 10) are associated with the executive control of working memory (see Fletcher & Henson, 2001, for review). Specifically, the DLPFC appears to be engaged in manipulation processes that operate on information already maintained in memory, whilst the AFC appears to be involved in more complex processes that entail maintaining the goals and products of one task while performing another. Although these high-level processes are preferentially lateralized to the left

for verbal material and lateralized to the right for spatial material (Fletcher & Henson, 2001), some investigators (e.g., Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; McCarthy *et al.*, 1994; Owen, Doyon, Petrides, & Evans, 1996) have demonstrated that the left DLPFC may also subserve the processing of spatial and object working memory, thus allowing a limited amount of spatial information to be maintained in an active state for a brief period of time. This led Tan *et al.* (2001) to posit that activation in the left DLPFC is associated with the unique square configuration of Chinese characters, which requires the fine-grained analyses of the visuo-spatial locations of strokes and sub-character components.

Comparing the Neuroanatomical Representation of English and Mandarin Phonology

Neuroanatomical Representation of English Phonology

The activation areas identified for phonological processing of English words vary in previous research. Again, the discrepancies in activation foci may be due to the diverse range of experimental paradigms employed by investigators. Access to the phonological components of language 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, Zuck, Levesque, & MacDonald, 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; Demonet, Price, Wise, & Frackowiak, 1994), nonword reading (e.g., Herbster, Mintun, Nebes, & Becker, 1997; Rumsey *et al.*, 1997), etc. The brain regions commonly reported across tasks include: (a) the left inferior frontal gyrus, BA 44, 45 (Herbster *et al.*, 1997; Paulesu, Frith, & Frackowiak, 1993; Rumsey *et al.*, 1997; Sergent *et al.*, 1992; Zatorre, Evans, Meyer, & Gjedde, 1992); (b) 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); and (c) 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). See Table 3 in Appendix A for a summary of the neuroimaging studies related to phonological processing in English unilinguals.

Neuroanatomical Representation of Mandarin Phonology

Tan *et al.* (2001) used a homophone decision task to investigate the neural correlates of Mandarin phonology. Participants were instructed to judge if two characters they viewed were homophones. For the homophone judgement task, relative to fixation, the investigators reported peak activation in the left middle frontal gyrus (BA 9). 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 postcentral 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 in the bilateral 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).

Two recent neuroimaging studies have also investigated the phonological processing of *lexical tones* in Mandarin. Using Positron Emission Tomography (PET), Hsieh, Gandour, Wong, and Hutchins (2001) conducted a crosslinguistic study to determine the influence of linguistic experience on the perception of segmental (consonants and vowels) and suprasegmental (tones) information. Both English (i.e., native speakers of American English) and Chinese (i.e., native speakers of Mandarin) participants were presented binaurally with lists consisting of five Chinese

monosyllabic morphemes (speech) or low-pass-filtered versions of the same stimuli (nonspeech). PET scans were acquired for five tasks presented twice: one passive listening to pitch (nonspeech) and four active tasks (speech = consonant, vowel, and tone; nonspeech = pitch). In the four active conditions, participants were required to make discrimination judgements of consonants, vowels, tones, and pitch patterns that occur in the first and last syllables of each list, ignoring the intervening syllables. In the passive listening condition, participants were required to listen to the filtered speech stimuli, alternately clicking the left and right mouse button after each list. Significant regional changes in blood flow were identified from comparisons of group-averaged images of active tasks relative to passive listening. Chinese participants showed increased activity in the left premotor cortex, pars opercularis (BA 44), and pars triangularis (BA 45) across the four tasks whilst English participants showed increased activity in the left inferior frontal gyrus regions only in the vowel task and in the right inferior frontal gyrus regions for the pitch task.

In the second study, Klein *et al.* (2001) compared tone perception in twelve native Mandarin speakers with that of twelve native English speakers using PET. Participants were scanned under two conditions: a silent resting baseline and a tonal task involving discrimination of pitch patterns in Mandarin words. Although both groups showed common regions of cerebral blood flow (CBF) increase, the most notable findings were the hemispheric differences between CBF activations for the two groups of participants. CBF changes observed only for the *Mandarin* speakers were all in the *left* hemisphere - in the ventromedial orbital frontal cortex, frontopolar cortex, pre- and postcentral gyri, in the inferior and superior parietal cortex, and in the lateral occipital-temporal and middle occipital gyri. By contrast, relative to the Mandarin speakers' activations, the only CBF changes observed for the *English*

speakers were in the *right* hemisphere, in the right ventrolateral frontal cortex, anterior orbitofrontal gyrus, lateral orbital gyrus, in the cingulate region, and in the superior temporal gyrus. Only the native English speakers showed activity in right inferior frontal cortex. The investigators attributed the lateralization effect to crosslinguistic differences because the tones were meaningful only to the Mandarin speakers (see also Van Lancker & Fromkin, 1973, for an earlier laterality study with a similar conclusion). See Table 4 in Appendix A for a summary of the neuroimaging studies related to phonological processing in Chinese unilinguals.

Differences in the Neuroanatomical Representation of English and Mandarin Phonology

It appears that the brain regions activated by the phonological processing of English words are located mainly in the left hemisphere. Specifically, the *left* superior temporal regions have been identified as being responsible for 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 is 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. According to Tan *et al.*, the right prefrontal regions subserve episodic memory processes by which the spatial features of perceived objects are retrieved (e.g., Haxby *et al.*, 1996; Kapur, Friston, Yong, & Frith, 1995; Lepage, Ghaffar, Nyberg, & Tulving, 2000; Nyberg *et al.*, 1996b), whilst the right superior and inferior parietal lobules are activated in spatial working memory tasks (e.g., Courtney *et al.*, 1998; Haxby, Ungerleider, Horwitz, Rapoport, & Grady, 1995; Jonides *et al.*, 1993; McCarthy *et al.*, 1994). Note 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 & Nyberg, 2000, pp. 26). Thus, the investigators posit that the right prefrontal and parietal regions are involved in perceiving the spatial locations of the strokes and the processes of stroke combinations.

As for tasks that require the phonological processing of lexical tones, it appears that *Mandarin* speakers recruit the *left* cortical areas whilst *English* speakers recruit the *right* cortical regions in the perception of suprasegmental (tone) information.

Comparing the Neuroanatomical Representation of English and Mandarin Semantics

Neuroanatomical Representation of English Semantics

Experimental paradigms that have been developed to isolate the semantic processing of English words usually require participants to make judgements concerning word meaning or determine if the stimulus is a member of a designated category (Joseph *et al.*, 2001). Neuroimaging studies investigating the semantic processing of English words have reported brain activations in the left inferior frontal cortex (i.e., BA 44, 45, 46, 47) (e.g., Demb *et al.*, 1995; Gabrieli *et al.*, 1996; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999) and in the left superior, middle and inferior temporal cortices (e.g., Binder *et al.*, 1995; Demonet *et al.*, 1992; Herbster *et al.*, 1997; Pugh *et al.*, 1996). These areas were identified using a variety of experimental paradigms that included word generation (e.g., Fiez & Petersen, 1993; McCarthy, Blamire, Rothman, Gruetter, & Shulman, 1993; Petersen *et al.*, 1988, 1989), categorical judgements (e.g., Demonet *et al.*, 1992; Price *et al.*, 1997; Pugh *et al.*, 1996), semantic monitoring, such as verb-noun comparison (e.g., Binder *et al.*, 1995; Demb *et al.*, 1995; Warburton *et al.*, 1996; Wise *et al.*, 1991), etc. Recent studies also suggest that the posterior temporal regions

may be responsible for the maintenance of semantic knowledge, whilst the inferior prefrontal regions may be involved in the executive processes of retrieving semantic information (see Fiez & Petersen, 1998). See Table 5 in Appendix A for a summary of the neuroimaging studies related to semantic processing in English unilinguals.

Neuroanatomical Representation of Mandarin Semantics

Tan *et al.* (2001) used a semantic judgement task to investigate the semantic processing of Mandarin. During the scanning procedure, participants were required to judge whether the two characters they viewed were semantically related. The comparison of the semantic judgement task with the fixation task produced a pattern of activation that encompassed the left middle frontal gyrus (BA 9), bilateral inferior and middle prefrontal gyri (BAs 45/47/11), bilateral anterior frontal cortex (BA 10), and precentral (motor) gyri (BAs 6 and 4). Other significant brain activations included the bilateral superior parietal lobules (BA 7), bilateral supramarginal gyrus (BA 40) and left infero-middle gyrus (BA 18). Activations in the right cortex covering the cuneus, fusiform, and inferior gyrus were stronger than activations in the left cortex. Activations in the temporal lobe were localized to the right superior and middle gyri (BA 38). The investigators noted that peak activation was again located in the left middle frontal cortex (BA 9). See Table 6 in Appendix A for a summary of the neuroimaging studies related to semantic processing in Chinese unilinguals.

Differences in the Neuroanatomical Representation of English and Mandarin Semantics

The semantic processing of Chinese characters seems to involve a more distributed neural network that spans both hemispheres whilst the activation observed for the semantic processing of English words is localized mainly in the left hemisphere. Specifically, the neural correlates of semantic processing in English

words are located mainly in the frontal and temporal regions of the left hemisphere. By contrast, Tan *et al.* (2001) reported bilateral activations in the frontal and parietal regions for the semantic processing of Chinese characters.

In summary, empirical evidence from psycholinguistic research on unilinguals suggests that there are differences in the neuroanatomical representation and cognitive processing of English and Mandarin at the levels of orthography, phonology and semantics. The crucial question is whether some or all of these crosslinguistic differences are evident in English-Chinese bilingual biscriptals. Specifically, are the brain regions at each level of language processing in bilinguals common or distinct? In order to address this question, it is first necessary to understand the basis of fMRI as a neuroimaging technique and how it is used to visualize brain activation associated with cognitive processing.

Functional Magnetic Resonance Imaging (fMRI)

Neuroimaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have been extensively used to explore the neural correlates of higher cognitive functions such as language and memory. More importantly, these techniques have helped cognitive neuroscientists to localize and elucidate the components of cognitive processing in the healthy human brain (Abutalebi, Cappa, & Perani, 2001). PET and fMRI are referred to as hemodynamic techniques because they investigate neural activity by measuring changes in metabolism or blood flow (Cabeza & Nyberg, 2000). Changes in behavioral and cognitive task demands lead to changes in neural activity, and this increased neural activity results in increased blood flow to the active brain region (Raichle, 1987). PET measures neural activity through blood property change relating to *blood flow* whilst fMRI measures neural activity indirectly, through changes in *oxygen content* of the

blood (Buckner & Logan, 2001). In the following sections, I will review the basic concepts and experimental design related to fMRI.

Physiological Basis of fMRI

In most fMRI studies, neural activity is detected using the blood oxygenation level dependent (BOLD) contrast mechanism (Miki *et al.*, 2001). The principle behind the BOLD method (Ogawa, Lee, Kay, & Tank, 1990a) is as follows: When a brain region is activated, it triggers an increase in blood supply which delivers more oxygen (carried by hemoglobin in the bloodstream) than is needed to meet metabolic demand. Since the activated neurons do not consume more oxygen, the net result is an increase in oxygenated blood and a relative decrease in deoxyhemoglobin concentration in the blood (when oxygen is absorbed, the hemoglobin becomes deoxygenated). Deoxyhemoglobin is paramagnetic, relative to oxyhemoglobin and the surrounding brain tissue (Ogawa, Lee, Nayak, & Glynn, 1990b), and this causes an increase in signal intensity with specific MRI pulse sequences that are sensitive to the inhomogeneity of magnetic fields (Kwong *et al.*, 1992). Thus, deoxyhemoglobin acts as an endogenous contrast agent in the BOLD method (Miki *et al.*, 2001).

Design of the fMRI Experiment

In most studies, MR images are obtained in at least two different conditions – a baseline, or resting state and an activation state (i.e., whilst engaging in an experimental task). In a 'block design' experiment, blocks of resting and activation conditions (in which stimuli are presented for fixed periods of time) are alternated during functional scanning. Block design is based on the 'pure insertion' hypothesis (Friston, 1997), which assumes that task-related neural activities add up linearly, with no interaction between tasks (Di Salle *et al.*, 1999). During functional scanning, fast imaging methods, such as echoplanar imaging (EPI) permits multi-slice images of the

brain to be taken repeatedly, and in sequence within a few seconds (Klose, Erb, Raddi, & Grodd, 1999).

In order to compare neural activity between the activation and baseline states, subtraction images are created by taking the difference between the two conditions. The logic of this comparison is that brain activity will change between the two states and any brain region showing relative increased activity is assumed to be engaged in the cognitive processing of the activation task (Cabeza & Nyberg, 2000).

However, the block design suffers from a number of drawbacks (see Bub, 2000, for critical review). The main criticism of this approach is that there is no guarantee that the processing components unique to the activation state will not interact with the processing components in the baseline state during the scanning procedure. As it is difficult to truly isolate mental processes unique to the experimental state, it has been suggested that this limitation can be overcome by providing behavioural data, along with imaging data, to demonstrate the behavioural differences between tasks outside the MRI scanner (Raichle *et al.*, 1994).

Block design is the most time-efficient method of comparing brain responses to different tasks during the imaging experiment (see Friston, Zarahn, Josephs, Henson, & Dale, 1999). Matthews (2001) has argued recently that it "remains an ideal design for many types of experiment, particularly in an early, exploratory stage" (p. 18). For these reasons, block design was used for the fMRI experiment, and I used parallel tasks to collect behavioural data, with both reaction times and error rates as dependent variables.

Neuroanatomical Representation of fMRI Data

The specific locations of activated brain regions are often expressed in the form of three-dimensional coordinates according to the atlas of Talairach and Tournoux

(1988): x (left/right), y (anterior/posterior), and z (superior/inferior). The use of these stereotaxic coordinates allows fMRI results to be presented in a standard format, and facilitates the comparison of results across studies. Some studies also report fMRI results with reference to Brodmann's cytoarchitectonic map (Brodmann, 1909). Cytoarchitectonic maps (see Figure 1 on pp. 5) are constructed according to the type of cell that exists in specific regions of the brain. In Brodmann's map, there are more than 50 areas identified on the basis of cytoarchitectonic criteria, and there is good correlation between these areas and underlying brain function. For example, Area 44 corresponds to Broca's area, an area related to speech production (Martin, 1998). As Brodmann's map is widely used as a guide to the brain's regions, the results presented in this study will be discussed with reference to Brodmann's cytoarchitectonic map.

Individual Versus Group Analysis of fMRI Data

The statistical analysis of fMRI data remains a challenge although averaging across participants is still used in most fMRI studies (e.g., Kim *et al.*, 1997; Tan *et al.*, 2001). Demb *et al.* (1999) have argued that averaging functional data may result in reduced activation because of the inter- and intra- individual anatomical variation, and this in turn can lead to reduced overlap of similar functional regions across brains. Another problem related to averaging is that the contribution of each participant to the group result remains unknown (Coulon *et al.*, 2000). Thus, in order to preserve individual information, and to overcome the possible limitations of the spatial normalization used to compare different participants, the activations detected at the individual level will be analyzed, but only the most commonly and consistently activated regions across participants will be reported.

Limitations of fMRI

The limitations of BOLD fMRI must be acknowledged. Firstly, it is extremely sensitive to motion artifacts. Brain motion arising from participant movement or even motion associated with respiratory and cardiac cycles can disrupt the data acquisition process. Another limitation is that BOLD fMRI does not allow uniform brain sampling. Problems related to the physics of image acquisition mean that activations in the orbital frontal cortex, and the anterior temporal regions, are difficult to detect (Buckner & Logan, 2001). Lastly, fMRI has poor temporal resolution. Electromagnetic techniques such as ERPs (event-related potentials) and MEG (magneto-encephalography) both measure neural activity directly and can identify changes within milliseconds, but the temporal resolution of fMRI is rather limited because a BOLD response can take several seconds (Cabeza & Nyberg, 2000).

Advantages of fMRI

fMRI has several potential advantages over PET techniques used in other studies of language. PET requires an intravenous injection of a radioactive isotope, but fMRI is a relatively safe, noninvasive procedure that may be used repeatedly on the same individual. Also, more complex experimental designs (e.g., parametric and multi-factorial designs) can be used with fMRI (Frackowiak & Friston, 1995). Other advantages of fMRI include its superior spatial resolution and the speed with which fMRI data can be acquired (Miki *et al.*, 2001).

Past research on the cerebral lateralization of language in bilinguals relied largely on behavioural techniques like tachistoscopic presentation (Albert & Obler, 1978; Vaid, 1987), dichotic listening (Galloway & Scarcella, 1982), monaural presentation (Vaid & Lambert, 1979), and bilateral visual presentation (Hoosain & Shiu, 1989). Researchers using these techniques often report either nonsignificant or

conflicting results (see Paradis, 1990, 1997 for critical review) but recent meta-analytic reviews suggest that there is a difference in lateralization between bilinguals and unilinguals and between early and late bilinguals (Hull & Vaid, 2003; Vaid & Hall, 1991). The main disadvantage of using laterality techniques is that the conclusions are limited to finding which cerebral hemisphere is dominant for the languages or language tasks in question. With the advent of neuroimaging techniques like fMRI, researchers can determine both the inter- and intra-hemispheric lateralization of one language relative to another in the bilingual brain. Furthermore, neuroimaging data can also reveal the precise locations of the brain regions that are associated with the subcomponents of language processing, and determine if common or distinct neural substrates are activated across the two languages.

Objectives of the Present Study

Given that English and Mandarin are based on such different writing systems, it is surprising that neuroimaging studies involving English-Chinese bilinguals have so far failed to demonstrate any difference in their neuroanatomical representation. Behavioural research suggests there are differences in the cognitive processing of English and Mandarin at the levels of orthography, phonology and semantics. Neuroimaging studies on English and Chinese unilinguals also suggest that the neural correlates for both languages differ. Thus, there is good reason to predict that the neuroanatomical representation of both languages might differ in one or more of the three main components of language processing in English-Chinese bilingual biscriptals.

The main aim of this study is to investigate the differential processing of English and Mandarin for orthographic, phonological and semantic processing at both the cognitive and neuroanatomical level. At the cognitive level, reaction times and

error rates of the various language tests will be measured to assess task demands. At the neuroanatomical level, the neural correlates of both languages will be compared across the three components of language processing using fMRI. The behavioral data can give an indication of the differences in cognitive processing whilst fMRI data provides information about the loci of processing in the brain.

Language processing will be tested at the single word level for two reasons: (a) the sentential level involves more complex cognitive processing and makes it difficult to tease apart any differences at the neuroanatomical level; and (b) to date, there are no reports of fMRI or PET experiments employing a comprehensive language battery (across the three components of language processing) on English-Chinese bilinguals at the single word level.

Besides being theoretically driven by extant models of language, e.g., the dual-route model, the experimental tasks were also designed to test specific components of language. The tasks for English and Mandarin were matched as closely as possible to ensure that the cognitive demands were comparable across languages.

At the *orthographic* level, the lexical decision task was used to investigate the visual processing of word or nonword, and character or non-character, in English-Chinese bilingual biscriptals. Given that the visual features of English and Mandarin are completely different, it is expected that their neuroanatomical representations may differ in the occipital regions (i.e., in the striate or extrastriate cortices). Also, as reading in Mandarin may involve greater memory demands, the pattern of neural activation across the two scripts may also differ in the frontal regions (Fletcher & Henson, 2001).

At the *phonological* level, a homophone matching task was used to investigate aspects of phoneme and tone processing. The neuroanatomical representation for the

two languages was expected to be very different at this level because Mandarin is a tonal language whilst English is nontonal. The task required participants to judge if character pairs presented in Mandarin have the same tone and whether word pairs presented in English have the same string phonology. As reading in Mandarin requires the additional processing of tonal information, the Mandarin task should elicit more distinct and/or greater cortical activation in some brain regions than English.

At the *semantic* level, a synonym judgement task was used to investigate processes related to the semantics of words and characters. Participants were instructed to judge if pairs of stimuli have the same or similar meaning. Some investigators have demonstrated that there are spatially segregated cortical areas where electrical stimulation interfered with naming in Chinese-English polyglots (Rapport, Tan, & Whitaker, 1983), but others have demonstrated that common cortical areas are activated during a lexical search task in English-Chinese fluent bilinguals (Klein *et al.*, 1999). It was not clear whether separate neural representations for semantic processing in English and Mandarin would be observed, but, a priori, more overlap for English and Mandarin was expected for synonym judgement than for lexical decision or homophone judgement.

CHAPTER 2

METHOD

The behavioral study was conducted to ascertain participants' accuracy scores and response latencies and, thereby, to determine the relative processing demands of the parallel English and Mandarin reading tasks. During the imaging experiment, error responses but not response latencies were recorded due to the physical constraints of the fMRI setup. The pool of experimental stimuli used for the behavioural experiment and the fMRI experiment were the same.

Participants

Forty-one undergraduate students (33 females and 8 males) from the National University of Singapore, ranging in age from 18 to 23 years, participated in the behavioral study. They received S$15 upon completion of the experiment. Six right-handed volunteers (3 males and 3 females), with no known neurological disorders, were then recruited from the behavioral study group to participate in the imaging study. They gave informed consent and received S$40 for their participation. A summary of their language backgrounds is shown in Table 7. The Ethics Committee of Department of Social Work and Psychology, National University of Singapore and the Ethics Board of the Singapore General Hospital approved the imaging study. Although all participants knew that they were volunteering for a scientific experiment concerning language, they were unaware of the specific research aims.

Table 7

Language background characteristics of fMRI participants.

Participant	Sex	Age	Age English Exposure	Age Mandarin Exposure	Dialects Spoken at Home	Other Languages
1	F	19	3	1	Cantonese	None
2	F	19	4	2	Hokkien	Japanese
3	F	19	3	1	Teochew	None
4	M	23	5	2	Futsig	None
5	M	21	7	5	Hokkien	None
6	M	21	5	1	Hokkien, Teochew	None

All participants were screened behaviourally for language abilities using the Language Background Questionnaire (Rickard Liow & Poon, 1998) and a battery of language subtests (Rickard Liow & Wee, unpublished) (see Appendix B). The three criteria for inclusion in this study were that participants: (a) scored at least 70% or better in accuracy for all the language screening tests, as these scores were used as an indication of competence in both languages; (b) be right-handed (based on self-report); and (c) have no known history of neurological impairment.

Design

A 2 X 3 repeated measures design was used to investigate two main independent variables: language (English or Mandarin) and type of task (Lexical Decision, Homophone Matching or Semantic Judgement task).

Materials

The three language tasks were designed to investigate the major components of language processing: orthography, phonology and semantics in English-Chinese bilingual biscriptals. The English and Mandarin versions of the tasks were matched as closely as possible across languages but even so, some variation in task demands was expected given the contrasting nature of the two scripts.

At the phonological and semantic levels, the stimuli for the English tasks were adapted from subtests found in the Psycholinguistic Assessment of Language Processing Abilities (PALPA) battery developed by Kay *et al.* (1992). The PALPA battery is founded on the assumption of modularity and is based on the dual-route model (Coltheart, 1978). Subtests in PALPA incorporate a range of psycholinguistic principles to assess cognitive processes concerned with the recognition, comprehension and production of spoken and written words and sentences.

Parallel stimuli for the Mandarin tasks were compiled using a psycholinguistic database developed by Wee & Rickard Liow (unpublished manuscript). Appendix C lists the stimuli used in both English and Mandarin tasks. Note that the stimuli used in the Mandarin tasks were matched in terms of *relative* language frequency, rather than absolute values, because there are many more different words in English than there are different characters in Chinese.

Stimuli

The number of trials for each of the three tasks was determined in pilot behavioural studies with five participants. Based on participants' feedback, the number of trials for the Mandarin tasks had to be reduced. Note also that the timing for each trial was necessarily based on the run-time for the fMRI experiment. The activation condition for each run in the fMRI experiment lasted a total of 120 s, so the timing of each stimulus was derived by dividing the total time for the activation condition by the number of trials.

Language Experiments Involving Orthographic Processing

English Lexical Decision Task

Stimuli consisted of words and nonwords, each 5 letters in length. They were divided into 4 blocks, each containing 15 trials. Two blocks contained 8 'yes' trials

and 7 ‘no’ trials whilst the other two blocks contained 7 ‘yes’ trials and 8 ‘no’ trials. Nonwords were created by rearranging one or more of the graphemes in each word (e.g., VAELH was derived from HALVE). See Appendix C for the list of words and nonwords.

Mandarin Lexical Decision Task

Stimuli consisted of either single Chinese characters or pseudo-characters. They were divided into 4 blocks, each containing 15 trials. Two blocks contained 8 ‘yes’ trials and 7 ‘no’ trials whilst the other two blocks contained 7 ‘yes’ trials and 8 ‘no’ trials. Pseudo-characters were created by combining semantic and phonetic radicals that do not make Chinese characters (Law & Or, 2001). See Appendix C for the list of characters and pseudo-characters.

Language Experiments Involving Phonological Processing

English Homophone Matching Task

The stimuli taken from Kay *et al.* (1992) 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 made 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 stimuli were divided into 4 blocks, each containing 15 trials. Two blocks contained 8 ‘yes’ trials and 7 ‘no’ trials whilst the other two blocks contained 7 ‘yes’ trials and 8 ‘no’ trials. The three types of word pairs were equally distributed in each block. The ‘no’ trials consisted of distractor pairs that were not homophonic but matched closely to the target pairs. See Appendix C for list of word pairs.

Mandarin Homophone Matching Task

Stimuli consisted of pairs of Chinese characters that were either matched or unmatched in tone. They were divided into 4 blocks, each containing 12 trials. Of the 12 trials, 6 were 'yes' trials and 6 were 'no' trials. For the 'yes' trials in each block, each of the 4 distinct tones found in the Mandarin vernacular was sampled at least once. See Appendix C for list of character pairs.

Language Experiments Involving Semantic Processing

English Synonym Judgement Task

Stimuli from Kay *et al.* (1992) consisted of word pairs that were close in meaning and distractor items that were unrelated in meaning. They were divided into 4 blocks, each containing 15 trials. Two blocks contained 8 'yes' trials and 7 'no' trials whilst the other two blocks contained 7 'yes' trials and 8 'no' trials. Half of the stimuli were high in imageability (e.g., marriage-wedding) and the other half were low in imageability (e.g., advice-counsel). Both sets were matched for word frequency (Kay *et al.*). See Appendix C for list of word pairs.

Mandarin Synonym Judgement Task

Stimuli consisted of word pairs that were close in meaning and distractor items that were unrelated in meaning. They were divided into 4 blocks, each containing 12 trials. Of the 12 trials, 6 were 'yes' trials and the other 6 were 'no' trials. Half of the stimuli were high in imageability and the other half were low in imageability. See Appendix C for list of word pairs.

Apparatus and Procedure

Behavioural Experiment Procedure

Participants were tested in a quiet room equipped with two IBM-compatible computers. They were asked to perform language tasks similar to those planned for

the imaging experiment, except the fixation condition was not included. Stimuli were presented in black and lower case, in the centre of the screen against a white background, and subtended a horizontal visual angle of approximately 2 degrees, at a viewing distance of about 40 cm.

The order of presentation for each language (English or Mandarin) and the three tasks (Lexical Decision, Homophone Matching and Semantic Judgement task) for each language was counterbalanced across subjects, such that half the participants were tested in English first and half in Mandarin, and within language, task order was varied. Participants were given a short break at the end of each set of language tasks.

All six language tasks involved a forced-choice decision. The "3" (on the number pad) and "z" keys on the keyboard were designated as response keys for the "yes" and "no" responses respectively. Participants were instructed to indicate a "yes" response by pressing the "3" key with their right index finger and a "no" response by pressing the "z" button with their left index finger. For each of the tasks, half of the trials were 'yes' trials and the other half were 'no' trials. The trials were presented randomly without replacement for each task. Participants were asked to respond as accurately and as quickly as possible.

English Lexical Decision Task

A practice block of 10 trials was presented first to ensure that the task was understood. This was followed by 4 experimental blocks with 15 trials in each block. A word or nonword was displayed on the screen for 1975 ms. Participants were required to judge if the letter string was a word or nonword. The next trial began automatically even if no response was registered in the allocated time. No feedback was given.

English Homophone Matching Task

Participants were given a practice block of 10 trials followed by 4 experimental blocks with 15 trials in each block. A word pair was displayed on the screen for 1975 ms. Participants were required to judge if the presented word pair had the same sound. The next trial began automatically even if no response was registered in the allocated time. No feedback was given.

English Synonym Judgement Task

Participants were given a practice block of 12 trials followed by 4 experimental blocks with 15 trials in each block. A word pair was displayed on the screen for 1975 ms. Participants were required to judge if the presented word pair had roughly the same meaning. The next trial began automatically even if no response was registered in the allocated time. No feedback was given.

Mandarin Lexical Decision Task

Participants were given a practice block of 10 trials followed by 4 experimental blocks with 15 trials in each block. A single Chinese character or pseudo-character was displayed on the screen for 1975 ms. Participants were required to judge if the stimulus was a Chinese character or meaningless pseudo-character. The next trial began automatically even if no response was registered in the allocated time. No feedback was given.

Mandarin Homophone Matching Task

Participants were given a practice block of 10 trials followed by 4 experimental blocks with 12 trials in each block. A pair of Chinese characters was displayed on the screen for 2469 ms. As Mandarin is a tonal language, participants were required to judge if the presented pair of characters had the same tone. The next trial began

automatically even if no response was registered in the allocated time. No feedback was given.

Mandarin Synonym Judgement Task

Participants were given a practice block of 12 trials followed by 4 experimental blocks with 12 trials in each block. A pair of Mandarin words was displayed on the screen for 2469 ms. Participants were required to judge if the presented word pair had roughly the same meaning. The next trial began automatically even if no response was registered in the allocated time. No feedback was given.

fMRI Experiment Procedure

Imaging was performed on a 1.5 Tesla whole-body magnetic resonance imaging (MRI) scanner (Siemens Vision; Erlangen, Germany) at the Singapore General Hospital, Department of Diagnostic Radiology. Prior to imaging, participants were briefed on the scanning procedures and experimental conditions so as to minimize anxiety and enhance task 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 head 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 30dB. They were able to receive instructions using these headphones before each run commenced.

The presentation of written words and characters was controlled by a laptop (Dell Inspiron, 1999), located outside the scanning room, running the computer software E-prime Beta 4.0 (Psychology Software Tools, Inc., USA, 1999). 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. Participants viewed the screen through a specially designed mirror mounted on the head coil. They were asked

to respond to the visually presented words and characters by pressing one of two response buttons placed in each hand. For all trials, participants were instructed to indicate a 'yes' response by pressing the button with their right hand and a 'no' response by pressing the button with their left hand i.e., the fMRI setup was made as similar as possible to the behavioural procedure.

All six participants took part in one scanning session. Each scanning session consisted of nine experimental task runs. Each run consisted of four periods of the same language task (i.e., activation condition), interleaved with four periods of fixation (i.e., baseline condition) (see Figure 3).

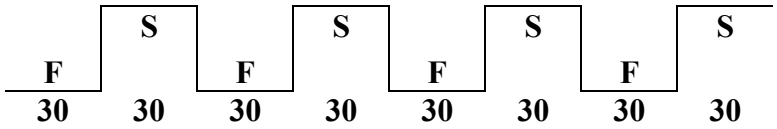

Figure 3. Diagrammatic representation of the experimental paradigm in each run. Alternating blocks of fixation (F) and stimuli (S), each lasting 30 seconds, were presented.

During fixation periods, participants were instructed to focus their entire attention on a fixation point ('+' sign) shown on the middle of the screen. Fixation served as a baseline condition. The comparison of the activation tasks and fixation was intended to engage the entire set of processes related to language processing.

Structural Images

Prior to the fMRI scans, tri-planar scout images in the sagittal plane and T1-weighted 3D coronal anatomical images using the MPRAGE sequence were acquired for each participant. This procedure provided high-resolution images of the entire brain and subsequently served as the structural scans for Talairach transformation (Talairach and Tournoux, 1988). Functional images were obtained with a T2-weighted gradient echo, echo planar imaging (EPI) sequence (i.e., with slice thickness = 8mm, TR/TE/θ = 9.7msec/4.0msec/90°, FOV = 240 X 240 mm and acquisition matrix = 128

X 128) using blood oxygen level-dependent (BOLD) contrast. Ten contiguous oblique, axial slices covering most of the brain were acquired. For each slice, 800 images were acquired with a total scan time of 237s in a single run.

Functional Images

Prior to scanning in each run, participants were given practice trials (i.e., one fixation task and one experimental task) using stimuli sets that were different from those presented during scanning. During scanning, a 1000ms cue ('!' sign) appeared prior to stimuli presentation, reminding participants to get ready to respond.

Testing sessions began with either the English or Mandarin set of tasks, with order of tasks (Lexical Decision, Homophone Matching and Semantic Judgement) counterbalanced across participants. At the end of each set, participants were given a short break. During the fixation period, participants were encouraged not to verbalize to themselves and not to think about their performance in the previous trials.

CHAPTER 3

RESULTS

Behavioural Experiment Analyses

Response times and error rates data were analyzed using SPSS v9.0 (SPSS Inc, Chicago, Illinois). The latency data were based on correct "yes" responses made in all the tasks. Response times 2.5 standard deviations above the respective cell mean were treated as errors. Thirteen participants were subsequently excluded from analyses as their error rates exceeded 30% for one or more of the language tasks, leaving twenty-eight participants.

fMRI Experiment Analyses

The fMRI data were analyzed using the BrainVoyager ™ (Version 4.2 Beta 2) software package (Brain Innovation, R. Goebel, Maastricht, The Netherlands, http:// www.brainvoyager.de). The first two volume scans of each series were discarded to eliminate the T1-weighted saturation effect. Pre-processing of functional scans included two-dimensional and three-dimensional motion correction[3], but smoothing in space and time domains was not performed[4]. The functional images were co-registered with each participant's 3-dimensional anatomical images and transformed into Talairach space (Talairach & Tournaux, 1988). Then, 3D functional data sets (volume time courses) were generated for each participant and task.

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[3] As the fMRI data can be corrupted by small involuntary movements made by the participant between volume acquisitions, it is essential to "correct" for the motion between volumes over the course of the fMRI experiment (Ardekani, Bachman, & Helpern, 2001).

[4] According to the BrainVoyager software guide, the standard settings for the preprocessing of functional scans offer good results. For individual data analysis, spatial data smoothing is also not recommended. For these reasons, smoothing in space and time domains was not performed. See http://www.brainvoyager.de/GettingStartedGuide.html.

Each participant's 3D functional data sets were analyzed individually. Multiple regression analysis was performed on the 3D functional volume time courses using the General Linear Model. Two predictors were used – one for the Mandarin task (+) and the other for the English task (-). The overall model fit was assessed using the *F* statistic. The relative contribution of each of the two predictors $RC = (b_1 - b_2)/(b_1 + b_2)$ was visualized with a red-blue-green pseudo-color scale. Blue activated voxels depicted brain regions where the Mandarin task produced a significant effect, whilst red activated voxels depicted brain regions where the English task produced a significant effect. Green activated voxels depicted brain regions where both predictors were equally activated. Voxels were considered activated and significant only when they formed part of a cluster of 200 mm^3 or more, with an associated *p*-value of < .00001. Results were visualized by superimposing 3D statistical maps on the averaged dataset.

Anatomical labels and Brodmann Areas (BA) were then identified using a 3D electronic brain atlas software, BAFI v1.1 (Brain Atlas for Functional Imaging: Clinical and Research Applications, Thieme Medical Publishers: Medical Publications, Nowinski, W.L., Thirunavuukarasuu, A. & Kennedy, D. N., 2002. http://www.cerefy.com). The number of active voxels in each BA for each participant (for all language tasks) was counted using the Voxel Count software that was developed in-house (Stocker Yale Asia Pte Ltd, 2002). The number of red, blue and green activated voxels was collated and tabulated, and subsequently analyzed using the Wilcoxon signed-rank test. For each task, only activation sites that were significant for at least four participants (out of six) are reported.

Behavioral Experiment Results

For the purpose of comparison, behavioural data collected from the six participants in the fMRI experiment are presented both separately and collectively with the data from the remaining twenty-two participants. Table 8 summarizes the mean response times and error rates for each task, for both subsets of participants. In order to compare the performance between 'all behavioural experiment' participants and 'fMRI experiment' participants, a series of Mann-Whitney tests were performed for the response times and error rates across all tasks and both languages. No significant differences in performance were found between the two groups at $p < .05$.

Table 8

Mean response times (RT) in milliseconds and % error rates with standard deviations (*SD*) across language tasks for all behavioural experiment participants (*N* = 28) and fMRI experiment participants (*n* = 6).

	All Participants (*N* = 28)		**fMRI Experiment Participants (*n* = 6)**	
Language Tasks	**Mean RT (*SD*)**	**% Error Rates (*SD*)**	**Mean RT (*SD*)**	**% Error Rates (*SD*)**
English Lexical Decision	831.46 (108.97)	12.56 (4.04)	766.85 (71.12)	12.50 (3.61)
English Homophone Matching	1308.66 (105.50)	15.12 (5.27)	1259.24 (95.43)	13.61 (5.31)
English Synonym Judgement	1065.76 (129.92)	9.58 (4.10)	1028.49 (144.03)	6.39 (1.25)
Mandarin Lexical Decision	823.86 (111.22)	17.14 (6.86)	785.92 (82.30)	20.28 (7.41)
Mandarin Homophone Matching	1589.76 (193.08)	21.28 (6.93)	1644.35 (209.35)	24.65 (7.62)
Mandarin Synonym Judgement	1496.30 (202.58)	12.95 (7.00)	1443.22 (210.18)	14.24 (9.90)

The behavioural data for both groups were analyzed using a two-way analysis of variance (ANOVA), with language (English or Mandarin) and task (Lexical Decision, Homophone Matching or Synonym Judgement task) both as within-participant factors.

Analyses of All Behavioral Experiment Participants' Results

There was a significant main effect for language for both RT [F (1, 27) = 150.31, $p < .001$, $\eta^2 = 0.85$] and % error rates [F (1, 27) = 17.58, $p < .001$, multivariate $\eta^2 = 0.39$], and a significant main effect for type of task for both RT [F (2, 54) = 536.42, $p < .001$, $\eta^2 = 0.95$] and % error rates [F (2, 54) = 21.16, $p < .001$, $\eta^2 = 0.44$]. There was also a significant interaction (see Figure 4) between language and type of task for RT [F (2, 54) = 74.05, $p < .001$, $\eta^2 = 0.73$], though not for % error rates [F (2, 54) = 1.35, $p > 0.05$]

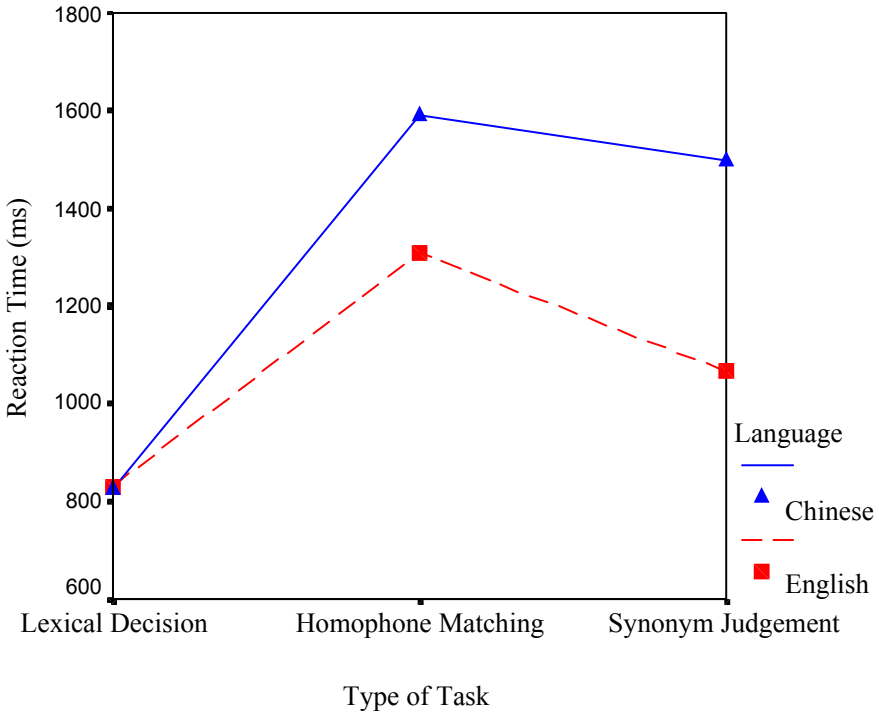


Figure 4. The language X type of task interaction for RT in all behavioural experiment participants.

Simple effects tests using paired-samples t-tests with Bonferroni corrections were conducted to find out which of the three tasks differed across both languages. For RTs, Mandarin decisions took significantly longer for both the homophone matching task [mean difference = 281.11, t (27) = 7.94, $P_{adjusted} < .05$] and synonym judgement task [mean difference = 430.54, t (27) = 14.09, $P_{adjusted} < .05$] but not for lexical decision task [mean difference = - 7.61, t (27) = - 0.48, $P_{adjusted} > .1$]. For % error rates, there were significantly more incorrect decisions for the Mandarin task in all three tasks - lexical decision task [mean difference = 4.58, t (27) = 3.36, $P_{adjusted} < .05$), homophone matching task [mean difference = 6.16, t (27) = 3.58, $P_{adjusted} < .05$] and synonym judgement task [mean difference = 3.36, t (27) = 2.47, $P_{adjusted} < .05$].

Analyses of fMRI Experiment Participants' Results

The sample size (n = 6) was very small, nevertheless the ANOVA for behavioural data collected from fMRI experiment participants revealed similar results. A significant main effect for language was found for both RT [F (1, 5) = 34.43, p = .002, η^2 = 0.87] and % error rates [F (1, 5) = 11.68, p = .019, η^2 = 0.70]. Similarly, there was a significant main effect for type of task for both RT [F (2, 10) = 112.25, p < .001, η^2 = 0.96] and % error rates [F (2, 10) = 11.18, p = .003, η^2 = 0.69]. The interaction between language and type of task was also significant for RT [F (2, 10) = 15.77, p = .001, η^2 = 0.76] (see Figure 5) though again not for % error rates [F (2, 10) = 0.74, p > .01].

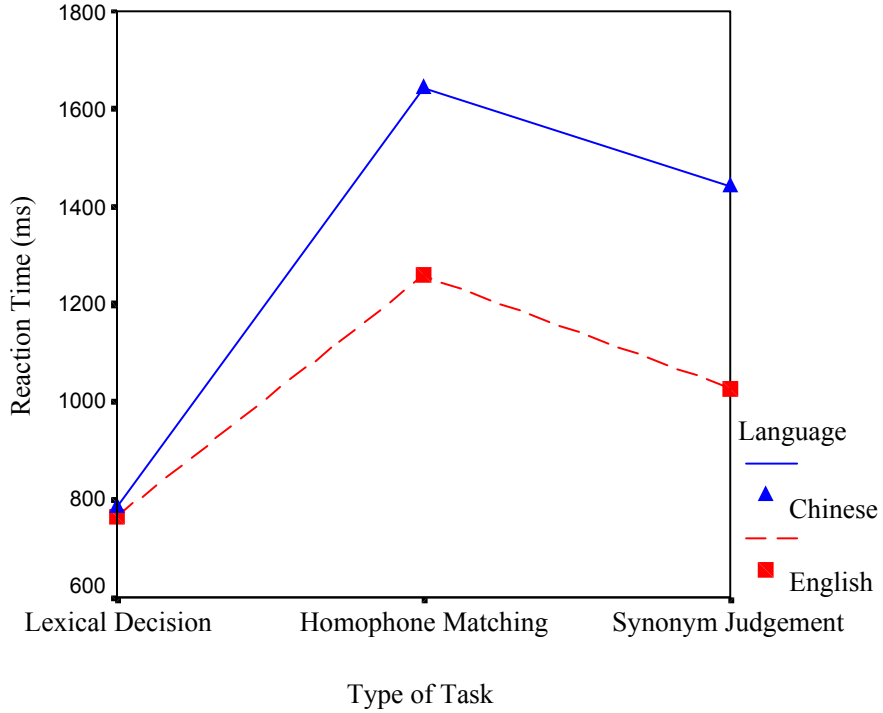


Figure 5. The language X type of task interaction for RT in fMRI experiment participants.

Using paired-samples t-tests with Bonferroni corrections for RTs, significant differences were also found for both the homophone matching task [mean difference = 385.11, t (5) = 4.40, $P_{adjusted} < .05$] and synonym judgement task [mean difference = 414.73, t (5) = 6.60, $P_{adjusted} < .05$]. However, a borderline difference was found for pairwise comparisons on % error rates, significant differences were found only in two tasks - lexical decision task [mean difference = 7.78, t (5) = 2.83, $P_{adjusted} < .05$] and homophone matching task [mean difference = 11.04, t (5) = 5.14, $P_{adjusted} < .05$].

In summary, the overall pattern of results for the six fMRI participants was very similar to the results for all behavioural experiment participants. In other words, the six participants recruited for the fMRI experiments were a representative sample of the English-Chinese bilingual biscriptal participants recruited for the behavioural experiments. Nevertheless, the results of the behavioural experiments suggest the processing demands for Mandarin remained greater, despite attempts to equate for

relative frequency of English words and Chinese characters, and the decision to reduce the number of trials per run for Mandarin tasks. Differences in processing demands between English and Mandarin are unavoidable for some tasks (notably Homophone Matching and Synonym Judgement). Such differences are more likely to be attributable to the respective properties of the two languages, rather than the language proficiencies of the participants, because the task demands for Lexical Decision were broadly similar.

The question of task demands raises two interesting issues. First, it underscores the importance of using more than one task with the same group of fMRI participants. Second, but equally important, if there are differences in task demands for some levels of language, differences in levels of BOLD fMRI activation should be observed even in the same brain areas (Carpenter, Just, Kelly, Eddy, & Thulborn, 1999; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Moro *et al.*, 2001). It follows, therefore, that fMRI has the potential to reveal two kinds of differences between processing English and Mandarin: within the same brain area, processing Chinese characters will result in more intense BOLD activation, but there might also be activations in spatially distinct brain areas.

Thus a systematic investigation of the English-Chinese bilingual brain rests on solid behavioural data as well as fMRI experiments in two or more tasks for the same subset of participants.

fMRI Results

The fMRI data revealed that for both English and Mandarin, both common and distinct brain regions were activated for orthography, phonology and semantics. In the next section, the detailed fMRI results for each task will be presented as follows: (a) summary of brain regions activated by each language; (b) the common and distinct brain regions activated across both languages; and (c) the brain regions that showed statistical significance when the activated voxels were compared across both languages.

Lexical Decision Relative to Fixation

Summary of Brain Regions Activated by the English Lexical Decision Task

In the *frontal* lobes, significant brain activations were observed in the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), bilateral anterior cingulate cortex (BAs 24 and 32), bilateral inferior frontal gyrus (BA 44) and left inferior frontal gyrus (BA 45).

In the *parietal* lobes, significant brain activations were observed in the bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate cortex (BA 31), bilateral angular gyrus (BA 39) and left supramarginal gyrus (BA 40). In the postcentral gyrus, BA 3 was activated bilaterally whilst BA 2 showed activation only in the left parietal lobe.

In the *temporal* lobes, bilateral activations of the fusiform gyrus (BA 37) were observed.

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

In addition to activation in the cortical areas, activation was also seen in the right putamen. See Table 9 for the number of participants showing neural activation in each brain region.

Table 9

Activated brain regions with corresponding Brodmann Areas (BAs) for the English Lexical Decision Task relative to fixation.

Brain Region	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	5	4
Pre-motor Cortex	6	5	6
Anterior Cingulate Cortex	24	4	5
Anterior Cingulate Cortex	32	4	4
Inferior Frontal Gyrus	44	5	4
Inferior Frontal Gyrus	45	6	0
Parietal Lobe			
Postcentral Gyrus	2	4	0
Postcentral Gyrus	3	4	4
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	31	5	5
Angular Gyrus	39	5	4
Supramarginal Gyrus	40	4	0
Temporal Lobe			
Fusiform Gyrus	37	4	4
Occipital Lobe			
Striate Cortex	17	5	5
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	6
Subcortical Areas			
Putamen		0	5

Summary of Brain Regions Activated by the Mandarin Lexical Decision Task

In the *frontal* lobes, significant brain activations were observed in the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), bilateral anterior cingulate cortex (BAs 24 and 32), bilateral inferior frontal gyrus (BA 44), right superior frontal gyrus (BA 8), right anterior superior frontal gyrus (BA 10) and left inferior frontal gyrus (BA 45). In the middle frontal gyrus, BA 9 was activated bilaterally whilst BA 46 showed activation only in the right frontal lobe.

In the *parietal* lobes, bilateral activations were observed in the postcentral gyrus (BA 3), superior parietal gyrus (BA 7), posterior cingulate cortex (BA 31) and angular gyrus (BA 39).

In the *temporal* lobes, bilateral activations of the fusiform gyrus (BA 37) were observed.

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

In addition to the cortical areas, other activated brain regions include the left nucleus caudatus, left thalamus and right putamen. See Table 10 for the number of participants showing neural activation in each brain region.

Table 10

Activated brain regions with corresponding Brodmann Areas (BAs) for the Mandarin Lexical Decision Task relative to fixation.

Brain Region	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	5	5
Pre-motor Cortex	6	6	5
Superior frontal gyrus	8	0	4
Middle Frontal Gyrus	9	4	4
Anterior Superior frontal gyrus	10	0	4
Anterior Cingulate Cortex	24	5	6
Anterior Cingulate Cortex	32	5	5
Inferior Frontal Gyrus	44	6	6
Inferior Frontal Gyrus	45	4	0
Middle Frontal Gyrus	46	0	5
Parietal Lobe			
Postcentral Gyrus	3	5	5
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	31	5	5
Angular Gyrus	39	6	4
Temporal Lobe			
Fusiform Gyrus	37	5	4
Occipital Lobe			
Striate Cortex	17	5	6
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	6
Subcortical Areas			
Nucleus Caudatus		4	0
Thalamus		4	0
Putamen		0	5

Common and Distinct Neural Substrates of Orthographic Processing for English and Mandarin Based on Lexical Decision Task

Although the results of the individual analyses showed considerable variation across participants and tasks, there were common and distinct neural substrates activated. At the orthographic level of processing, the *common* brain regions subserved by both the English and Mandarin Lexical tasks were:

a) Frontal lobe – activation of the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), bilateral anterior cingulate cortex (for both BAs 24 and 32), bilateral inferior frontal gyrus (BA 44) and left inferior frontal gyrus (BA 45).
b) Parietal lobe – activation of the bilateral postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate cortex (BA 31) and bilateral angular gyrus (BA 39).
c) Temporal lobe – activation of the bilateral fusiform gyrus (BA 37).
d) Occipital lobe – activation of the bilateral striate cortex (BA 17) and bilateral extrastriate cortices (BAs 18 and 19).
e) Other subcortical areas activated include the right putamen.

Brain regions activated by the English and *not* Mandarin Lexical Decision task were the left postcentral gyrus (BA 2) and left supramarginal gyrus (BA 40).

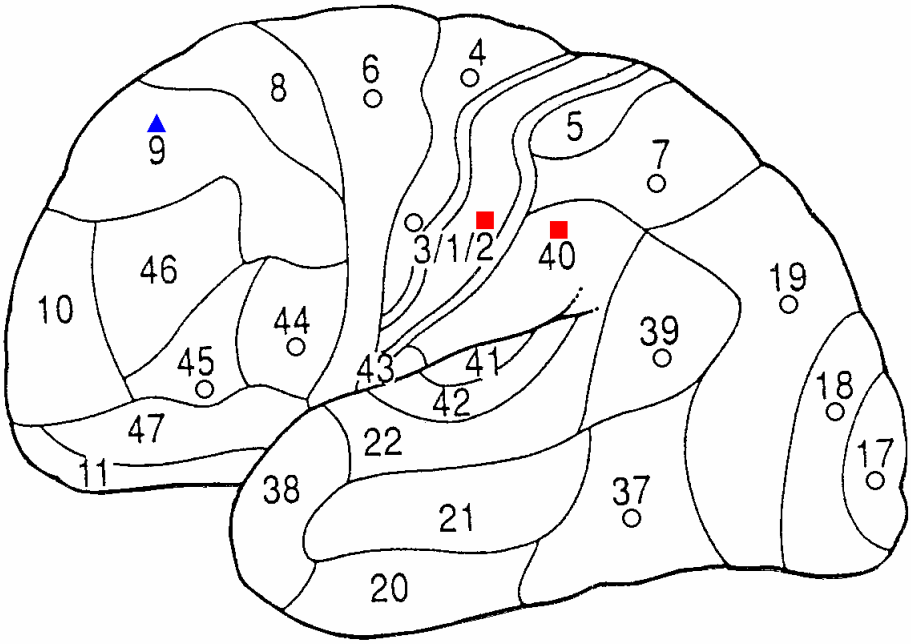
Brain regions activated by the Mandarin but *not* English Lexical Decision task were observed in the right superior frontal gyrus (BA 8), bilateral middle frontal gyrus (BA 9), right anterior superior frontal gyrus (BA 10), right middle frontal gyrus (BA 46), left nucleus caudatus and left thalamus.

Comparing Mandarin and English Representation at the Orthographic level

Statistical analyses of the voxel counts in each brain region across languages revealed that the extent of activation was significantly greater for the Mandarin than

English Lexical Decision task in the right inferior frontal gyrus (BA 44) and right extrastriate cortices (BAs 18 and 19). This is consistent with the increased task demands for Mandarin observed in behavioural data. See Figures 6 and 7 for the schematic diagram showing the brain regions activated by both the English and Mandarin Lexical Decision Tasks in both hemispheres of the brain.

Lateral Surface



Medial Surface

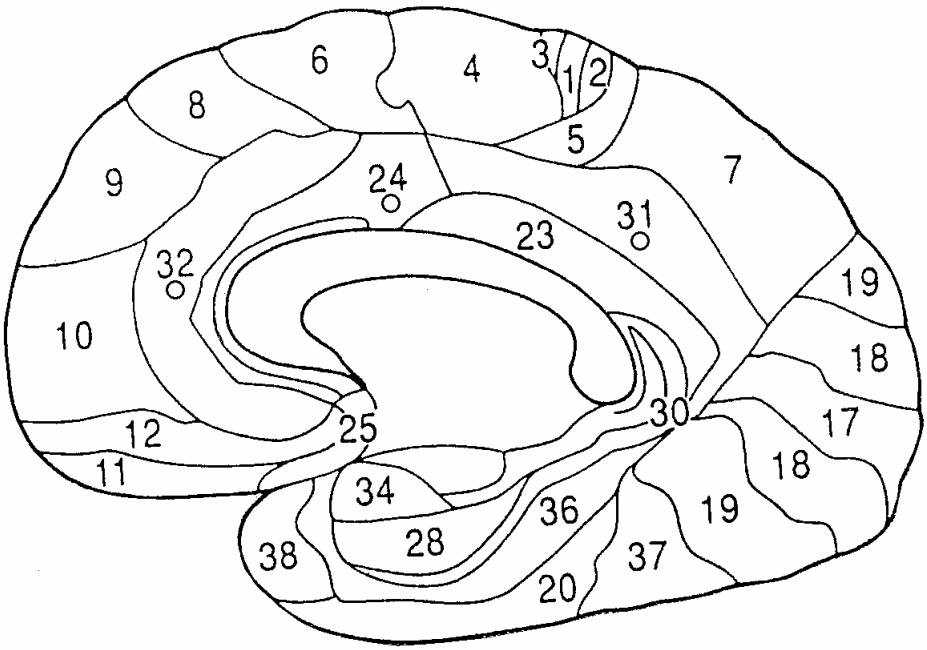
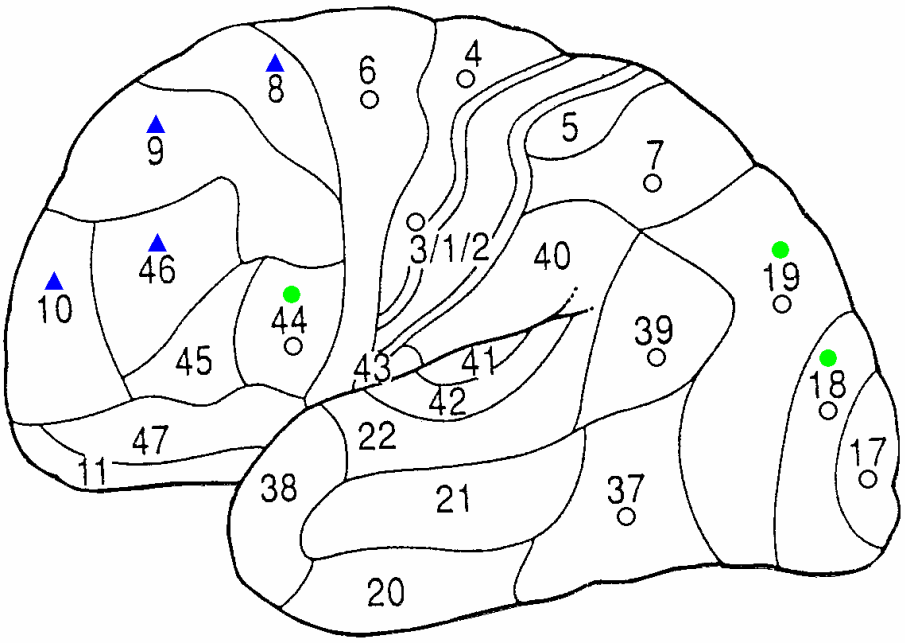


Figure 6. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *left* hemisphere for the *Lexical Decision Task (LDT)*. Note: Brain regions activated by the English LDT only are shown with red squares. Brain regions that are activated by the Mandarin LDT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English LDT are shown with green circles.

Lateral Surface



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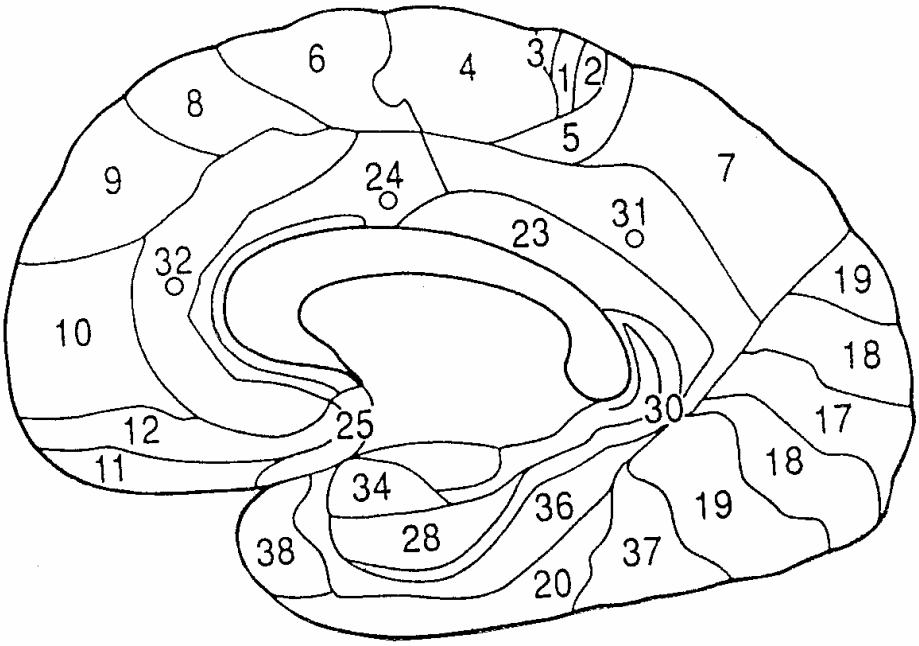


Figure 7. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *right* hemisphere for the *Lexical Decision Task (LDT).* Note: Brain regions activated by the English LDT only are shown with red squares. Brain regions that are activated by the Mandarin LDT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English LDT are shown with green circles.

Homophone Matching Relative to Fixation

Summary of Brain Regions Activated by the English Homophone Matching Task

In the *frontal* lobes, significant brain activations were observed in the left primary motor cortex (BA 4), left pre-motor cortex (BA 6), left superior frontal gyrus (BA 8), right anterior superior frontal gyrus (BA 10) and bilateral inferior frontal gyrus (BAs 44, 45 and 47). In the middle frontal gyrus, BA 46 was activated bilaterally whilst BA 9 showed activation only in the left frontal lobe. In the anterior cingulate cortex, BA 32 was activated bilaterally whilst BA 24 showed activation only in the right frontal lobe.

In the *parietal* lobes, significant brain activations were observed in the left postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate cortex (BA 31) and bilateral angular gyrus (BA 39).

In the *temporal* lobes, activations in the left middle temporal gyrus (BA 21), left fusiform gyrus (BA 37) and left superior temporal gyrus (BA 38) were observed.

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

In addition to activation in the cortical areas, activation was also seen in the right thalamus. See Table 11 for the number of participants showing neural activation in each brain region.

Table 11

Activated brain regions with corresponding Brodmann Areas (BAs) for the English Homophone Matching Task relative to fixation.

Brain Area	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	6	0
Pre-motor Cortex	6	6	0
Superior frontal gyrus	8	4	0
Middle Frontal Gyrus	9	5	0
Anterior Superior frontal gyrus	10	0	4
Anterior Cingulate Cortex	24	0	5
Anterior Cingulate Cortex	32	5	5
Inferior Frontal Gyrus	44	5	4
Inferior Frontal Gyrus	45	5	4
Middle Frontal Gyrus	46	5	4
Inferior Frontal Gyrus	47	5	4
Parietal Lobe			
Postcentral Gyrus	3	5	0
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	31	4	5
Angular Gyrus	39	5	4
Temporal Lobe			
Middle Temporal Gyrus	21	4	0
Fusiform Gyrus	37	4	0
Superior Temporal Gyrus	38	4	0
Occipital Lobe			
Striate Cortex	17	5	5
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	5
Subcortical Areas			
Thalamus		0	4

Summary of Brain Regions Activated by the Mandarin Homophone Matching Task

In the *frontal* lobes, significant brain activations were observed in the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), bilateral anterior superior frontal gyrus (BA 10), bilateral anterior cingulate cortex (BAs 24 and 32) and left superior frontal gyrus (BA 8). In the middle frontal gyrus, BA 46 was activated bilaterally whilst BA 9 showed activation only in the left frontal lobe. In the inferior frontal gyrus, BAs 44 and 45 were activated bilaterally whilst BA 47 showed activation only in the left frontal lobe.

In the *parietal* lobes, significant brain activations were observed in the bilateral postcentral gyrus (BAs 2 and 3), bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate cortex (BAs 23 and 31), bilateral angular gyrus (BA 39) and left supramarginal gyrus (BA 40).

In the *temporal* lobes, bilateral activations of the fusiform gyrus (BA 37) were observed.

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

In addition to the cortical areas, other activated brain regions include the bilateral nucleus caudatus and bilateral putamen. See Table 12 for the number of participants showing neural activation in each brain region.

Table 12

Activated brain regions with corresponding Brodmann Areas (BAs) for the Mandarin Homophone Matching Task relative to fixation.

Brain Region	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	6	5
Pre-motor Cortex	6	6	5
Superior frontal gyrus	8	4	0
Middle Frontal Gyrus	9	6	0
Anterior Superior frontal gyrus	10	4	5
Anterior Cingulate Cortex	24	4	5
Anterior Cingulate Cortex	32	6	6
Inferior Frontal Gyrus	44	6	4
Inferior Frontal Gyrus	45	6	4
Middle Frontal Gyrus	46	5	5
Inferior Frontal Gyrus	47	4	0
Parietal Lobe			
Postcentral Gyrus	2	4	5
Postcentral Gyrus	3	5	5
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	23	5	4
Posterior Cingulate Cortex	31	5	5
Angular Gyrus	39	5	5
Supramarginal Gyrus	40	5	0
Temporal Lobe			
Fusiform Gyrus	37	4	5
Occipital Lobe			
Striate Cortex	17	5	5
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	6
Subcortical Areas			
Nucleus Caudatus		4	4
Putamen		4	5

Common and Distinct Neural Substrates of Phonological Processing for English and Mandarin Based on Homophone Matching Task

At the phonological level of processing, the *common* brain regions subserved by both the English and Mandarin Homophone Matching tasks were:

a) Frontal lobe – activation of the left primary motor cortex (BA 4), left pre-motor cortex (BA 6), left superior frontal gyrus (BA 8), middle frontal gyrus – bilateral activations for BA 46 and activation in the left frontal lobe for BA 9, right anterior superior frontal gyrus (BA 10), inferior frontal gyrus – bilateral activations for BAs 44 and 45, and activation in the left frontal lobe for BA 47 and anterior cingulate cortex - bilateral activations for BA 32 and activation in the right frontal lobe for BA 24.
b) Parietal lobe – activation of the left postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate cortex (BA 31) and bilateral angular gyrus (BA 39).
c) Temporal lobe – activation of the left fusiform gyrus (BA 37).
d) Occipital lobe – activation of the bilateral striate cortex (BA 17) and bilateral extrastriate cortices (BAs 18 and 19).

Brain regions showing activation for only the English and *not* Mandarin Homophone Matching task were observed in the right inferior frontal gyrus (BA 47), left middle temporal gyrus (BA 21), left superior temporal gyrus (BA 38) and right thalamus.

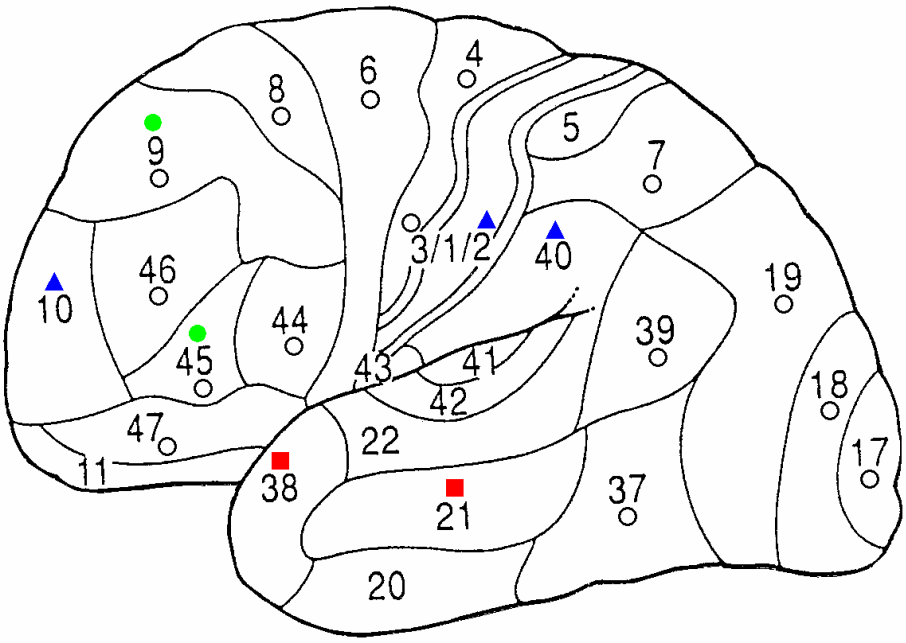
Brain regions activated by the Mandarin but *not* English Homophone Matching task include the right primary motor cortex (BA 4), right pre-motor cortex (BA 6), left anterior superior frontal gyrus (BA 10), left anterior cingulate cortex (BA 24), right fusiform gyrus (BA 37), postcentral gyrus – bilateral activations for BA 2 and

activation in the right parietal lobe for BA 3, bilateral posterior cingulate cortex (BA 23), left supramarginal gyrus (BA 40), bilateral nucleus caudatus and bilateral putamen.

Comparing Mandarin and English representation at the Phonological level

Statistical analyses of the voxel counts in each brain region across languages showed that the extent of activation was significantly greater for the Mandarin than English Homophone Matching task in the left middle frontal gyrus (BA 9), left inferior frontal gyrus (BA 45) and right extrastriate cortices (BAs 18 and 19). See Figures 8 and 9 for the schematic diagram showing the brain regions activated by both the English and Mandarin Homophone Matching Task in both hemispheres of the brain.

Lateral Surface



Medial Surface

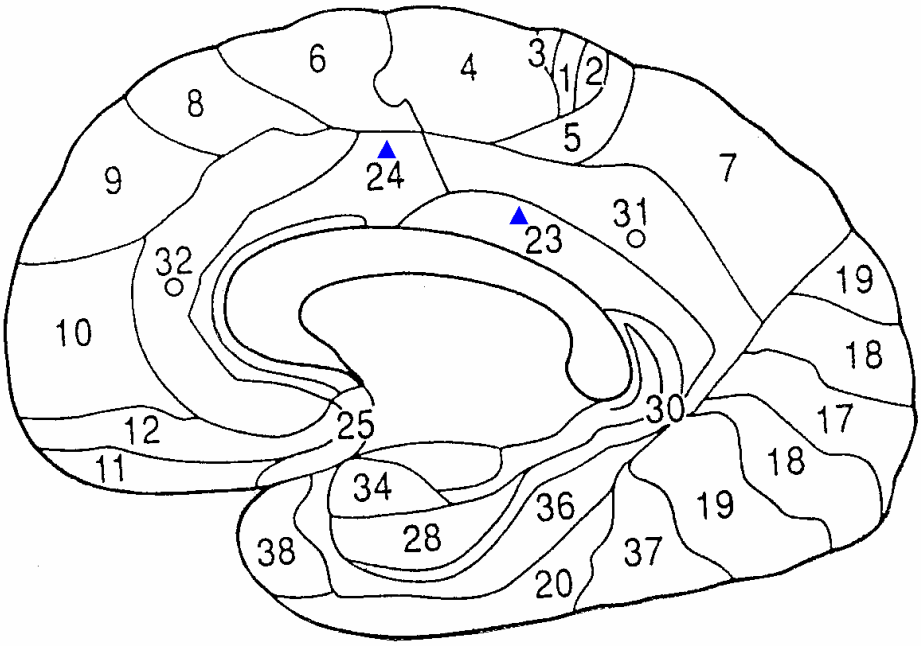
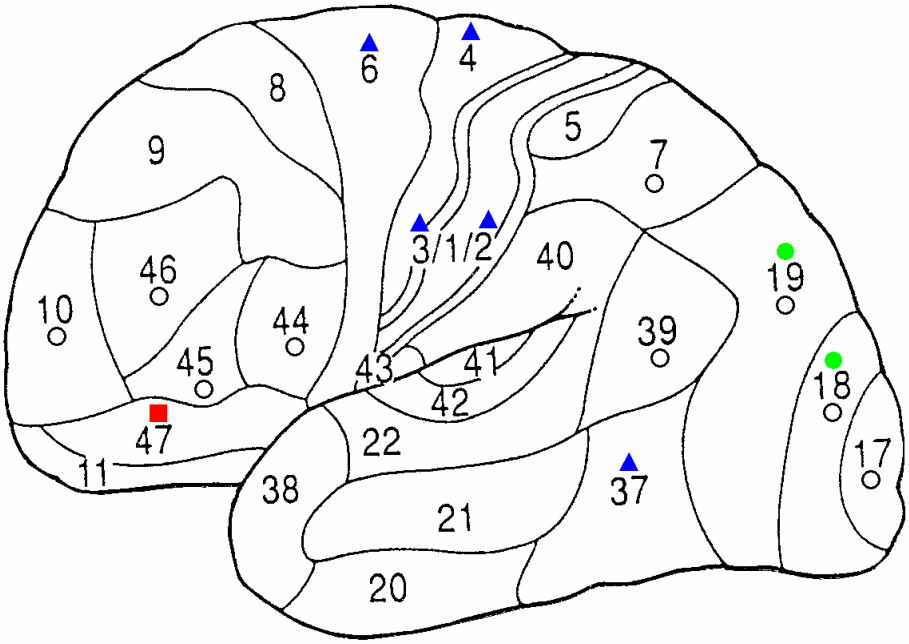


Figure 8. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *left* hemisphere for the *Homophone Matching Task (HMT)*. Note: Brain regions activated by the English HMT only are shown with red squares. Brain regions that are activated by the Mandarin HMT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English HMT are shown with green circles.

Lateral Surface



Medial Surface

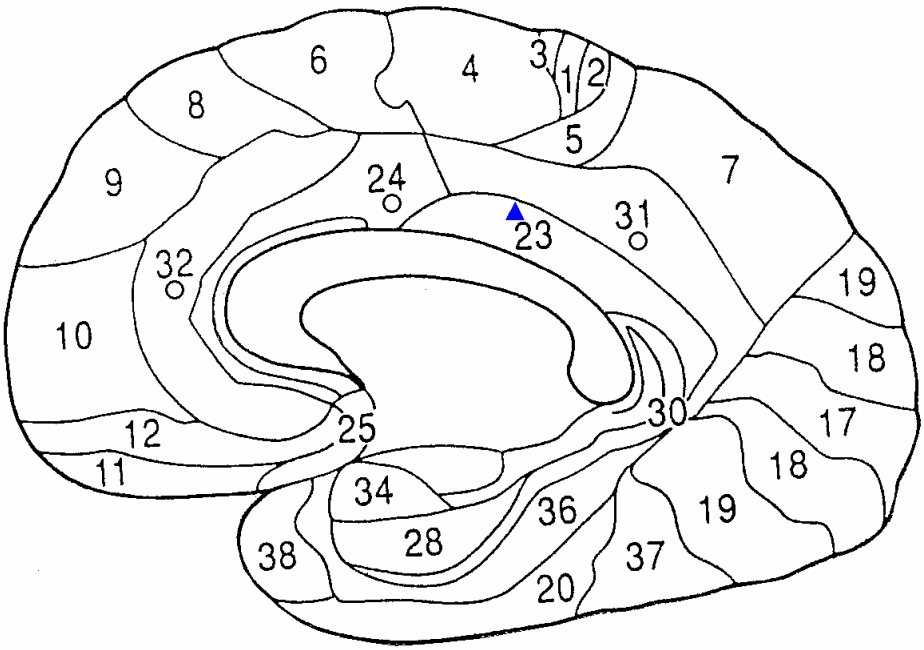


Figure 9. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *right* hemisphere for the *Homophone Matching Task (HMT)*. Note: Brain regions activated by the English HMT only are shown with red squares. Brain regions that are activated by the Mandarin HMT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English HMT are shown with green circles.

Synonym Judgement Relative to Fixation

Summary of Brain Regions Activated by the English Synonym Judgement Task

In the *frontal* lobes, significant brain activations were observed in the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), left superior frontal gyrus (BA 8), bilateral anterior superior frontal gyrus (BA 10) and bilateral anterior cingulate cortex (BAs 24 and 32). In the middle frontal gyrus, BA 46 was activated bilaterally whilst BA 9 showed activation only in the right frontal lobe. In the inferior frontal gyrus, BA 44 was activated bilaterally whilst BA 45 showed activation only in the right frontal lobe.

In the *parietal* lobes, significant brain activations were observed in the right postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral angular gyrus (BA 39) and left supramarginal gyrus (BA 40). In the posterior cingulate gyrus, BA 31 was activated bilaterally whilst BA 23 showed activation only in the left parietal lobe.

In the *temporal* lobes, significant brain activations were observed in the right inferior temporal gyrus (BA 20), left middle temporal gyrus (BA 21), left superior temporal gyrus (BA 22) and bilateral fusiform gyrus (BA 37).

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

Brain regions activated outside the cortical areas include the bilateral nucleus caudatus, bilateral putamen and right thalamus. See Table 13 for the number of participants showing neural activation in each brain region.

Table 13

Activated brain regions with corresponding Brodmann Areas (BAs) for the English Synonym Judgement Task relative to fixation.

Brain Region	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	5	6
Pre-motor Cortex	6	6	6
Superior frontal gyrus	8	4	0
Middle Frontal Gyrus	9	5	0
Anterior Superior frontal gyrus	10	5	4
Anterior Cingulate Cortex	24	6	6
Anterior Cingulate Cortex	32	6	4
Inferior Frontal Gyrus	44	6	5
Inferior Frontal Gyrus	45	6	0
Middle Frontal Gyrus	46	4	5
Parietal Lobe			
Postcentral Gyrus	3	0	5
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	23	4	0
Posterior Cingulate Cortex	31	6	4
Angular Gyrus	39	6	4
Supramarginal Gyrus	40	6	0
Temporal Lobe			
Inferior Temporal Gyrus	20	0	4
Middle Temporal Gyrus	21	4	0
Superior Temporal Gyrus	22	5	0
Fusiform Gyrus	37	5	5
Occipital Lobe			
Striate Cortex	17	5	5
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	6
Subcortical Areas			
Nucleus Caudatus		4	4
Thalamus		0	5
Putamen		4	4

Summary of Brain Regions Activated by the Mandarin Synonym Judgement Task

In the *frontal* lobes, significant brain activations were observed in the bilateral primary motor cortex (BA 4), bilateral pre-motor cortex (BA 6), left superior frontal gyrus (BA 8) and bilateral anterior superior frontal gyrus (BA 10). In the middle frontal gyrus, BA 46 was activated bilaterally whilst BA 9 showed activation only in the left frontal lobe. In the inferior frontal gyrus, BAs 44 and 45 were activated bilaterally whilst BA 47 showed activation only in the left frontal lobe. In the anterior cingulate cortex, BA 24 was activated bilaterally whilst BA 32 showed activation only in the left frontal lobe.

In the *parietal* lobes, significant brain activations were observed in the bilateral postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral angular gyrus (BA 39) and left supramarginal gyrus (BA 40). In the posterior cingulate cortex, BA 31 was activated bilaterally whilst BA 23 showed activation only in the left parietal lobe.

In the *temporal* lobes, significant brain activations were observed in the left middle temporal gyrus (BA 21), left superior temporal gyrus (BA 22) and bilateral fusiform gyrus (BA 37).

In the *occipital* lobes, bilateral activations were observed in the striate cortex (BA 17) and extrastriate cortices (BAs 18 and 19).

In addition to the cortical areas, other activated brain regions include the right nucleus caudatus, right thalamus and bilateral putamen. See Table 14 for the number of participants showing neural activation in each brain region.

Table 14

Activated brain regions with corresponding Brodmann Areas (BAs) for the Mandarin Synonym Judgement Task relative to fixation.

Brain Region	BA	No. of Participants Showing Activation in the Left Hemisphere	No. of Participants Showing Activation in the Right Hemisphere
Frontal Lobe			
Primary Motor Cortex	4	5	5
Pre-motor Cortex	6	6	6
Superior frontal gyrus	8	4	0
Middle Frontal Gyrus	9	5	0
Anterior Superior frontal gyrus	10	5	4
Anterior Cingulate Cortex	24	6	5
Anterior Cingulate Cortex	32	6	0
Inferior Frontal Gyrus	44	6	5
Inferior Frontal Gyrus	45	6	4
Middle Frontal Gyrus	46	6	4
Inferior Frontal Gyrus	47	4	0
Parietal Lobe			
Postcentral Gyrus	3	4	4
Superior Parietal Gyrus	7	6	6
Posterior Cingulate Cortex	23	4	0
Posterior Cingulate Cortex	31	6	6
Angular Gyrus	39	6	6
Supramarginal Gyrus	40	6	0
Temporal Lobe			
Middle Temporal Gyrus	21	4	0
Superior Temporal Gyrus	22	5	0
Fusiform Gyrus	37	6	5
Occipital Lobe			
Striate Cortex	17	5	5
Extrastriate Cortex	18	6	6
Extrastriate Cortex	19	6	6
Subcortical Areas			
Nucleus Caudatus		0	5
Thalamus		0	5
Putamen		4	5

Common and Distinct Neural Substrates of Semantic Processing for English and Mandarin based on Synonym Judgement Task

At the semantic level of processing, the *common* brain regions subserved by both the English and Mandarin Synonym Judgement tasks were:

a) Frontal lobe – activation of the bilateral primary cortex (BA 4), bilateral pre-motor cortex (BA 6), left superior frontal gyrus (BA 8), middle frontal gyrus – bilateral activations for BA 46 and activation in the left frontal lobe for BA 9, bilateral anterior superior frontal gyrus (BA 10), anterior cingulate cortex - bilateral activations for BA 24 and activations in the left frontal lobe for BA 32 and inferior frontal gyrus - bilateral activations for BA 44 and activation in the left frontal lobe for BA 45
b) Parietal lobe – activation of the right postcentral gyrus (BA 3), bilateral superior parietal gyrus (BA 7), bilateral angular gyrus (BA 39), left supramarginal gyrus (BA 40) and posterior cingulate cortex - bilateral activations for BA 31 and activation in the left parietal lobe for BA 23.
c) Occipital lobe – activation of the bilateral striate cortex (BA 17) and bilateral extrastriate cortices (BAs 18 and 19).
d) Subcortical areas – activation of the bilateral putamen, right nucleus caudatus and right thalamus.

Distinct brain regions activated by the English but *not* the Mandarin Synonym Judgement task include the right anterior cingulate cortex (BA 32), right inferior temporal gyrus (BA 20) and left nucleus caudatus.

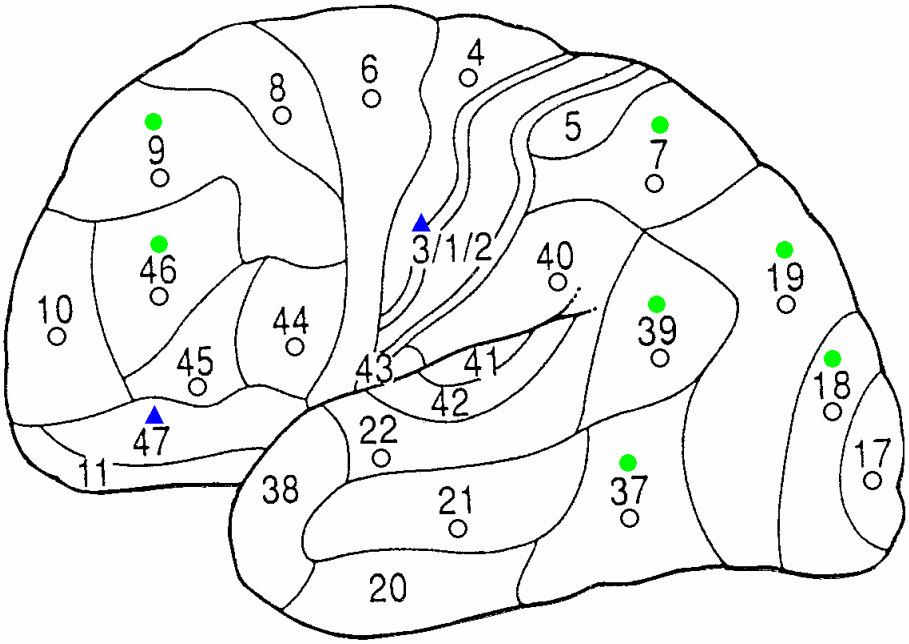
Brain regions activated by the Mandarin but *not* the English Synonym Judgement task include the right inferior frontal gyrus (BA 45), left inferior frontal gyrus (BA 47) and left postcentral gyrus (BA 3).

Comparing Mandarin and English Representation at the Semantic level

Statistical analyses of the voxel counts in each brain region across languages revealed that the extent of activations was significantly greater for the Mandarin than English Synonym Judgement task in the left middle frontal gyrus (BAs 9 and 46), bilateral fusiform gyrus (BA 37), left superior parietal gyrus (BA 7), right posterior cingulate cortex (BA 31), left angular gyrus (BA 39) and bilateral extrastriate cortices (BAs 18 and 19). See Figures 10 and 11 for the schematic diagram showing the brain regions activated by both the English and Mandarin Synonym Judgement Task in both hemispheres of the brain.

In summary, the fMRI data revealed that across languages, both common and distinct brain regions are involved for each subcomponent of language processing. Across all tasks, statistical analyses of the voxel counts in some brain regions revealed that the extent of activations was always significantly greater for Mandarin than English tasks. See Table 15 in Appendix D for a summary of the activated brain regions for all tasks across both languages.

Lateral Surface



Medial Surface

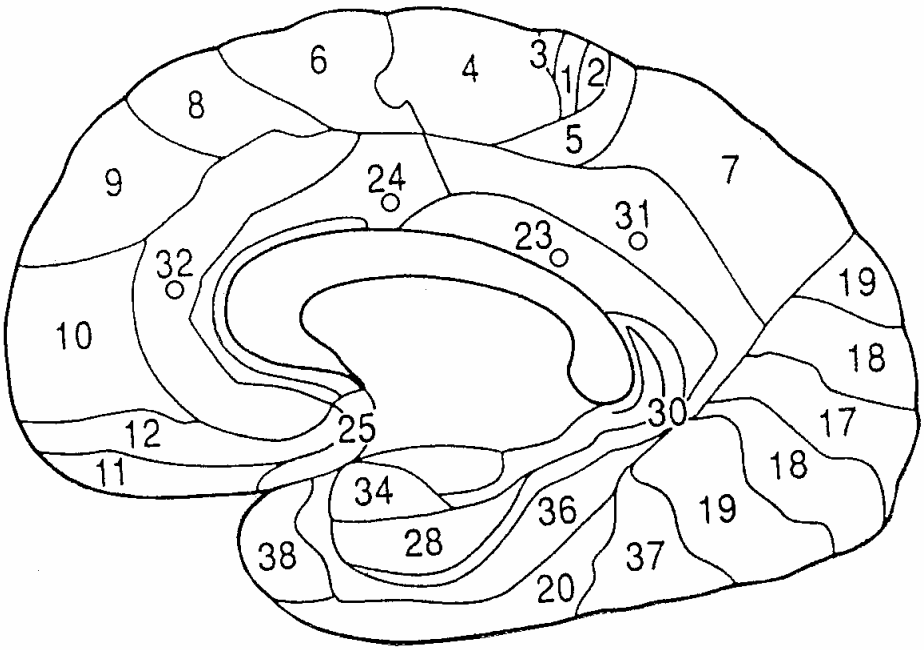
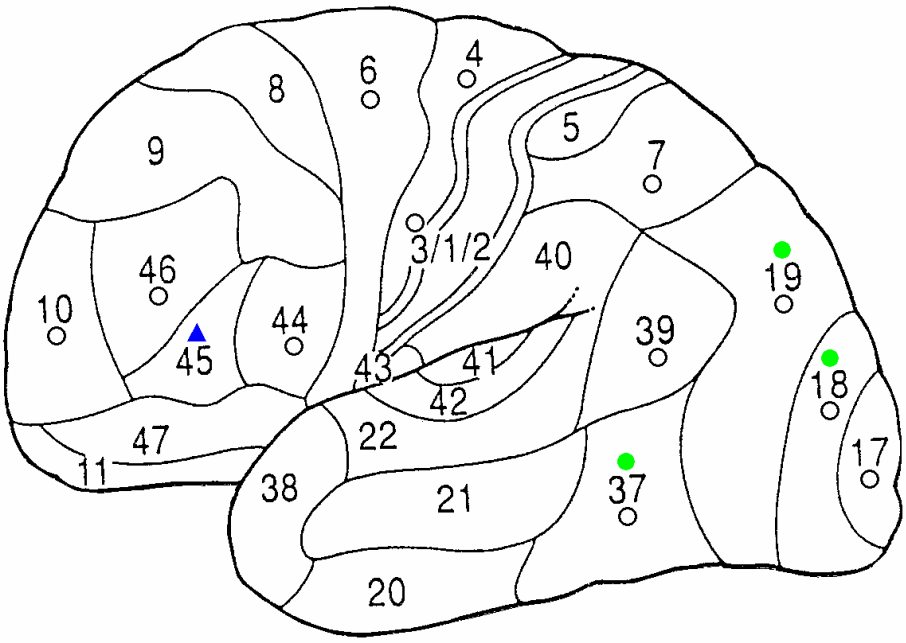


Figure 10. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *left* hemisphere for the *Synonym Judgement Task (SJT)*. Note: Brain regions activated by the English SJT only are shown with red squares. Brain regions that are activated by the Mandarin SJT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English SJT are shown with green circles.

Lateral Surface



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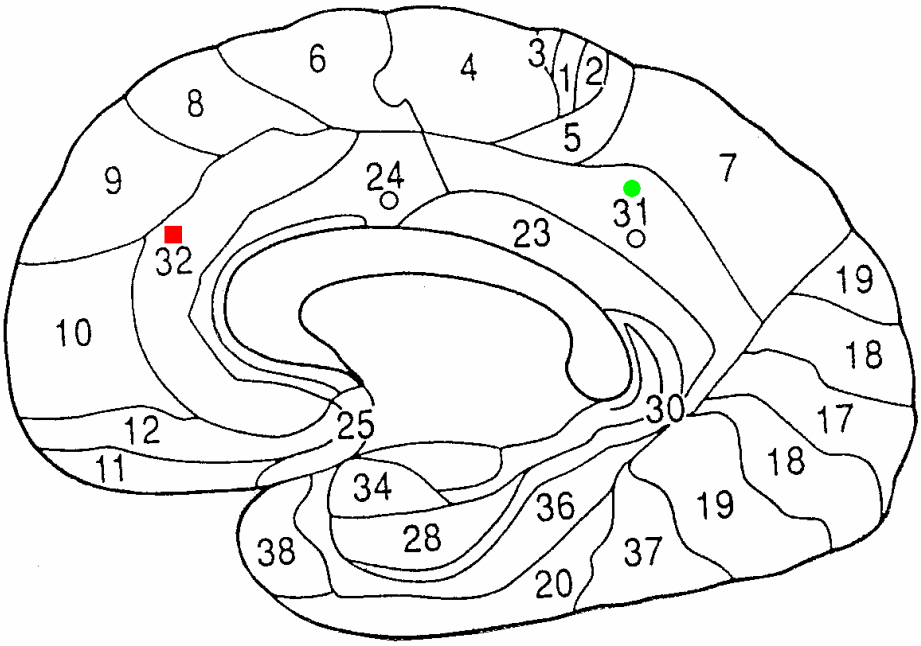

Figure 11. Schematic diagram showing the brain regions activated (based on Brodmann's cytoarchitectonic map) on both the lateral and medial surfaces of the *right* hemisphere for the *Synonym Judgement Task (SJT)*. Note: Brain regions activated by the English SJT only are shown with red squares. Brain regions that are activated by the Mandarin SJT only are shown with blue triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin compared to English SJT are shown with green circles.

CHAPTER 4

DISCUSSION

To date, neuroimaging experiments involving English-Chinese bilingual biscriptals suggest that common brain areas subserve the two languages. Given that the oral and written forms of English and Mandarin differ so markedly, and differences have been reported for bi-alphabetic readers, the null findings for English-Chinese bilingual biscriptals warrant a systematic investigation. The main aim of this thesis was to identify differences in the neuroanatomical representation of English and Mandarin at three levels of language: orthography, phonology and semantics.

The pattern of activations observed for the bilinguals showed strong consistencies with past neuroimaging studies that investigated the neural correlates of language processing in English and Chinese unilinguals, although the bilinguals showed less left lateralization. The fMRI data for Mandarin and English confirmed that many common brain regions were found to subserve both languages and, as expected, all showed greater activation for Mandarin than English. More importantly, and contrary to previous fMRI studies, a number of distinct brain regions were activated for English and Mandarin at the level of orthography, phonology and semantics. Across all tasks, brain regions activated *only* during the English tasks were generally observed to be located in the *parietal* and *temporal* lobes, whereas those areas activated *only* during the Mandarin tasks were generally observed to be located in the *frontal* and *parietal* lobes. In what follows, these results will be discussed in more detail.

Common Brain Regions Activated Across All Tasks for Both Languages

The fMRI data suggest that there is a large degree of overlap in the brain regions subserving English and Mandarin. Across *all* tasks, the common brain regions activated by *both* languages included the left primary motor cortex (BA 4), left pre-motor cortex (BA 6), anterior cingulate cortex – activations in the right for BA 24 and activations in the left for BA 32, inferior frontal gyrus – bilateral activations for BA 44 and activations in the left for BA 45, left fusiform gyrus (BA 37), bilateral superior parietal gyrus (BA 7), bilateral posterior cingulate gyrus (BA 31), bilateral angular gyrus (BA 39), bilateral striate cortex (BA 17) and bilateral extrastriate cortices (BAs 18 and 19). This shared functional neuroanatomy across diverse writing systems, confirms that the same primary and secondary visual association areas (i.e., BAs 17, 18, 19) are involved in reading whatever the nature of the script. A number of other neuroimaging studies looking at reading or word recognition in English and/or Mandarin have also reported activations in the inferior frontal regions, such as BA 44, 45 (e.g., Demb *et al.*, 1995; Demonet *et al.*, 1992; Illes *et al.*, 1999; Petersen *et al.*, 1998; Tan *et al.*, 2001; Zatorre *et al.*, 1992), the ventral occipital-temporal regions, such as BAs 17, 18 and 37 (e.g., Petersen *et al.*, 1990; Pugh *et al.*, 1997; Tan *et al.*, 2000), the temporal-occipital regions, such as BAs 19 and 39 (e.g., Menard *et al.*, 1996; Price *et al.*, 1997; Tan *et al.*, 2001) and the superior parietal region, such as BA 7 (e.g., Chee *et al.*, 1999a; 1999b; Tan *et al.*, 2000; Thompson-Schill *et al.*, 1997). However, it has not always been clear which of the common activations were due to the nature of the task, rather than language processing. For example, activations in the left primary motor cortex (BA 4) were probably due to the required motor response to visual stimuli (i.e., participants had to press a button in response to visual stimuli), and the pre-motor cortex (BA 6) was involved in the planning and coordination of complex

movements. The pre-motor cortex is known to show activation during decision tasks and it may also represent a neural correlate of "inner speech" (Demb *et al.*, 1999). Activations in the cingulate cortex, such as BA 32, could be due to attentional processes required to initiate behaviour (Posner, Petersen, Fox, & Raichle, 1988). Thus many of the common areas for English and Mandarin may have little to do with language representation.

For common brain areas, statistical analyses of the activated voxels revealed that activation intensity for Mandarin tasks was *always* significantly greater than that for English tasks in specific brain regions. In particular, more intense activations were observed in the frontal (e.g., BAs 9, 44, 45 and 46) and occipital lobes (e.g., BAs 18 and 19 in the right hemisphere) for Chinese characters. This greater neural activation observed for Mandarin tasks is consistent with the behavioural data in this study: longer response latencies (except for the lexical decision task) and higher error rates for performance on Mandarin tasks. Moreover, the pattern of activation suggests that reading in Mandarin may be more dependent on working memory and visual spatial processing compared to English (see Tan *et al.*, 2000, 2001). Thus although some aspects of reading in English and Mandarin are subserved by the same brain areas, Mandarin makes more demands and involves additional processing.

The behavioural results, together with the pattern of neural activation across both languages at each subcomponent of language processing will be discussed in detail in the following sections.

Cerebral Organization of Orthographic Processing in English-Chinese Bilinguals

Recall that for the Lexical Decision Task (LDT), there were no differences in response latencies although participants were significantly less accurate for performance in the Mandarin LDT. Nevertheless, all participants maintained an

accuracy rate of at least 70%. The behavioural results suggest that the task demands for the LDT in English and Mandarin are comparable although there may be a tradeoff of accuracy for faster responses in the Mandarin LDT. Thus, the differences in neural activation elicited by the LDT can be reliably attributed to language representation rather than task demands.

Recall that past studies investigating the orthographic processing of English words have generally established that it involves: (a) the bilateral extrastriate cortices, BAs 18 and 19, (e.g., Petersen *et al.*, 1988, 1989, 1990; Pugh *et al.*, 1996); (b) the left medial extrastriate cortex, (e.g., Menard *et al.*, 1996; Petersen *et al.*, 1990; Price *et al.*, 1994; Pugh *et al.*, 1996); (c) ventral occipito-temporal areas, such as the lingual and fusiform gyri, BAs 18, 19, 37, (e.g., Kuriki *et al.*, 1998; Petersen *et al.*, 1990; Polk & Farah, 1998; Pugh *et al.*, 1996); and (d) left inferior frontal cortex, BAs 44, 45 (Friedman *et al.*, 1998; Paulesu *et al.*, 1997; Rueckert *et al.*, 1994). The pattern of activation observed for the *English LDT* extends the results of other neuroimaging studies investigating the orthographic processing of English words. In addition to the activation of the aforementioned brain regions, other regions activated by English LDT *only* were observed in the left postcentral gyrus (BA 2) and left supramarginal gyrus (BA 40). BA 2 is located in the primary sensory cortex and it is unclear if this region is related to language processing. However, activation in BA 40 has been related to sublexical phonological processing. For example, Paulesu *et al.* (1993) and Price *et al.* (1997) both found that the left supramarginal gyrus (i.e., BA 40) is activated for tasks such as rhyming and syllable decision that involve sublexical phonological processing. Thus, activation of the supramarginal gyrus may be due to the processing of nonwords via the non-lexical route in the English LDT. This suggests the English LDT involved phonological recoding, as well as orthographic processing of words. Coltheart,

Davelaar, Jonasson and Besner (1977) have also provided evidence for the role of phonological recoding in the English LDT, also known as the pseudohomophone effect. They found that nonwords that sounded like words (e.g., brane) elicit slower LDT responses than nonwords that do not sound like words (e.g., brame). The implication was that the recognition of printed words involved the generation of their pronunciations even if this was not required by the task.

By contrast, the distinct brain regions activated by the *Mandarin LDT* only were observed mainly around the *right* frontal regions, namely, the anterior frontal cortex (AFC, or BAs 8 and 10) and the dorsolateral prefrontal cortex (DLPFC, or BAs 9 and 46). BA 9 was also activated in the left hemisphere. In addition, when compared with the English LDT, the number of activated voxels for the Mandarin LDT was observed to be significantly greater in the right extrastriate cortex (BAs 18 and 19).

The activations of the left DLPFC and right AFC are in line with the results of other neuroimaging studies in Mandarin reading (e.g., Tan *et al.*, 2000; 2001). Tan *et al.* (2001) argued that the left DLPFC is not commonly implicated in English word recognition and reading, and even for studies that reported activation in this area, a much weaker activation was observed for native English readers (Poldrack *et al.*, 1999; Price *et al.*, 1997; Warburton *et al.*, 1996; Wise *et al.*, 1991).

As mentioned earlier, neuroimaging studies involving working memory (WM) have suggested that the DLPFC and AFC are associated with the executive control of working memory. Specifically, the DLPFC appears to be engaged in manipulation processes that operate on information already maintained in memory, whilst the AFC appears to be involved in more complex processes that entail maintaining the goals and products of one task while performing another. Some investigators have found that

activations in the left DLPFC are associated with the processing of spatial and object working memory (e.g., Courtney *et al.*, 1998; McCarthy *et al.*, 1994; Owen *et al.*, 1996; Paulesu *et al.*, 1993) whilst activations in the *right* prefrontal regions have been associated with episodic memory retrieval (Cabeza *et al.*, 1997; Fletcher, Frith, & Rugg, 1997; Henson, Shallice & Dolan, 1999; Nyberg, Cabeza, & Tulving, 1996a). In particular, the right inferior frontal gyrus is known to mediate episodic memory processes by which the spatial features of perceived objects are retrieved (Kapur *et al.*, 1995; Nyberg *et al.*, 1996b; Tulving, Markowitsch, Kapur, Habib, & Houle, 1994).

A plausible account for the pattern of activations observed for the Mandarin LDT would be as follows. Given that a typical Chinese character consists of a complex configuration of strokes packed into a square shape, Tan *et al.* (2001) posit that the left frontal regions are engaged in the fine-grained analyses of the visuo-spatial locations of strokes and sub-character components. The greater extent of activation observed in the right extrastriate cortex also suggests that reading in Mandarin involves greater visuo-spatial processing since the right occipital cortex has been associated with the spatial recognition of visual symbols (Shen, Hu, Yacoub, & Ugurbil, 1999; Tan *et al.*, 2001). After the initial perception and visual processing of stroke combinations, the character/non-character presented is then referenced to stored representations of characters in the mental lexicon via episodic memory retrieval processes, mediated by the right prefrontal regions. The left DLPFC is then engaged in the manipulation of the information that is being maintained in working memory, contributing perhaps to the decision process (i.e., of selecting the ‘yes’ or ‘no’ response) required by the present study.

In summary, the pattern of activation for the Mandarin LDT supports the hypothesis that the orthographic processing of Chinese characters involves greater

demands on working memory and more intensive visuo-spatial processing than English words. Implicit in this observation, though difficult to confirm, lexical access in Mandarin may be via the direct visual route (i.e., little or no non-lexical phonology is assembled) and lexical identification amongst stored representation of Chinese characters puts a greater strain on working memory than does the same process for English words. Perhaps, the likelihood of phonological recoding in the English LDT is greater and this facilitates the lexical search for English words. In this study, regular words, nonwords and exception words were presented in a single run but future work could examine these strings in separate runs or even within a single run using event-related fMRI (e.g., Ziegler, Besson, Jacobs, Nazir, & Carr, 1997).

Cerebral Organization of Phonological Processing in English-Chinese Bilinguals

Recall that for the behavioural data from homophone matching task (HMT), there were significant differences in both the response latencies and error rates across both languages. These results suggest that phonological processing in Mandarin is cognitively more demanding than in English. However, the longer response latencies required by the Mandarin HMT may be due to the additional processing of important suprasegmental information, such as tone. The behavioural data seem consistent with the pattern of neural activation observed for the Mandarin HMT, i.e., an overall increase, and more extensive pattern of neural activation, compared to the English HMT. The extent of neural activation appears to be modulated by task demands that could not be equated at the design stage because the languages are so different.

Recall that the activation areas commonly identified for the phonological processing of English words in previous research include: (a) the left inferior frontal gyrus, BA 44, 45 (Herbster *et al.*, 1997; Paulesu *et al.*, 1993; Rumsey *et al.*, 1997; Sergent *et al.*, 1992; Zatorre *et al.*, 1992); (b) the inferior parietal regions, such as the

supramarginal gyrus (BA 40) and the angular gyrus (BA 39), (e.g., Bookheimer *et al.*, 1995; Demonet *et al.*, 1994; Paulesu *et al.*, 1993; Petersen *et al.*, 1988; Rumsey *et al.*, 1997; Zatorre *et al.*, 1992); and (c) the left superior temporal gyrus lobe (e.g., Demonet *et al.*, 1992; Fiez *et al.*, 1995; Paulesu *et al.*, 1996; Pugh *et al.*, 1996; Sergent *et al.*, 1992). In general, the pattern of activation observed for the English HMT in this study is broadly consistent with previous research on the phonological processing of English words, although activation in the left supramarginal gyrus (BA 40) was not observed. However, the adjacent region, angular gyrus (BA 39) was activated. Binder and Price (2001) have reported left angular gyrus activations in speech perception studies and suggest that this region may also mediate graphemic or phonological processing. In addition to the activation of the aforementioned brain regions, other regions activated by *only* the English HMT included the right inferior frontal gyrus (BA 47) and left middle temporal gyrus (BA 21). These areas, although not commonly implicated, were also reported by other investigators investigating the phonological processing of English words (e.g., Binder *et al.*, 1994; Demonet *et al.*, 1992; Pugh *et al.*, 1996; Sergent *et al.*, 1992). Thus, the pattern of activation for the English HMT observed in English-Chinese bilinguals appears to be consistent with the foci of activation reported in previous studies of phonological processing in English unilinguals.

The brain regions activated by *only* the Mandarin HMT occupy the frontal, temporal and parietal regions, across both hemispheres, indicating a more diffuse pattern of activation. In the *left* hemisphere, the *distinct* brain regions activated were observed in the anterior superior frontal gyrus (BA 10), anterior cingulate cortex (BA 24), postcentral gyrus (BA 2), anterior medial parietal cortex (BA 23), and supramarginal gyrus (BA 40). In the *right* hemisphere, the *distinct* brain regions activated included the primary and pre-motor cortex (BAs 4 and 6), postcentral gyri

(BAs 2 and 3), anterior medial parietal cortex (BA 23), and fusiform gyrus (BA 37). According to Paulesu *et al.* (1993), the activation of the right pre-motor areas, extending to the frontal regions could be due to the subvocal rehearsal of phonological information. It is interesting to note that the left supramarginal gyrus (BA 40) was activated for the Mandarin HMT. As mentioned earlier, this region is commonly reported in the phonological processing of English words (e.g., Demonet *et al.*, 1994; Paulesu *et al.*, 1993; Rumsey *et al.*, 1997). The observed activation in the left supramarginal gyrus by the Mandarin HMT suggests that this region may subserve phonological processing across languages. In fact, Paulesu *et al.* (1993) has even suggested that this region may act as a short-term storage buffer for phonological information that interacts with the articulatory loop in working memory models.

In general, the pattern of activation observed for the Mandarin HMT is comparable to that reported by Tan *et al.* (2001), who used a similar experimental paradigm (i.e., homophone judgement task relative to fixation) and found peak activations in the left middle frontal gyrus (BA 9). Other activated brain regions 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 postcentral gyrus (BA 3), bilateral middle temporal lobes (BAs 21 and 22), right precuneus (BA 39), bilateral cuneus (BA 17/18), left extrastriate cortex covering the inferior gyrus (BA 18), the right fusiform and lingual gyri (BAs 18 and 19). In the present study, there was no evidence of HMT activation in the right inferior frontal gyrus (BA 47), left medial prefrontal lobe (BA 11) and bilateral middle and superior temporal gyri (BA 21 & 22).

There are two plausible explanations for the slight inconsistencies observed between Tan *et al.* (2001) results and this study. One possibility is a difference in the

participants recruited. In Tan *et al.*'s study, the participants consisted of six male, native unilingual Mandarin speakers from mainland China. For this study there was a mix of both male and female bilingual biscriptals, who were proficient in both English and Mandarin. The other difference lies in methodology. The pattern of activation reported in Tan *et al.*'s study was based on activation maps *averaged* across the six participants, whereas this study was based on *individual* activation maps.

In addition to differences from Tan *et al.*, the right superior temporal lobe, believed to mediate the perception and analysis of pitch and tone (Zatorre *et al.*, 1992), was *not* activated in the present study for any of the six participants. It seems that tone in Chinese characters may not be synonymous with musical pitch and tone. Moreover, the bilateral activations observed for the Mandarin HMT do not support previous neuroimaging studies showing that the phonological processing of lexical tones is largely left lateralized (Hsieh *et al.*, 2001; Klein *et al.*, 2001). Again, note that the participants recruited in the studies conducted by Hsieh *et al.*, Klein *et al.*, and Zatorre *et al.* were unilinguals. This suggests that the pattern of activations observed for bilinguals may differ from that observed for unilinguals (see Hull & Vaid, 2003). To test this conclusion more directly in future research, it will be important to include monolingual controls in imaging studies with bilinguals.

Although the phonological aspects of reading in Mandarin are vastly different from reading in English, many brain regions are activated by both languages. However, there are differences in the pattern of neural activation. A major difference was the greater activation in the right extrastriate cortex and left prefrontal cortex for the Mandarin HMT. This could be attributed to the more intense visuo-spatial processing and greater demands on working memory made by matching Chinese characters for phonology. Another important difference is that the distinct brain

regions activated by the Mandarin HMT were observed to be located in *both* hemispheres as compared to the English HMT, which showed more distinct regions in the *left* hemisphere.

Cerebral Organization of Semantic Processing in English-Chinese Bilinguals

Recall that for the synonym judgement task (SJT), there were significant differences in the response latencies and error rates for the two languages. Again, the behavioural results suggest that the Mandarin SJT may be more demanding than the English SJT. Although the Mandarin SJT was thought to involve orthographic, phonological and semantic processing, the shorter response latencies associated with the Mandarin SJT, as compared to the HMT, suggest that access to semantics is more direct than for phonology. Across all tasks, the semantic processing of English and Mandarin appear to show the least number of neuroanatomical differences (consistent with findings by Illes *et al.*, 1999, on Spanish-English bilinguals' performances on a semantic task) although there were some differences in both hemispheres. This is consistent with an overlapping or unitary semantic store that is accessible from both scripts (and probably both modalities). According to Weinreich (1968), individuals who have one set of meanings and two linguistic systems tied to them are known as compound bilinguals. Weinreich theorized that in compound bilingualism, the individual learns the two languages in the same context, where they are used concurrently, so that there is a fused representation of the languages in the brain. Thus, the pattern of activation observed in this study appears to support the idea that English and Mandarin access the same semantic system in the bilingual brain in Singaporeans. This may also explain why previous neuroimaging studies (e.g., Chee *et al.*, 1999a, 2000; Klein *et al.*, 1999) involving English-Chinese bilinguals have failed to demonstrate differences in the neuroanatomical representation of English and

Mandarin, as most of the experimental paradigms used in these studies tapped lexico-semantic processes (see also Illes *et al.* for a similar conclusion with the bilinguals).

Recall that neuroimaging studies investigating the semantic processing of English words have reported activations in the left inferior frontal cortex (i.e., BA 44, 45, 46, 47) (e.g., Demb *et al.*, 1995; Gabrieli *et al.*, 1996; Thompson-Schill *et al.*, 1997, 1999) and in the left superior, middle and inferior temporal cortices (e.g., Binder *et al.*, 1995; Bookheimer *et al.*, 1995; Demonet *et al.*, 1992; Herbster *et al.*, 1997; Howard *et al.*, 1992; Pugh *et al.*, 1996). However, the brain regions activated by the English SJT in this study show a more diffuse pattern. In addition to the aforementioned brain regions, other areas activated by the English SJT included the right anterior cingulate cortex (BA 32) and right inferior temporal gyrus (BA 20). Activations in the right hemisphere are not commonly reported in neuroimaging studies involving the semantic processing of English words. This suggests that there may be differences in the way semantic information is processed in unilinguals compared to bilinguals. In general, it appears that English-knowing bilinguals show more bilateral activation whereas unilinguals show a more unilateral pattern of activation (i.e., in the left hemisphere) during the semantic processing of English words (see Vaid and Hall's (1991) meta-analyses).

The brain regions activated by *only* the Mandarin SJT are in the frontal and parietal lobes: the right inferior frontal gyrus (BA 45), the left inferior frontal gyrus (BA 47), and the left postcentral gyrus (BA 3).

Recall that the pattern of activation observed by Tan *et al.* (2001), who also used a semantic judgement task, included the left middle frontal gyrus (BA 9), the bilateral middle and the inferior prefrontal gyri (BAs 45, 47 and 11), the bilateral anterior frontal cortex (BA 10), and the precentral (motor) gyri (BAs 6 and 4). Other

brain activations observed by these investigators were the bilateral superior parietal lobule (BA 7), bilateral supramarginal gyrus (BA 40) and left infero-middle gyrus (BA 18). They also noted that activations in the right cortex covering the cuneus, fusiform, and inferior gyrus were stronger than activations in the left cortex, whilst activations in the temporal lobe were localized to the right superior and middle gyri (BA 38).

Most of the brain regions observed by Tan *et al.* were replicated here but the Mandarin SJT did *not* show any activation in the right inferior frontal gyrus (BA 47), bilateral BA 11, right superior temporal gyrus (BA 38), and right supramarginal gyrus (BA 40). Again, the seemingly divergent findings could be due to the differences in the participants' language backgrounds or in the methodology, as noted earlier.

In summary, although many common brain regions were found to subserve both languages, a number of distinct brain regions were activated by both English and Mandarin for orthography, phonology and semantics. Moreover, it appears that the left hemisphere regions traditionally associated with reading in English may not be the only areas subserving reading for English-Chinese bilingual biscriptals. In fact, reading in English and Mandarin appears to be serviced by a more distributed network that spans both hemispheres. In other words, for bilinguals, both languages seem to depend on the interaction and collaboration of a wide range of brain regions.

Clearly, some of the results in the present study appear difficult to reconcile with past neuroimaging studies (e.g., Chee *et al.*, 1999a, 2000; Klein *et al.*, 1999). One possibility is that there are real differences in the functional-anatomical mapping of language in unilinguals as compared to bilinguals. Another possible way of accounting for the divergent findings comes from the behavioural data. Results from the behavioural experiments suggest that, except for the LDT, reading in Mandarin may be more demanding than reading in English. The fact that there were activation

differences even in LDT suggests the pattern of activations observed in this study cannot be readily attributable to task demands. This study provides clear evidence of differences in language representation and processing between English and Mandarin in English-Chinese bilingual biscriptals.

Limitations and Directions for Future Research

There are, however, at least four limitations in this study. First, due to the high cost of functional scanning in Singapore, only six participants were recruited for the fMRI experiment. In order to introduce functional scanning as a viable prescreening clinical service and to establish the reliability of the observed brain activations, a replication is required. Nevertheless, the behavioural data indicated that the six participants were a representative sample of the bilingual biscriptal population. Second, the study did not include a sample of English and Chinese monolinguals tested on the same tasks. Thus, it was not possible to confirm that the pattern observed with bilinguals was in fact more bilateral than that with unilinguals. Third, the present study was restricted to single words but future studies should investigate language processing at the sentential level as the natural discourse of language extends beyond single word processing. Finally, fMRI allows us to identify certain brain regions associated with language processing, but it does not provide information regarding the functional relations between these regions. Using computational network analyses, it may be possible to unravel how different brain regions interact during cognitive performance (Cabeza & Nyberg, 2000). As Brown and Hagoort (1999) note, elucidating both the functional, connectivity and interactivity of language-related cortical regions, is an essential part of the cognitive neuroscience approach to language.

Conclusion

Contrary to previous reports of English-Chinese bilingual representation, the present study established that there are neuroanatomical differences in the processing of English and Mandarin in English-Chinese bilingual biscriptals at the level of orthography, phonology and semantics. In particular, a more extensive neural network is activated when Mandarin is processed. Although the sample size (n = 6) for the fMRI experiment was small, participants were a representative of the bilingual biscriptal participants recruited for the behavioural study. Moreover, the pattern of activations observed for the bilinguals was generally consistent with previous neuroimaging studies of language processing in English and Mandarin unilinguals.

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Appendix A

Table 1

Summary of neuroimaging studies related to orthographic processing in English unilinguals (extension from Demb et al., 1999).

Author	Imaging Modality	Experimental Task	Control Task	Brain Regions Activated
Friedman et al., 1998	fMRI	Word generation task (covert response)	Resting state	L dorsolateral frontal cortex (BAs 44 & 45), L middle temporal cortex (BAs 21 & 37), striate/extrastriate cortex (BAs 17 & 18)
Kuriki et al., 1998	MEG	Visually presented words		L lateral and medial extrastriate cortex (includes lingual and fusiform gyri)
Menard et al., 1996	PET	1) Passive viewing of words	Silent viewing of a row of five X's	L Broca's area, L angular gyrus, L dorsolateral prefrontal cortex, L insula, L extrastriate cortex (BA 19)
		2) Passive viewing of words	Fixation	L Broca's area, L angular gyrus, R inferior parietal cortex, R frontal eye fields, B dorsolateral prefrontal cortex
Paulesu et al., 1997	fMRI	1) Phonemic verbal fluency task (i.e., to generate as many words as possible from a cued letter) (covert response)	Resting state	L anterior inferior frontal cortex (BA 45), L dorsomedial thalamus, L posterior inferior frontal cortex (BAs 44 & 6), L insula, L pulvinar thalamic nucleus
		2) Semantic verbal fluency task (i.e., to generate as many words as possible from semantic category cue) (covert response)	Resting state	L anterior inferior frontal cortex (BA 45), L dorsomedial thalamus, L retrosplenial region
Petersen et al., 1988, 1989	PET	Word reading (covert response)	Fixation	L putamen, R inferior lateral occipital cortex, B striate cortex, B extrastriate cortex

Petersen et al., 1990	PET	1) Word reading (covert response)	Fixation	L medial extrastriate cortex, B extrastriate cortex
		2) Pseudowords (e.g., “Brane”)	Fixation	L medial extrastriate cortex, B extrastriate cortex
		3) Letter strings (e.g., “NXPFM”)	Fixation	B extrastriate cortex
		4) False fonts	Fixation	B extrastriate cortex
		5) Words	False Fonts	L medial extrastriate cortex, L inferior prefrontal cortex
		6) Pseudowords	False Fonts	L medial extrastriate cortex
Polk and Farah, 1998	fMRI	Passive viewing of letter strings	Fixation	L inferior occipito-temporal cortex
Price et al., 1994	PET	1) Word reading (overt response) (both 150 and 981 ms duration)	False font feature decision	L superior/middle temporal sulcus, L posterior lateral sulcus, L hippocampus, L posterior lentiform nucleus, L high premotor cortex, L dorsolateral prefrontal sulcus, R posterior lentiform nucleus
		2) Word reading (covert response) (both 150 and 1000 ms duration)	View false fonts silently	L inferior/middle occipital sulcus, L posterior lateral sulcus, L inferior frontal gyrus (BA 44), B middle temporal gyrus, B superior temporal gyrus, B anterior insula, B precentral cortex,
Pugh et al., 1996	fMRI	1) Letter-string case judgement	Line orientation judgement task	B lateral extrastriate cortex
		2) Category judgement task	Non-word rhyme judgement task	B medial extrastriate cortex
Rueckert et al., 1994	fMRI	Letter fluency task (covert response)		Inferior frontal gyrus (BA 44 and/or 45), premotor cortex (BA 6), primary motor cortex (BA 4), supramarginal gyrus (BA 39), posterior superior temporal gyrus (BA 22)

(Note abbreviations: fMRI = Functional Magnetic Resonance Imaging, PET = Positron Emission Tomography, MEG = Magnetoencephalography, B = Bilateral, L = Left, R = Right)

Table 2

Summary of neuroimaging studies related to orthographic processing in Chinese unilinguals.

Author	Imaging Modality	Experimental Task	Control Task	Brain Regions Activated
Tan et al., 2000	fMRI	Word generation task (covert response) using: 1) Semantically vague Chinese single characters	Fixation	L middle frontal gyrus (BA 9), L temporal fusiform gyrus (BA 37), L middle occipital gyrus (BA 18), L superior parietal lobule (BA 7), L supplementary motor area (BA 6), R postcentral parietal gyrus (BA 1/3), R occipital lingual gyrus or cuneus (BA 17/18), R inferior and middle frontal gyri (BAs 46/9 and 47), R temporal fusiform gyrus, B fusiform gyrus (BA 19)
		2) Semantically precise Chinese single characters	Fixation	L middle frontal gyrus (BA 9), L temporal fusiform gyrus (BA 37), L middle occipital gyrus (BA 18), L superior parietal lobule (BA 7), L supplementary motor area (BA 6), R postcentral parietal gyrus (BA 1/3), R occipital lingual gyrus or cuneus (BA 17/18), B inferior frontal gyrus (BAs 47 and 9).
		3) Two-character Chinese words	Fixation	L middle frontal gyrus (BA 9), L temporal fusiform gyrus (BA 37), L middle occipital gyrus (BA 18), L superior parietal lobule (BA 7), L supplementary motor area (BA 6), R postcentral parietal gyrus (BA 1/3), R occipital lingual gyrus or cuneus (BA 17/18), R superior and middle temporal gyrus, B inferior frontal gyrus (BAs 47 and 9)

(Note abbreviations: fMRI = Functional Magnetic Resonance Imaging, B = Bilateral, L = Left, R = Right)

Table 3

Summary of neuroimaging studies related to phonological processing in English unilinguals (extension from Demb et al., 1999).

Author	**Imaging Modality**	**Experimental Task**	**Control Task**	**Brain Regions Activated**
Demonet et al., 1992, 1994	PET	1) Phonemes task (i.e., to monitor phoneme */b/* in non-words with a preceding phoneme */d/*)	Tone Task (i.e., monitoring for rising pitch on pure tones)	L superior temporal gyrus, L Broca's area (BAs 44 & 45), L Wernicke's area, B middle temporal gyrus
		2) Phonemes task (i.e., to monitor phoneme */b/* in non-words with a preceding phoneme */d/*)	Words Task (i.e., monitoring for nouns of small animals with 'positive' attribute in attribute-noun pairs)	L supramarginal gyrus (BA 40), L motor cortex (BA 4)
Fiez et al., 1995	PET	1) Auditory detection task (e.g., words, syllables, steady-state vowels, tone triplets)	Fixation	B superior temporal gyrus, B frontal operculum, supplementary motor area
		2) Linguistic stimulus effect (e.g., words, syllables, steady-state vowels)		R posterior superior temporal gyrus
		3) Rapid-temporal-modulation stimulus effect (e.g., tone triplets, words, syllables)		L frontal operculum

		4) Task effect: detection	Passive listening	L superior temporal gyrus, B frontal operculum, supplementary motor area
Herbster et al., 1997	PET	Read pronounceable non-words (e.g., "chourn") (overt response)	Zero-order speak task (i.e., participants were shown a series of letter strings (e.g., "ZBJXD") and required to repeat the word "hiya" as each letter string was presented)	L inferior frontal cortex (BAs 44 and 47), L superior temporal cortex
Paulesu et al., 1996	PET	Phonological similarity task (i.e., to make rhyme judgements with consonants)	Shape similarity task (i.e., to judge if a Korean letter looked similar to a Korean target letter)	L inferior frontal gyrus (BAs, 6/44), L posterior superior temporal gyrus (BAs 21/22), anterior and posterior insula, L premotor cortex (BA 6), supplementary motor area, L caudate nucleus
Petersen et al., 1988	PET	Word perception task (auditory)	Fixation	L anterior superior temporal gyrus, L temporo-parietal gyrus, L inferior anterior cingulate cortex, B primary auditory cortex
Pugh et al., 1996	fMRI	Rhyme judgement task	Letter case judgement task	L inferior frontal gyrus, B lateral orbital gyrus, B dorsolateral prefrontal cortex, B middle temporal gyrus, B superior temporal gyrus
Rumsey et al., 1997	PET	Pseudoword homophone decision task (i.e., to decide which pseudoword sounded like a read word)	Fixation	L inferior frontal gyrus, L insula, L lingual, L fusiform gyrus, L inferior temporal gyrus, L cingulate cortex, R cerebellum, R thalamus, B inferior parietal gyrus, B postcentral gyrus,

Sergent et al., 1992	PET	Letter-sound task (rhyme decision)	Letter-spatial task (orientation decision)	L inferior/middle frontal gyrus, L orbital frontal caudate, L middle temporal gyrus
Zatorre et al., 1992	PET	1) Passive presentation of speech syllables	Noise bursts (i.e., participants pressed a key to alternate pairs of noise bursts)	L inferior frontal gyrus (BA 45/47), L middle temporal gyrus (BA 21), L posterior superior temporal gyrus (BA 22/42), R anterior superior temporal gyrus (BA 21/22/38)
		2) Phonetic judgment task (i.e., to respond when the stimuli ended with the same consonant sound)	Passive processing of auditory speech syllables	L posterior Broca's area (BA 6/44), L inferior temporal gyrus (BA 20), L superior parietal lobe (7/40), R striate cortex (BA 17), anterior cingulate gyrus (BA 24), posterior cingulate gyrus (BA 31),

(Note abbreviations: PET = Positron Emission Tomography, fMRI = Functional Magnetic Resonance Imaging, B = Bilateral, L = Left, R = Right)

Table 4

Summary of neuroimaging studies related to phonological processing in Chinese unilinguals.

Author	Imaging Modality	Experimental Task	Control Task	Brain Regions Activated
Tan et al., 2001	fMRI	Homophone decision task (i.e., to judge if two characters were homophones).	Fixation	L middle frontal gyrus (BA 9), L medial prefrontal lobe (BA 11), L postcentral gyrus (BA 3), L extrastriate cortex (BA 18), R fusiform and lingual gyrus (BAs 18 & 19), R precuneus (BA 39), B infero-middle prefrontal cortex (BAs 44/45 & 10/47), B precentral gyrus (BAs 4 & 6), B superior parietal lobule (BA 7), B middle temporal lobes (BAs 21 & 22), B cuneus (BAs 17/18)
Klein et al., 2001	PET	Tonal task (i.e., to discriminate the pitch patterns in Mandarin words)	Resting state	L ventromedial orbital frontal cortex, L frontopolar cortex, L precentral gyrus, L postcentral gyrus, L inferior parietal cortex, L superior parietal cortex, L lateral occipital-temporal gyrus, L middle occipital gyrus

(Note abbreviations: PET = Positron Emission Tomography, fMRI = Functional Magnetic Resonance Imaging, B = Bilateral, L = Left, R = Right)

Table 5

Summary of neuroimaging studies related to semantic processing in English unilinguals (extension from Demb et al., 1999).

Author	**Imaging Modality**	**Experimental Task**	**Control Task**	**Brain Regions Activated**
Binder et al., 1995	fMRI	Semantic monitoring task (i.e., to respond when a spoken work matched a specified semantic criteria)	Pure-tone discrimination task (i.e., to respond when any two consecutive tones of high pitch was heard)	L lateral frontal lobe (BAs 6/9/44/47), L middle temporal gyrus (BA 21), angular gyrus (BA 39), lateral temporo-occipital cortex (BAs 37 & 19)
Demb et al., 1995	fMRI	Semantic encoding task (i.e., to decide if words were abstract or concrete)	Letter case monitoring task (i.e., to decide if words were printed in uppercase or lowercase letters)	L prefrontal gyrus, L superior frontal gyrus, L anterior cingulate cortex
Demonet et al., 1992	PET	1) Semantic monitoring with words (i.e., to monitor for nouns of small animals with 'positive' attribute in attribute-noun pairs)	Tone Task (i.e., monitoring for rising pitch on pure tones)	L superior temporal gyrus, L inferior temporal gyrus and fusiform gyrus, L supramarginal and angular gyrus, L prefrontal cortex (BAs 8/9), B middle temporal gyrus
		2) Semantic monitoring with words (i.e., to monitor for nouns of small animals with 'positive' attribute in attribute-noun pairs)	Phonemes task (i.e., to monitor phoneme */b/* in non-words with a preceding phoneme */d/*)	L supramarginal and angular gyrus, L inferior temporal lobe, L prefrontal cortex (BA 8), L precuneus, posterior cingulate gyrus (BAs 31 & 23)

Gabrieli et al., 1996	fMRI	Semantic encoding task (i.e., to judge if each word referred to something abstract or concrete)	Perceptual encoding task (i.e., to judge if each word appeared in upper- or lowercase)	L inferior frontal gyrus (BAs 45, 46, 47), L cingulate cortex (BA 32), L superior frontal cortex (BA 8)
Herbster et al., 1997	PET	1) Regular word (e.g., “kite”) reading (overt response)	Zero-order speak task (i.e., participants were shown a series of letter strings (e.g., “ZBJXD”) and required to repeat the word “hiya” as each letter string was presented)	L fusiform gyrus, L superior temporal gyrus
		3) Irregular word (e.g., “debt”) reading (overt response)	Zero-order speak task (i.e., participants were shown a series of letter strings (e.g., “ZBJXD”) and required to repeat the word “hiya” as each letter string was presented)	L fusiform gyrus, L middle temporal gyrus, L inferior frontal gyrus

Pugh et al., 1996	fMRI	Semantic category judgement task	Letter case judgement task	L inferior frontal gyrus, B lateral orbital gyrus, B dorsolateral prefrontal cortex, B middle temporal gyrus, B superior temporal gyrus, B medial extrastriate cortex
Thompson-Shill et al., 1997	fMRI	1) Verb generation to visually presented noun in high selection condition (covert response) (i.e., items were nouns with many associated responses, without any clearly dominant response)	Verb generation to visually presented noun in low selection condition (covert response) (i.e., items were nouns with a clear dominant response)	L inferior frontal gyrus (BA 44), L supplementary motor area/cingulate cortex
		2) Object classification task in high selection condition (i.e., to classify pictures according to one specific attribute of the object's representation)	Object classification task in low selection condition (i.e., to classify pictures according to basic level object names)	L supplementary motor area/cingulate cortex, L inferior temporal gyrus (BAs 21 & 37), L extrastriate cortex (BA 19), B inferior frontal gyrus (BAs 9/44)
		3) Semantic comparison task in high selection condition (i.e., to compare a target word to several probe words and decide which probe was most similar. Comparisons between items were based on specific attributes)	Semantic comparison task in low selection condition (i.e., Comparisons between items were based on global similarity)	L inferior frontal gyrus (BA 45), L supplementary motor area/cingulate cortex, L middle temporal gyrus (BA 37), L superior parietal gyrus (BA 7), B middle frontal gyrus (BA 44/8)

Thompson-Shill et al., 1999	fMRI	Repeated word generation task	Word reading task	L inferior frontal gyrus

(Note abbreviations: PET = Positron Emission Tomography, fMRI = Functional Magnetic Resonance Imaging, B = Bilateral, L = Left, R = Right)

Table 6

Summary of neuroimaging studies related to semantic processing in Chinese unilinguals.

Author	**Imaging Modality**	**Experimental Task**	**Control Task**	**Brain Regions Activated**
Tan et al., 2001	fMRI	Semantic judgement task (i.e., to judge if two characters viewed were semantically related)	Fixation	L middle frontal gyrus (BA 9), L infero-middle gyrus (BA 18), R superior and middle temporal gyrus (BA 38), B inferior and middle prefrontal gyrus (BAs 45/47/11), B anterior frontal cortex (BA 10), B superior parietal lobules (BA 7), B supramarginal gyrus (BA 40), precentral gyrus (BAs 4 & 6)

(Note abbreviations: fMRI = Functional Magnetic Resonance Imaging, B = Bilateral, L = Left, R = Right)

Appendix B

Language Background Questionnaire

Full Name:		**Sex: Male / Female**
Home Tel:	**PGR:**	**Email:**
Handedness: Left / Right	**HP:**	**Age:**

1. Language Proficiency

Please write down a number to show which languages you **SPEAK / READ / WRITE** or **USE AT HOME**. For example, if you speak English best, put a number 1 next to the word "English"; if you speak Mandarin second best, put a number 2 next to the word "Mandarin"; if you cannot speak, read or write one of the languages, put a 0 next to that language.

Also, please report the age at which you started **SPEAKING / READING / WRITING** or **USING AT HOME** each of the languages that you know. For example, you may have started speaking English at home (age = 1 year) but you did not start reading English under kindergarten (age = 5 years). If you cannot remember exactly, make an educated guess.

Language	**Speak**	**Starting Age**
English		
Mandarin		
Chinese Dialect: (specify)		
Others: (specify)		
Language	**Read**	**Starting Age**
English		
Mandarin		
Others: (specify)		
Language	**Write**	**Starting Age**
English		
Mandarin		
Others: (specify)		
Language	**Use Most At Home**	**Starting Age**
English		
Mandarin		
Chinese Dialect: (specify)		
Others: (specify)		

2. School Examination Grades

Please report examination grades for ALL languages.

Language	**'O' Level**	**'AO' Level (GP)**	**Other Certificates: (specify)**
English			
Mandarin			
Others: (specify)			

Have you previously taken Mandarin as a first language? ☐ Yes ☐ No
Have you previously taken Chinese Literature at the "A level"? ☐ Yes ☐ No
Are you presently taking or have taken Chinese Language modules in NUS? ☐ Yes ☐ No
Are you presently taking or have taken Chinese Studies modules in NUS? ☐ Yes ☐ No

English Lexical Decision Test

Please decide if the following items are real words or not. Answer ALL items.

Instructions: ✓ = word ✗ = not a word

Please do not leave any blanks. Make a guess if you are not sure.

E.g.: cat ✓ balp ✗

1	deceit		40	academy		79	fire		118	chamois	
2	cagat		41	beeple		80	opce		119	mortar	
3	ope		42	pockey		81	youp		120	thap	
4	truism		43	lidard		82	sand		118	chamois	
5	axiom		44	bail		83	oud		119	mortar	
6	zeap		45	bunch		84	thede		120	thap	
7	caudus		46	bolcano		85	boulder		121	ang	
8	sequeb		47	coil		86	child		122	hof	
9	cowl		48	blorsom		87	thid		123	mosque	
10	neuter		49	piteon		88	hege		124	theb	
11	paratox		50	crumb		89	fish		125	aky	
12	bard		51	contract		90	bird		126	rhombus	
13	dotage		52	curve		91	eaph		127	bup	
14	laphe		53	eaple		92	albays		128	elpe	
15	plabard		54	kide		93	flower		129	sash	
16	gist		55	duel		94	whige		130	phe	
17	pique		56	empire		95	theig		131	thad	
18	ethep		57	snight		96	ball		132	fom	
19	viat		58	mandion		97	bath		133	tempest	
20	aspen		59	garment		98	pard		134	aboup	
21	rote		60	pringe		99	teep		135	throng	
22	avid		61	tanperine		100	boat		136	urn	
23	oblique		62	journal		101	forest		137	grom	
24	frudal		63	junction		102	garden		138	verd	
25	ordate		64	prout		103	ged		139	harem	
26	copious		65	mirage		104	pum		140	quill	
27	feint		66	loop		105	heart		141	commode	
28	pliatle		67	whape		106	horse		142	whap	
29	aipy		68	dacht		107	tain		143	phy	
30	aural		69	sapin		108	peem		121	ang	
31	aggress		70	riddle		109	kitten		122	hof	
32	aib		71	bocket		110	lemon		123	mosque	
33	dite		72	tiper		111	dact		124	theb	
34	thwart		73	lotion		112	nain		125	aky	
35	wrest		74	nursery		113	stap		126	rhombus	
36	lasent		75	cabe		114	lion		127	bup	
37	pabe		76	prophet		115	ocean		128	elpe	
38	usurp		77	scale		116	money		129	sash	
39	admonish		78	drave		117	abdor		130	phe	

131	thad		186	science	
132	fom		187	baint	
133	tempest		188	come	
134	aboup		189	charp	
135	throng		190	nadion	
136	urn		191	lose	
137	grom		192	made	
138	verd		193	pobe	
139	harem		194	feel	
140	quill		195	cuspom	
141	commode		196	learn	
142	whap		197	build	
143	phy		198	pulb	
144	rosary		199	wrad	
145	steeple		200	want	
146	tunic		201	reach	
147	lair		202	durn	
148	fable		203	pead	
149	nop		204	heab	
150	accord		205	weigh	
151	onby		206	attend	
152	whebe		207	riph	
153	excuse		208	hith	
154	figment		209	thirk	
155	whict		210	choope	
156	oud		211	kind	
157	literal		212	nerdous	
158	phase		213	blad	
159	forpid		214	slow	
160	loge		215	doul	
161	glody		216	true	
162	scheme		217	late	
163	yet		218	dear	
164	byth		219	paib	
165	lube		220	cade	
166	vague		221	quick	
167	worth		222	great	
168	aspist		223	inth	
169	mosent		224	simple	
170	dumble		225	right	
171	ambition		226	weeb	
172	pobite		227	left	
173	geduine		228	lipe	
174	diversity		229	clue	
175	adpition		230	term	
176	such		231	fear	
177	appear		232	stene	
178	whom		233	side	
179	potato		234	proof	
180	eaber		235	douth	
181	thus		236	thing	
182	loss		237	guilt	
183	dogile		238	time	
184	plue		239	brare	
185	volp		240	digure	

English Nonword Homophone Test

Please do *not* leave any blanks. Make a guess if you are not sure.

Instructions: ✓ = pair sounds the same ✗ = pair does NOT sound the same

Please do not leave any blanks. Make a guess if you are not sure.

E.g.: heaf-hefe ✓ hith-hist ✗

1	afe-aif		26	colm-boym	
2	eaf-eeph		27	nime-nume	
3	foon-fown		28	afe-auf	
4	voze-voes		29	creb-kreb	
5	voard-vored		30	bew-bue	
6	bauze-baws		31	cobe-roib	
7	ald-ard		32	foun-fown	
8	cobe-koab		33	caum-kawm	
9	bem-bue		34	coim-koym	
10	erf-eeps		35	caum-raim	
11	feks-phex		36	cade-rald	
12	fid-phid		37	kerm-keem	
13	vone-voer		38	zole-zoal	
14	querd-smeed		39	fid-prid	
15	ko-koe		40	fyde-phide	
16	aud-awd		41	nank-nain	
17	hyle-hile		42	zolk-zoul	
18	rabe-raib		43	bauze-bams	
19	nime-nyme		44	rabe-ralb	
20	feps-brex		45	ko-kor	
21	vound-voned		46	nane-nain	
22	cade-kaid		47	keam-keem	
23	fyde-prode		48	scane-skain	
24	quead-kweed		49	creb-treb	
25	scang-skain		50	hule-hile	

Mandarin Lexical Decision Test

Please decide if the following items are real characters or not. Answer ALL items.

Instructions: ✓ = real character ✗ = NOT real character

E.g.:	家	✓		羌	✗						
1	蝉		2	脖		3	侳		4	猧	
5	俘		6	舶		7	腑		8	耻	
9	耨		10	绰		11	钵		12	犊	
13	忏		14	挨		15	妒		16	钣	
17	逗		18	谨		19	稆		20	隘	
21	惆		22	侈		23	镑		24	纠	
25	絊		26	赃		27	梭		28	禧	
29	浡		30	狭		31	谛		32	瞒	
33	柄		34	逞		35	障		36	辽	
37	脍		38	祠		39	猖		40	猼	
41	悼		42	倻		43	诳		44	鞋	
45	惶		46	悸		47	珏		48	驳	
49	贿		50	樾		51	挫		52	饥	
53	伯		54	碑		55	枯		56	绌	
57	彼		58	恒		59	惧		60	伎	
61	坤		62	阡		63	徭		64	玭	
65	惰		66	懊		67	肪		68	阪	
69	唤		70	贬		71	扼		72	搏	

73	陡		74	肭		75	栋		76	谏	
77	蚌		78	猹		79	矸		80	绁	
81	愧		82	硌		83	堤		84	鞍	
85	贱		86	逮		87	搒		88	帔	
89	诽		90	狈		91	俭		92	迥	
93	糎		94	胶		95	拸		96	犊	
97	哎		98	拌		99	缤		100	饵	
101	娩		102	珠		103	恰		104	秩	
105	圩		106	眢		107	灼		108	恦	
109	阴		110	殃		111	猜		112	饭	
113	惍		114	谊		115	桂		116	朽	
117	钾		118	诜		119	涔		120	烯	
121	押		122	忆		123	妽		124	佢	
125	偈		126	浯		127	殀		128	泫	
129	烟		130	怩		131	炜		132	娟	
133	倚		134	昧		135	纪		136	恰	
137	捊		138	谁		139	镟		140	绪	
141	讶		142	拈		143	怀		144	烟	
145	侨		146	揎		147	诎		148	陆	
149	饷		150	揘		151	汪		152	打	
153	饶		154	恻		155	眈		156	猁	
157	遘		158	摘		159	浢		160	泗	

161	怯		162	伊		163	暖		164	侄	
165	饥		166	娱		167	汁		168	圢	
169	译		170	钓		171	艳		172	恮	
173	扎		174	炆		175	烁		176	洽	
177	殊		178	陫		179	慡		180	伄	
181	辏		182	迲		183	胼		184	惕	
185	眩		186	贿		187	轶		188	脂	
189	湲		190	坛		191	悕		192	悦	
193	蚀		194	眄		195	缢		196	褚	
197	艳		198	悟		199	畸		200	眠	

Mandarin Homophone Matching Test

Please tick (✓) the character that sounds identical to the target.

E.g.:	叶		业	✓	也		爷		野
	Target		Choose ONE of these four characters.						
1	毁		挥		悔		会		回
2	妻		奇		起		期		气
3	游		友		诱		邮		忧
4	持		翅		吃		齿		池
5	系		希		喜		习		戏
6	箱		详		象		香		想
7	舵		躲		夺		多		惰
8	属		树		鼠		书		赎
9	倾		请		轻		情		庆
10	碍		爱		挨		矮		哀
11	夜		爷		椰		叶		野
12	吉		机		急		计		挤
13	还		缓		患		欢		环
14	指		职		制		纸		知
15	颗		客		咳		科		渴
16	楚		出		畜		厨		储
17	姓		醒		行		幸		星
18	比		逼		闭		笔		鼻
19	身		绳		声		省		盛

20	同		痛		统		童		通
21	住		竹		煮		助		猪
22	接		解		街		界		杰
23	仇		抽		愁		丑		臭
24	府		妇		夫		福		斧
25	答		大		打		搭		达
26	全		权		劝		圈		犬
27	丰		封		逢		讽		奉
28	艺		椅		遗		意		医
29	费		肥		匪		飞		废
30	毯		叹		贪		坦		谈
31	怦		捧		碰		烹		朋
32	矩		居		局		具		举
33	犯		烦		翻		饭		返
34	呼		忽		虎		护		湖
35	刘		六		流		溜		柳
36	千		浅		钱		牵		歉
37	瞧		敲		俏		巧		桥
38	引		饮		音		银		印
39	演		厌		眼		颜		烟
40	设		蛇		舍		社		奢
41	啼		提		替		体		梯

42	劳		酪		牢		老		捞
43	婴		英		影		迎		硬
44	川		喘		串		船		穿
45	帝		地		滴		敌		底
46	要		咬		妖		药		摇
47	尾		威		卫		维		伟
48	凸		图		突		土		兔
49	泪		勒		雷		类		磊
50	笆		把		拔		巴		霸
51	斋		债		宅		摘		窄
52	裁		财		菜		彩		猜
53	戒		节		借		接		姐
54	悬		眩		选		玄		宣
55	语		迂		玉		鱼		雨
56	倘		躺		汤		堂		趟
57	频		品		聘		拼		贫
58	妒		督		赌		度		毒
59	郭		国		锅		过		果
60	血		谢		鞋		写		歇
61	压		鸦		讶		雅		牙
62	恙		样		央		养		阳
63	原		远		冤		院		圆

64	显		闲		仙		险		线
65	时		石		始		事		师
66	假		家		夹		甲		驾
67	售		瘦		收		熟		手
68	陶		逃		讨		滔		套
69	瘟		问		稳		温		文
70	献		贤		显		羡		鲜
71	舞		屋		武		无		物
72	辞		此		词		次		疵

Chinese Character Transcription Test

Please write the hanyu pinyin transcription, including tone marking with numerals, for each of these Chinese characters. Please answer ALL items. E.g. 起 qi (3)

1	胜		2	记		3	姑	
4	缔		5	订		6	坟	
7	板		8	蚊		9	论	
10	饼		11	粽		12	踌	
13	抽		14	浩		15	胎	
16	旺		17	扯		18	妃	
19	扰		20	袖		21	消	
22	魂		23	庞		24	村	
25	庇		26	持		27	枯	
28	拙		29	抹		30	汗	
31	碑		32	姓		33	拱	
34	饱		35	特		36	牲	
37	锈		38	供		39	脍	
40	柚		41	讨		42	打	
43	犹		44	猖		45	疼	
46	拢		47	批		48	酷	
49	优		50	精		51	肝	
52	唱		53	始		54	仙	
55	脾		56	宠		57	洪	

58	瑰		59	清		60	迨	
61	猜		62	沫		63	珑	
64	讪		65	社		66	绘	
67	跑		68	叮		69	拼	
70	抬		71	愧		72	晴	
73	肚		74	皈		75	涛	
76	厅		77	伦		78	嫖	
79	诱		80	终		81	咚	
82	埋		83	淙		84	理	
85	趾		86	灿		87	杞	
88	悄		89	油		90	奸	
91	饭		92	较		93	返	
94	胞		95	踪		96	咬	

Appendix C

Stimuli used in behavioural and fMRI experiments

English Lexical Decision Task

	Stimuli	WordType
Practice Trials	frock	w
	brute	w
	brawl	w
	flair	w
	halve	w
	krofe	nw
	trube	nw
	warlb	nw
	railf	nw
	vaelh	nw
Block 1	clove	w
	thyme	w
	spook	w
	tempt	w
	wrest	w
	knoll	w
	spout	w
	waltz	w
	volce	nw
	meyth	nw
	koosp	nw
	pemtt	nw
	strew	nw
	nollk	nw
	poust	nw
Block 2	graft	w
	grate	w
	stile	w
	bland	w
	psalm	w
	reign	w
	vague	w
	trafg	nw
	trage	nw
	leist	nw
	balnd	nw
	malsp	nw
	twalz	nw
	grine	nw
	gauve	nw

	Stimuli	WordType
Block 3	whiff	w
	smelt	w
	maize	w
	mince	w
	aisle	w
	stunt	w
	plumb	w
	troop	w
	fhiwf	nw
	stelm	nw
	zaime	nw
	cneim	nw
	siale	nw
	tunst	nw
	blump	nw
Block 4	broil	w
	clang	w
	croak	w
	quake	w
	beech	w
	crank	w
	lathe	w
	roilb	nw
	glanc	nw
	roack	nw
	kaque	nw
	proute	nw
	cheeb	nw
	narck	nw
	thale	nw

Note:
Stimuli Duration is 1975 milliseconds
w: word
nw: nonword

English Homophone Matching Task

	Stimuli	PairType	WordType
Practice Trials	earm-urme		h
	yook-yuke		h
	wase-wais		h
	neik-nake		h
	zame-zaim		h
	earm-aeme		nh
	seip-sipe		nh
	wast-wats		nh
	kein-kine		nh
	zume-zime		nh
Block 1	dual-jewel	R	h
	bury-berry	E	h
	zole-zoal	N	h
	weigh-way	R	h
	dough-doe	E	h
	heem-heam	N	h
	pray-prey	R	h
	quay-key	E	h
	duet-cruet	R	nh
	fury-ferry	E	nh
	noal-nool	N	nh
	neigh-nigh	R	nh
	roe-rough	E	nh
	peam-pame	N	nh
	flay-flee	R	nh
Block 2	quib-kwib	N	h
	beach-beech	R	h
	break-brake	E	h
	tain-tane	N	h
	pail-pale	R	h
	pear-pair	E	h
	byme-bime	N	h
	fray-fey	E	nh
	thib-shib	N	nh
	peach-poach	R	nh
	weak-wake	E	nh
	hain-hine	N	nh
	sail-soil	R	nh
	dear-dare	E	nh
	wime-waim	N	nh

	Stimuli	PairType	WordType
Block 3	sea-see	R	h
	sew-so	E	h
	phex-feks	N	h
	maid-made	R	h
	pour-pore	E	h
	voar-vore	N	h
	sore-saw	R	h
	some-sum	E	h
	pea-pie	R	nh
	new-no	E	nh
	grex-geks	N	nh
	raid-ride	R	nh
	pout-port	E	nh
	zoar-zure	N	nh
	bore-bow	R	nh
Block 4	fick-phic	N	h
	cell-sell	R	h
	earn-urn	E	h
	coim-koym	N	h
	might-mite	R	h
	route-root	E	h
	scad-skad	N	h
	home-hum	E	nh
	bick-blic	N	nh
	kill-sill	R	nh
	ear-oar	E	nh
	foym-fyme	N	nh
	sight-sigh	R	nh
	shoot-soot	E	nh
	shad-chad	N	nh

Note:
Stimuli Duration is 1975 milliseconds
R: Regular Word
E: Exception Word
N: NonWord
h: Homophonic pairs
nh: Non-homophonic pairs

English Synonym Judgement Task

	Stimuli	SynonymType	WordType
Practice Trials	desert - wilderness	H	s
	dispair - hopelessness	L	s
	grin - smile	H	s
	mockery - ridicule	L	s
	sack - bag	H	s
	trace - vestige	L	s
	desert - cable	H	ns
	despair - consent	L	ns
	smile - money	H	ns
	mockery - notion	L	ns
	sack - happiness	H	ns
	trace – hopelessness	L	ns
Block 1	story - tale	H	s
	menace - threat	L	s
	marriage - wedding	H	s
	advice - counsel	L	s
	shovel - spade	H	s
	impotence -weakness	L	s
	harvest - crop	H	s
	realm - kingdom	L	s
	joy - crop	H	ns
	pardon - plan	L	ns
	gift - sea	H	ns
	menace - discovery	L	ns
	grave - blossom	H	ns
	reality - notion	L	ns
	ocean – donation	H	ns
Block 2	throng - crowd	H	s
	chance - luck	L	s
	lantern - lamp	H	s
	blame - reproach	L	s
	ship - boat	H	s
	idea - notion	L	s
	joy - happiness	H	s
	safety - truth	L	ns
	battle - money	H	ns
	scheme - reproach	L	ns
	ship - tomb	H	ns
	realm - compassion	L	ns
	cash - fight	H	ns
	pity - falsehood	L	ns
	story – implement	H	ns

	Stimuli	SynonymType	WordType
Block 3	pardon - forgiveness	L	s
	ocean - sea	H	s
	detection - discovery	L	s
	flower - blossom	H	s
	reality - truth	L	s
	gift - donation	H	s
	safety - security	L	s
	battle - fight	H	s
	impotence - consent	L	ns
	shovel - tale	H	ns
	agreement - threat	L	ns
	marriage - lamp	H	ns
	advice - forgiveness	L	ns
	throng - spade	H	ns
	chance – weakness	L	ns
Block 4	scheme - plan	L	s
	grave - tomb	H	s
	pity - compassion	L	s
	cash - money	H	s
	lie - falsehood	L	s
	tool - implement	H	s
	agreement - consent	L	s
	harvest - happiness	H	ns
	detection - kingdom	L	ns
	tool - crowd	H	ns
	lie - luck	L	ns
	lantern - wedding	H	ns
	blame - counsel	L	ns
	flower - boat	H	ns
	idea – security	L	ns

Note:
Stimuli Duration is 1975 milliseconds
H: High Imageability
L: Low Imageability
s: synonym pairs
ns: non-synonym pairs

Mandarin Lexical Decision Task

	No.	Character	Pseudo-character
Practice Trials	P1	哎	伎
	P2	蚌	阵
	P3	猹	碴
	P4	悼	障
	P5	饵	烟
Block 1	1	猖	汛
	2	惰	谁
	3	诽	殁
	4	饥	惍
	5	枯	眄
	6	辽	偈
	7	恒	褚
	8	胼	睥
Block 2	9	洽	浯
	10	殊	掇
	11	坛	娟
	12	悟	铗
	13	押	扎
	14	摘	钓
	15	耻	胶
Block 3	16	纠	稆
	17	愧	猜
	18	眠	陫
	19	俭	圳
	20	烁	拈
	21	惕	打
	22	绪	佢
	23	艳	烟
Block 4	24	脂	恰
	25	侈	珠
	26	惧	饭
	27	唤	绪
	28	忆	轷
	29	灼	惆
	30	驳	赸

Note:
Stimuli Duration is 1975 milliseconds

Mandarin Homophone Matching Task

	No.	Same Tone	Tone Sampled	Different Tone	Tone Sampled
Practice Trials	1	楚 - 储	1	楚 - 厨	4
	2	游 - 邮	2	游 - 诱	3
	3	持 - 池	3	持 - 翅	2
	4	指 - 纸	4	指 - 制	1
	5	还 - 环	1	还 - 缓	4
Block 1	1	倾 - 轻	1	刘 - 溜	2
	2	舵 - 惰	2	瞧 - 俏	3
	3	颗 - 科	3	引 - 银	4
	4	毁 - 悔	4	设 - 奢	1
	5	住 - 助	1	啼 - 梯	3
	6	接 - 街	2	斋 - 债	4
Block 2	7	仇 - 愁	3	裁 - 彩	1
	8	献 - 羡	4	辞 - 疵	2
	9	毯 - 坦	1	悬 - 眩	4
	10	怦 - 烹	2	倘 - 趟	1
	11	矩 -举	3	频 - 拼	2
	12	犯 - 饭	4	妒 - 赌	3
Block 3	13	刘 - 流	1	倾 - 情	2
	14	瞧 - 桥	2	舵 - 躲	3
	15	引 - 饮	3	颗 - 渴	4
	16	设 - 社	4	毁 - 挥	1
	17	啼 - 提	1	住 - 猪	3
	18	斋 - 摘	2	接 - 解	4
Block 4	19	裁 - 财	3	仇 - 抽	1
	20	辞 - 词	4	献 - 贤	2
	21	悬 - 玄	1	毯 - 谈	4
	22	倘 - 躺	2	怦 - 捧	1
	23	频 - 贫	3	矩 -局	2
	24	妒 - 度	4	犯 - 返	3

Note:
Stimuli Duration is 2468.75 milliseconds

Mandarin Synonym Judgement Task

		High Imeageability		Low Imageability	
		S	**NS**	**S**	**NS**
Practice Trials	1	沉－重	沉－海	同意－赞成	同意－消沉
	2	掉－落	掉－扔	低沉－消沉	低沉－概念
	3	胖－肥	重－肥	概念－观念	赞成－观念
Block 1	1	现款－金钱	现款－价钱	所以－因此	所以－不然
	2	高兴－快乐	高兴－金钱	特别－尤其	特别－希奇
	3	工具－器具	创造－器具	体系－系统	尺度－系统
Block 2	4	价格－价钱	价格－相同	选择－挑选	一般－选择
	5	风景－景色	风景－乡村	赞美－称赞	赞美－赶快
	6	世界－天下	帮助－天下	分外－格外	称赞－格外
Block 3	7	标记－标志	标记－目标	连忙－赶快	连忙－挑选
	8	农村－乡村	农村－世界	奇怪－希奇	奇怪－仔细
	9	目标－目的	停留－目的	一般－普通	好象－普通
Block 4	10	帮忙－帮助	帮忙－快乐	否则－不然	否则－因此
	11	停顿－停留	停顿－礼拜	标准－尺度	标准－体系
	12	创造－发明	工具－发明	查问－盘问	发表－盘问

Note:
Stimuli Duration is 2468.75 milliseconds
S: Synonym pairs
NS: Non-synonym pairs

Appendix D

Table 15

Summary of activated brain regions with corresponding Brodmann Areas (BAs) for all tasks across both languages.

		LDT		HMT		SJT	
Brain Region	**BA**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Frontal Lobe							
Primary Motor Cortex	4	○	○	○	▲	○	○
Pre-motor Cortex	6	○	○	○	▲	○	○
Superior frontal gyrus	8		▲	○		○	
Middle Frontal Gyrus	9	▲	▲	○●		○●	
Anterior Superior frontal gyrus	10		▲	▲	○	○	○
Anterior Cingulate Cortex	24	○	○	▲	○	○	○
Anterior Cingulate Cortex	32	○	○	○	○	○	■
Inferior Frontal Gyrus	44	○	○●	○	○	○	○
Inferior Frontal Gyrus	45	○		○●	○	○	▲
Middle Frontal Gyrus	46		▲	○	○	○●	○
Inferior Frontal Gyrus	47			○	■	▲	
Parietal Lobe							
Postcentral Gyrus	2	■		▲	▲		
Postcentral Gyrus	3	○	○	○	▲	▲	○
Superior Parietal Gyrus	7	○	○	○	○	○●	○
Anterior Medial Parietal Cortex	23			▲	▲	○	
Posterior Cingulate Cortex	31	○	○	○	○	○	○●
Angular Gyrus	39	○	○	○	○	○●	○
Supramarginal Gyrus	40	■		▲		○	
Temporal Lobe							
Inferior Temporal Gyrus	20						■
Middle Temporal Gyrus	21			■		○	
Superior Temporal Gyrus	22					○	
Fusiform Gyrus	37	○	○	○	▲	○●	○●
Superior Temporal Gyrus	38			■			
Occipital Lobe							
Striate Cortex	17	○	○	○	○	○	○
Extrastriate Cortex	18	○	○●	○	○●	○●	○●
Extrastriate Cortex	19	○	○●	○	○●	○●	○●
Subcortical Areas							
Nucleus Caudatus		▲		▲	▲	■	○
Thalamus		▲			■		○
Putamen			○	▲	▲	○	○

Note: Brain regions activated by only the English tasks are shown with filled squares. Brain regions that are activated by only the Mandarin tasks are shown with filled triangles. Activation sites that are common to both languages are shown with empty circles. For the common activation sites, those brain regions that show significantly greater activation for Mandarin as compared to English tasks are shown with filled circles.

Appendix E

Ethics Declaration

In accordance to the requirements by the National University of Singapore, postgraduate student, Wendy Tham Wei Ping (student number: HD 98-2171W) has sought the permission from the The Ethics Committee of the Department of Social Work and Psychology, National University of Singapore and the Ethics Board of the Singapore General Hospital to conduct the behavioural and fMRI experiments in this study.

Signed:

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Associate Professor Susan Jane Rickard Liow
Department of Social Work and Psychology
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