Investigating the behavioral and neural correlates of auditory semantic processing in the Chinese language

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**INVESTIGATING THE BEHAVIORAL AND NEURAL CORRELATES OF AUDITORY
SEMANTIC PROCESSING IN THE CHINESE LANGUAGE**

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ABSTRACT

Everyday social communication emphasizes auditory semantic processing. To date, most existing models of auditory semantic processing are based on alphabetic languages like English. Given the substantial linguistic differences between character languages such as Chinese and alphabetic languages like English, it is unclear whether and how these models apply to the character-based Chinese language. The current thesis proposed a preliminary model for Chinese auditory semantic processing based on a meta-analysis of past findings, and then tested the model with present behavioral and neuroimaging studies.

In order to establish a model with regions consistently activated in Chinese auditory semantic processing, a meta-analysis was conducted to synthesize findings in 170 past studies in Study 1. Results suggest that the Chinese auditory semantic model may involve a network including the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex.

It is interesting that the occipito-temporal visual cortex, commonly associated with reading process, is suggested by the present meta-analysis to be involved in the Chinese auditory semantic model. Thus, it is worth investigating whether orthographic representation has an effect on Chinese auditory semantic processing in the absence of visual characters. To address this, a behavioral experiment was conducted in Study 2. Forty-eight Mandarin Chinese native speakers were recruited to perform a synonym judgment task in both visual and auditory sessions, where two of the four task conditions in each session were manipulated to only differ by the presence or absence of visual priming. After controlling for several possible confounds, the reaction time in the auditory session was longer for the condition without visual priming (e.g., ‘目的’ [mu4

di/ *goal*] & ‘木头’ [/mu4 tou/ *wood*]) than the condition with visual priming (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalogue*]), possibly resulting from the heavier visualization load for the condition without visual priming. In contrast, in the visual session where visual information was physically available all at once without ambiguity, the effect of visual priming disappeared. This finding is likely amongst the first behavioral evidence to suggest the involvement of Chinese visual form in auditory semantic processing where no character is visually presented.

The proposed model identified in the meta-analysis (Study 1) did not make differentiation between word-level and sentence-level processes which might have their respective unique regional networks. To further evaluate possible differences between these two levels of processes, two separate neuroimaging data sets were utilized. Study 3a employed an auditory semantic-tone task to evaluate word-level processing, while a forward-backward passive listening task was adopted in Study 3b to examine sentence-level processing. Results showed the activations in the word-level network (Study 3a) to be consistent with the regions proposed in our model, likely because the majority of the studies included in our meta-analysis examined word processing. Within the proposed network, the right posterior superior temporal gyrus, the left middle frontal gyrus, and the left ventral inferior frontal gyrus were functionally connected probably to aid auditory-to-lexicosemantic transformation. In contrast to word processing, the sentence-level processing showed involvement of all regions proposed in the model except the left occipito-temporal visual cortex (Study 3b). This was plausibly because homophones could be discriminated by contextual and syntactic scaffold when hearing Chinese sentences without much need to visualize to the written form.

Findings from the three studies have provided mutually corroborating evidence that stems from meta-analytic, behavioral, and neurobiological perspectives, and jointly propose a Chinese auditory semantic model for future research to reference from and improve upon. The model was found to apply both to the word-level and sentence-level Chinese auditory semantic processing, with exception of the left occipito-temporal cortex which was only found in the word-level but not sentence-level processing. This model generally fits into the classical models based on alphabetic writing systems, but with features specific to Chinese. While the left inferior parietal lobule underlying sublexical-level phonemic assembly may have little involvement in Chinese auditory semantic processing, the left middle frontal gyrus is more likely to be recruited for the sound-to-print mapping at the whole character level. With the current model, we could advance our understanding of how the linguistic, behavioral, and neurobiological representations interact during Chinese auditory semantic processing.

CHAPTER I: INTRODUCTION

Language is a unique ability evolved in humans. Spoken language and phonology are restricted to synchronous communication, limited by the temporal and spatial availability of each conversationalist. Hence, orthography and written language were developed and applied after-the-fact to enable conversationalists to communicate asynchronously from separate venues and times. Accordingly, semantic representations appeared first, followed by phonology, and finally orthography through evolution. This phylogenetic sequence seems to replay in ontogeny as well. Human infants are born to have some instinctive mentalese such as hunger and sleepiness, but are not able to talk about it until the phonology is mastered in two or three years, and are unable to write it down until orthography is acquired in school age (Evans & Levinson, 2009). According to these ontogenetic and phylogenetic viewpoints, semantic representation seems to have closer linkage to the spoken than written form. While the meaning of a language usually has to be expressed in spoken or written form, getting through these forms to access the fundamental semantic representation is always the ultimate goal in everyday language transmission (Assaf et al., 2006; Cabeza & Kingstone, 2006; Shafto, 2014). To this end, the current thesis seeks to investigate semantic processing specifically.

Behavioral Models

To achieve an in-depth understanding of semantic processing, it is critical to investigate the interaction of phonological and orthographic information in accessing semantic information for languages in general. Generally, the connectionist model or interactive activation model assumes bi-directional, symmetric, and amodal interconnections between phonological and orthographic units at both lexical and sublexical levels of processing (Grainger & Ferrand, 1996; Plaut, McClelland, Seidenberg, & Patterson, 1996; Slowiaczek, Soltano, Wieting, & Bishop, 2003; Ziegler & Ferrand, 1998; Ziegler, Muneaux, & Grainger, 2003). Based on this model, units

at one level (e.g., sublexical phonology) activate compatible units at another (e.g., sublexical orthography). Accordingly, phonological information can influence word reading, and orthographic information can affect spoken word recognition. The interaction of phonology and orthography will be unraveled below by examining the involvement of phonology in visual lexical processing as well as the involvement of orthography in auditory lexical processing.

Models Involving Phonology in Visual Lexical Processing

Among the studies investigating the interaction between linguistic information and presentation modality, most have examined the role of phonology in visual lexical processing. In general, two views have evolved: the strong, and weak phonological views (Harley, 2013).

The strong phonological view proposes the phonological mediation to occur during visual word recognition process, where orthographic processing leads to the activation of the phonological form, which in turn, activates the corresponding semantic representation (Frost, 1998; Van Orden, 1987; Van Orden, Pennington, & Stone, 1990). This seems to be congruent with the preceding ontogenetic and phylogenetic view, which holds that visual word recognition via phonology might be more spontaneous and more efficient than the direct lexical access from visual input, as phonology mediates the establishment of mapping visual forms and semantic representations during literacy acquisition (Evans & Levinson, 2009).

In contrast, the weak phonological view accumulates more support from existing models (Harley, 2013) including the classical dual-route model (Coltheart, 1978; Coltheart, 2004). Based on the dual-route model, visual word recognition is primarily driven by the lexical route, where word meaning could be directly accessed through the visual form in the absence of computing the phonology of the word (Rastle & Brysbaert, 2006; Wong & Chen, 1999). Only when the lexical route is less efficient, as what occurs in unskilled readers or when reading low frequency

words, the sublexical route of phonological mediation might come into play (Harley, 2013). In addition, the revised dual-route model (Morton & Patterson, 1980; Patterson & Morton, 1985) explicitly proposes a semantic lexical route (print - meaning - sound), where lexical semantics could be directly accessed from the visual form prior to and independent of phonological coding, lending further support for the weak phonological view.

Although the strong and the weak phonological views differ in whether phonological mediation is the primary or subsidiary process during visual lexical processing, both views have acknowledged the influence of phonology on visual word recognition through a body of empirical studies. For example, the lexical decision process was found to be slower for those visual words with a larger number of homophones (e.g., maid; Burton, Jongman, & Sereno, 1996; Pexman, Lupker, & Jared, 2001; Pexman, Lupker, & Reggin, 2002); the semantic categorization of a written word (e.g., 'zoo'/zu/) was inhibited if the word was primed by a phonologically-related but orthographically-unrelated word (e.g., 'clue'/klu/) than by a phonologically- and orthographically-unrelated word (e.g., 'soap'/sop/; Van Orden, 1987).

Models Involving Orthography in Auditory Lexical Processing

Unlike the consistently-reported involvement of phonology in visual word recognition, it is relatively unclear as to whether orthography has an effect on auditory lexical processing, where no orthographic information is overtly provided.

The interactive activation/connectionist model assumes the possibility of a word's orthography to be automatically activated upon the activation of its phonology. This is supported by the observations of the facilitation effect of dense orthographic neighborhood on auditory lexical decisions (Ziegler et al., 2003), the speed boost of the lexical decision for orthographically-consistent than -inconsistent spoken words (Ventura, Morais, Pattamadilok, &

Kolinsky, 2004; Ziegler & Ferrand, 1998), as well as the orthographic priming effect on the lexical decision of a spoken target (e.g., dream-gleam vs. scheme-gleam; Chereau, Gaskell, & Dumay, 2007; Pattamadilok, Kolinsky, Luksaneeyanawin, & Morais, 2008; Slowiaczek et al., 2003; Taft, Castles, Davis, Lazendic, & Nguyen-Hoan, 2008; Ventura et al., 2004; Ziegler, Petrova, & Ferrand, 2008).

On the other hand, the phylogenetic or ontogenetic view considers orthographic processing to be redundant and unnecessary in auditory lexical processing, as coactivating orthography in auditory listening might not be as economical as coactivating phonology in visual reading from the ontogenetic and phylogenetic perspective (Evans & Levinson, 2009). Through the evolution of language and the language development of individuals, phonology is acquired prior to and independent of orthography, and therefore lexical semantics may be more easily retrieved from the spoken form than written form, as is clearly the case in pre-school kids who have yet to learn how to read, and the illiterate (Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998; Muneaux & Ziegler, 2004). There are also empirical findings showing that the lexical decision speed of auditory targets was not significantly different between the orthographic-priming condition (e.g., head-bead) and no-priming condition (e.g., cash-bead; Burton et al., 1996).

Neurobiological Models

Recently, the development of functional neuroimaging technologies such as functional magnetic resonance imaging (fMRI) has allowed for more in-depth investigation of the fundamental brain basis of semantic processing, paving the way for the establishment of neurobiological models concerning semantic processing. One of the most prevailing models is dorsal- and ventral-stream model. This dual-stream model has been widely accepted in the visual

domain since the 1980s (Ingle, Goodale, & Mansfield, 1982), but has not gained empirical support for the auditory system until the 2000s (Rauschecker, 1998; Scott, 2005). This model proposes a distinction between the dorsal and the ventral streams respectively for a sensorimotoric ‘how’ pathway and a conceptual ‘what’ pathway in both the visual and the auditory domains (Hickok & Poeppel, 2000, 2004). While the dorsal stream involves the left frontal and parietal areas to support the interaction of motor articulation and auditory/visual sensory input, the vicinity of the temporal-parietal-occipital junction in the ventral stream functions to interface sounds or scripts with conceptual representations. In addition, the model conceptualizes the ventral stream as less left-lateralized and more bilaterally organized relative to the strongly left-dominant dorsal stream (Hickok & Poeppel, 2000, 2004).

Other evidence suggests that there is more than one dorsal stream and more than one ventral stream that are functionally separated (Friederici, 2011, 2012). Dorsally, one pathway underlying sensory-to-motor mapping connects the temporal cortex to the premotor cortex via the inferior parietal lobule; another pathway connects the temporal cortex to posterior Broca’s area (BA44, pars opercularis) to lend support to the processing of syntactically complex sentences. Ventrally, one pathway connects the anterior ventral Broca’s area (BA45/47) to the middle temporal gyrus to subserve semantic processing, while another pathway tapping basic syntactic processing connects the frontal operculum to the anterior superior temporal gyrus/sulcus (Friederici, Bahlmann, Heim, Schubotz, & Anwender, 2006). In contrast to the classical dorsal- and ventral-stream model with one pathway in each stream (Hickok & Poeppel, 2000, 2004), Friederici’s model specifies more precise structural and functional separation in language processing. Meanwhile, the identification of the two syntactic-related pathways enables this model to be compatible with sentence processing.

Recently, Price (2012) proposes a general anatomical model in the language domain, where speech comprehension as a subfield is also demonstrated. Based on the integration of the findings from hundreds of fMRI and positron emission tomography (PET) studies that have been published in the last two decades, this model depicts a map of auditory semantic areas and the most consistent functions that have been assigned to each of them. It is proposed that auditory semantic processing usually activates the left-lateralized areas. Anterior superior temporal gyrus is related to semantic associations, with activation for sentences spreading anteriorly into the temporal pole. Posterior middle/inferior temporal activations are regulated by task demands. Ventral inferior frontal areas (pars orbitalis & pars triangularis) and probably the dorsal superior frontal gyrus may subserve the selection of task-related semantic attributes. The lateral parietal areas such as the angular gyri are involved in the cross-modal integration of semantic features, while more medial parietal areas like precuneus and posterior cingulate are more sensitive to sentential rather than single word comprehension. However, it is also clarified in the model that the functional role and anatomical localization of each region described above are still insufficiently precise and far from the thorough unraveling of the neural basis underlying speech comprehension.

It is of note that both Hickok & Poeppel's dual-stream model (Hickok & Poeppel, 2000, 2004, 2007) and Price's anatomical model (2012) have mentioned the left-hemispheric dominance in speech recognition. Recently, McGettigan and Scott (2012) attempts to explain the left lateralization in their cortical asymmetry model. Historically the left lateralization of the temporal lobe was construed to arise from a preference of the left-hemispheric temporal lobe for non-linguistic acoustic features such as rapid/temporal sound which happen to be critical for speech (Poeppel, 2003; Zatorre & Belin, 2001). However, recent PET and fMRI studies have

reported that even after equating the amplitude and the spectral information between intelligible and unintelligible stimuli, left-lateralized temporal activation was not observed with unintelligible stimuli as compared to that seen in processing intelligible stimuli (McGettigan et al., 2012; Rosen, Wise, Chadha, Conway, & Scott, 2011). Thus, McGettigan and Scott (2012) has proposed that the left temporal lobe is more sensitive to linguistic-specific cues, while physical acoustic features of non-linguistic signals are usually modulated by the temporal lobe of the right hemisphere.

Models for the Chinese Language

Most of the preceding semantic models at the behavioral and neurobiological levels are based on alphabetically written languages such as English, where character languages like Chinese are largely underrepresented (Please note that “character languages” in the current thesis refers to the languages using ideographic writing systems where a single character can represent meaning). Although English is widely spoken as a second language, it is only the third when it comes to the number of native speakers in the world; in contrast, Chinese is the most widely-used native language with more than a billion native speakers (Lewis, Simons, & Fennig, 2009). It is thus unclear whether and how the models above could be applied to Chinese, and additionally, there seems to be no semantic model that has been systematically and particularly established for Chinese. Clearly, development of such a model specifically for the Chinese language would be invaluable to the understanding of Chinese semantic processing. Moreover, it would be of significance to see whether a different writing system could be incorporated into the architecture of the preceding models.

An Introduction to the Chinese Language

Before the introduction to the linguistic features of Chinese in contrast to English, some basic knowledge of the Chinese language will first be introduced below. Spoken by a large population for thousands of years, Chinese inevitably has a wide variety of dialects. Among these varieties, Mandarin Chinese is the standard and official language that is widely spoken by 1.3 billion Mainland Chinese and 23 million Taiwanese. While the spoken language is almost identical between the Mainland China and Taiwan, the written language is slightly divergent with simplified (e.g., ‘叶’) versus traditional Chinese (e.g., ‘葉’) being used in Mainland China and Taiwan, respectively. However, only around 2,700 out of over 50,000 characters differ between simplified and traditional varieties, and the remainder is all identical in both varieties, e.g., ‘古.’ As for those 2,700 characters, on average the stroke numbers of simplified characters are 22.5% fewer than their traditional counterparts; other than the writing, the pronunciation and meaning remain the same between the two varieties (Chen & Yuen, 1991; Gao, Fan, & Fei, 1993; McBride-Chang, Chow, Zhong, Burgess, & Hayward, 2005). The scope of the current thesis will focus on only Mandarin Chinese that uses both simplified and traditional Chinese characters. The characters exemplified in the following sections are mostly written in simplified Chinese, except those specified as traditional Chinese characters.

To understand the linguistic attributes of Chinese in contrast to English in depth, it may be helpful to start from the origination of their respective writing systems. The alphabetic writing system is derived from the symbolization of its phonology, whereas the character writing system originates from drawings of each character’s meaning (Harley, 2013; Whitney, 1998). Most existing writing systems today are alphabetic, including that of English, where Grapheme-Phoneme- Correspondence is applied on a sub-lexical basis. For instance, letters (units) of the

English word ‘peach’ map to minimal sound units (e.g., ‘p’ to /p/, ‘ea’ to /i:/, ‘ch’ to /tʃ/), by which the sound of the whole word /pi:tʃ/ is assembled. In contrast, Chinese utilizes a character writing system, where the semantic radical in a Chinese character until today still partly hints at the meaning of the whole character (Perfetti & Liu, 2005; Yin & Rohsenow, 1994). For example, the semantic radical of ‘桃’ (/tao2/ *peach*) is ‘木’ (/mu4/ *wood*), which is semantically associated with the whole character ‘桃’ (/tao2/ *peach*).

Although a Chinese character usually contains a phonetic radical as well, only 26% of Chinese characters have an identical pronunciation to the phonetic radical (Gao et al., 1993; Tan & Perfetti, 1998; Xing & Li, 2004). In the same example, when ‘兆’ (/zhao4/ *omen*) occurs as the phonetic radical of ‘桃’ (/tao2/ *peach*), ‘兆’ (/zhao4/ *omen*) is not read the same as ‘桃’ (/tao2/ *peach*) but instead only rhymes with it. With no reliable phonetic rule to follow, no subpart of a Chinese character directly corresponds to the consonant or vowel of its syllable (e.g., neither ‘木’ nor ‘兆’ maps to /t/ or /ao/ in ‘桃’ /tao2/) but a character usually arbitrarily maps to its syllable as a whole (e.g., ‘桃’ directly maps to /tao2/).

Consequently, the print-to-sound conversion in Chinese is mostly at the lexical instead of sub-lexical level, where Chinese learners have to memorize the sounds of most characters by rote. Therefore, Chinese readers might not sound out an unfamiliar character correctly but are quite likely to get some sense of its meaning purely from the character itself, while in English, sound can be retrieved from a novel letter combination that does not have learnt semantic associations (e.g. ‘thacy’) (Price, 2012; Zhang, Xiao, & Weng, 2012).

Past studies (Feldman & Siok, 1999; Hoosain, 1991) have reported that semantic radicals attract earlier and longer attention from Chinese readers as compared to phonetic radicals, and

thus may play a greater role in Chinese character identification. All these indicate that the writing system of Chinese seems to entail richer semantic than phonological information, in striking contrast to English writing system which more directly maps to the phonologic than semantic representation (Perfetti & Liu, 2005; Siok, Perfetti, Jin, & Tan, 2004). In other words, the print-to-meaning interrelation is probably stronger for Chinese than English, whereas the print-to-sound correspondence seems to be more regular and less arbitrary for English than for Chinese (Feng, Miller, Shu, & Zhang, 2001).

The occurrence of homophones is ubiquitous in Chinese due to the mono-syllable nature of Chinese characters. Chinese contains 5,265 frequently-used characters, but there are only about 400 different syllables independent of tone¹, or 1,277 syllables if a change in tone is considered to create a different syllable. Thus, each syllable is on average shared by more than four different characters (Chao, 1976; Yin & Rohsenow, 1994); approximately 55% of the syllables correspond to more than five homophones each, and the syllable of a target character rarely maps onto its meaning uniquely (Feng et al., 2001; Treiman, Baron, & Luk, 1981). For example, only hearing the syllable of a targeted character ‘叶’ (/ye4/) does not allow us to precisely retrieve its meaning, *leaf*, since many other heterographic homophones such as ‘页’ (/ye4/ *page*), ‘业’ (/ye4/ *career*), and ‘夜’ (/ye4/ *night*) may also be incidentally initiated and then interfere with the extract of this intended meaning.

In contrast to phonology, the written form of Chinese appears to be more differentiable. Apart from the fact that the number of characters is more than four times of Chinese syllables

¹ high tone1 ‘音’ (/yin1/ *sound*), rising tone2 ‘银’ (/yin2/ *silver*), falling-rising tone3 ‘饮’ (/yin3/ *drink*), and falling tone4 ‘印’ (/yin4/ *print*). The tone of each syllable is indicated by the number follows. In the current thesis, heterographic characters are considered as ‘homophonic’ only if they are phonetically identical in both the segmental elements (consonant & vowel) and the tones.

(Chao, 1976; Yin & Rohsenow, 1994), it is also attributable to the unique features of Chinese characters as detailed below. While the minimal written units in English are the 26 letters, Chinese radicals as graphemes are not only more than 26 in number but also are visually denser than English letters (Ehrich, Zhang, Mu, & Ehrich, 2013; Perfetti, Liu, & Tan, 2005). In addition, the layout of the radicals in a Chinese character could be left-right such as ‘叶’ (/ye4/ *leaf*), top-down such as ‘古’ (/gu3/ *ancient*), or outside-inside such as ‘田’ (/tian2/ *cropland*), which is more diversified than the uniform left-right letter array in an English word. It is probably the lower repetition rate, larger visual density, and more varied structure that conjointly contribute to the greater differentiability between Chinese characters. Therefore, the meanings of Chinese words are credibly less ambiguous in the visual than auditory form, in contrast to the word meanings in English which may be equally unambiguous via sound and print.

Clearly, the linguistic characteristics of Chinese are different from those of English. These linguistic discrepancies implicate that the behavioral and neurobiological models which are mainly grounded on alphabetically written languages might not be generalizable to character-written languages. Considering that there exist only a limited number of character languages and that Chinese may be taken as a possible representative of them (Perfetti & Dunlap, 2008), establishing a model for Chinese may initiate further model construction for character languages.

The Applicability of Existing Language Models to the Chinese Language

As stated at the beginning of this chapter, the main research interest of the current thesis is semantic processing, in particular, auditory semantic processing in the Chinese language. Therefore, a semantic neural network for alphabetically written languages will first be identified based on the integration of the preceding neurobiological models. The applicability of this neural

semantic network to the Chinese language or an adapted model specifically for Chinese semantic processing will then be examined.

In both versions of the dorsal- and ventral-stream model (Friederici, 2011, 2012; Hickok & Poeppel, 2000, 2004, 2007), a specific ventral stream interfacing sounds/prints with semantic representations has consistently been proposed, which involves the left ventral Broca's area (BA45/47), the left anterior superior temporal gyrus, the left middle temporal gyrus, and the left occipito-temporal cortex. Moreover, a brain map underlying speech comprehension has also been depicted in Price's anatomical model (2012), where the left lateral parietal areas are involved in the cross-modal integration of semantic features; the left ventral inferior frontal areas may subserve the selection of task-related semantic attributes; the left anterior and posterior portions of the superior temporal lobe are specialized for semantic composition and phonological perception, respectively.

In contrast to these models, the cortical asymmetry model (McGettigan and Scott, 2012) specifically focuses on speech perception rather than speech comprehension. This model implies that the functional segregation of the left and right temporal lobes should be taken into account when initiating a preliminary semantic model in the auditory modality. By taking together the semantic-related regions identified in these models, a possible semantic neural network for alphabetically written languages is thought to include the left inferior parietal lobule, the left (and possibly the bilateral) anterior and posterior superior temporal lobes, the left ventral Broca's area (BA45/47), the left middle temporal gyrus, and the left occipito-temporal cortex.

The compatibility of this semantic neural network with the Chinese language needs further investigation. For neuroimaging studies, we are able to provide a quantitative summary of past findings using a meta-analytic approach. Thus, the current thesis conducted a meta-analytic

comparison between neuroimaging studies of Chinese and English semantic studies. The quantitative comparison of neuroimaging findings allows us to better evaluate whether English and Chinese semantic processing engages the same or different areas, and which areas are more activated for each language. Using the findings from this meta-analysis, we are able to develop a preliminary model for Chinese auditory semantic processing. We further applied two secondary empirical datasets to obtain potential support for this tentative model.

As the written form of Chinese is unique from alphabetic languages, we wanted to further understand if visual representations were involved in the auditory semantic model proposed for Chinese. Thus, a behavioral investigation was conducted to examine whether the written Chinese form played a part in the conversion from speech to meaning. From the phylogenetic and ontogenetic perspective, there is no obvious benefit in activating orthography in auditory semantic processing, as the visual-to-semantic activation appears to be less economical and less efficient compared to the direct semantic access from spoken language. However, it is unclear whether this applies to Chinese, given the greater automaticity of the print-to-meaning mapping in Chinese as reasoned before.

As noted earlier, past findings involving alphabetically written languages (Burton et al., 1996; Ventura et al., 2004; Ziegler et al., 2003) are still inconclusive on whether orthography is involved in auditory semantic processing. Even less evidence is available for character written languages like Chinese, where only three studies have been found (Zhou & Marslen-Wilson, 1995; Zou, Desroches, Liu, Xia, & Shu, 2012; Zou, Packard, Xia, Liu, & Shu, 2015). In general, all these three studies have used an auditory-auditory priming paradigm to investigate whether difference in the response speed exists between visually-similar word pairs (e.g., ‘面包’ [/*mian4* *bao1*/*bread*] & ‘面孔’ [/*mian4* *kong3*/*face*]) and visually-dissimilar word pairs (e.g.,

‘灯光’ [/deng1 guang1/*illumination*] & ‘登山’ [/deng1 shan1/*mountain climbing*]). A lexical decision task has been employed in Zhou & Marslen-Wilson’s study (1995) and Zou et al.’s study (2012), and a morphological relatedness task has been used in Zhou et al.’s study (2015).

Interestingly, while Zou et al. (2012) captured a significant orthographic effect, only a non-significant trend was observed in the other two studies (Zhou & Marslen-Wilson, 1995; Zou et al., 2015). It could be speculated that the non-specificity of the processes involved in the lexical decision task might be responsible for the inconsistent results in Zhou and Marslen-Wilson’s study (1995) and Zou et al.’s study in 2012. Although the task is generally considered as semantic-related, semantic-based processing is not required. Thus, there is no guarantee of the extent to which semantic-level processing is involved, as the task is also likely to be completed by fluent native speakers at the level of sound perception without further involvement of semantic-level processing. As for Zou et al.’s two studies in 2012 and 2015, there seems to be no adequate treatment of possible confounds such as word frequency and word class (e.g., noun or verb). Therefore, it is difficult to estimate the extent to which semantic processing was involved and whether the absence or presence of the effect of orthography was biased by other covariates in these three studies. To address the issues highlighted above, a task that engaged semantic processing more clearly while ruling out possible confounds such as word frequency and word class was developed in the current thesis.

The Research Framework

Through the investigation of the behavioral and neural correlates of Chinese auditory semantic processing, the current thesis aims to propose a preliminary model for Chinese auditory

semantic processing. This research goal is addressed by three studies, with the research framework illustrated in Figure 1-1.

Study 1 proposed the model using a meta-analysis which was conducted to collate the convergence and divergence between Chinese and English semantic neuro-networks across existing studies. With this quantitative 'literature review,' findings from Study 1 provided us some basic understanding of Chinese auditory semantic network within a broad framework of language processing. Based on the allocation of Chinese processing in this framework, a preliminary model specifically for Chinese auditory semantic processing was then proposed. The regions involved in this model enabled the examination of functional connectivity between these regions.

As the activities of the visual cortex have been consistently reported in past studies of Chinese auditory semantic processing, this area was included in the model proposed in Study 1. To further understand the involvement of visual cortex in Chinese auditory semantic processing, Study 2 was conducted to assess whether orthographic representation was involved in Chinese auditory semantic processing when visual form was not presented. An auditory synonym judgment task was designed, with particular manipulation of the visual similarity between conditions. In addition, the task was administered in a visual session as well as an auditory session, considering the parallel results from the visual session might serve as a benchmark for the results in the auditory session. This research question was addressed by examining the behavioral responses in a synonym judgment task in study 2.

Using empirical neuroimaging data, Study 3 examined and refined the model proposed in Study 1. Here, two fMRI data sets of Chinese listening comprehension were adopted to focus on word-level (Study 3a) and sentence-level (Study 3b) processing, respectively. While Study 3a

administered an auditory semantic-tone task using words as stimuli and requiring responses from participants, participants in Study 3b were asked to passively listen to a series of sentences without requirement of responses. The examination of Chinese auditory semantic processing using different task paradigms in Study 3a and Study 3b is expected to serve as a cross-validation of the reliability and validity of the model proposed in Study 1.

Overall, the three studies attempt to approach our research objective from different angles using distinct methodologies, and thus their integrative findings could corroborate with each other and provide insights into the behavioral and neural correlates of Chinese auditory semantic processing.

Figure 1-1. Research framework

CHAPTER II: STUDY 1

Proposal for a Preliminary Chinese Auditory Semantic Model: A Meta-Analysis

(Study 1 has been partly presented as a poster in *the 24th Annual Meeting of International Society for Magnetic Resonance in Medicine*, Singapore, 07-13th May, 2016)

Introduction

Semantic access is central to language functioning (Shafto, 2012; Xu, Kemeny, Park, Frattali, & Braun, 2005). It is intriguing how the semantic representation of a language is processed by the brain and then becomes meaningful. As stated in the general introduction above, the dominant neurobiological language models have been mainly based on alphabetic languages like English. Given the linguistic differences between the alphabetic and the character writing systems, it is worth investigating whether and how these dominant neurobiological language models are applicable to a character language like Chinese. Before postulating a preliminary model for Chinese based on the existing models, it is crucial to understand how neural substrates for semantic processing differ between Chinese and English. Although studies have probed the neural correlates of semantic processing for Chinese and English independently, limited studies have made direct comparisons between them (e.g., Cao, Brennan, & Booth, 2015; Klein, Zatorre, Milner, & Zhao, 2001; Tan, Laird, Li, & Fox, 2005). Less is known about how these findings converge or diverge from each other in order to inform the initial construction of a Chinese model. In the current study, we attempted to address this using a meta-analytic approach, to identify the between-language differences in semantic activations based on the consistently-reported findings in past studies.

Among the studies that have assessed the difference in neural activity between Chinese and English, some have compared Chinese with English native speakers (e.g., Brennan, Cao, Pedroarena-Leal, McNorgan, & Booth, 2013; Cao et al., 2015; Chee, Tan, & Thiel, 1999; Hu et al., 2010); some have conducted within-subject comparisons for Chinese-English bilinguals or English-Chinese bilinguals (e.g., Liu & Perfetti, 2003; Nelson, Liu, Fiez, & Perfetti, 2005; Perfetti & Wang, 2006); there are also some studies that have discussed their findings observed

in the Chinese language compared with others' findings observed in the English language (e.g., Cao et al., 2010; Chou, Chen, Wu, & Booth, 2009; Siok et al., 2004; Tan et al., 2001; Tan et al., 2000). In addition, a variety of tasks have been adopted in these studies to evaluate diverse aspects of language processing. Some studies have employed rhyming tasks (Brennan, Cao, Pedroarena - Leal, McNorgan, & Booth, 2013; Cao et al., 2015; Cao et al., 2010) or homophone judgment (Siok et al., 2004; Tan et al., 2001) to assess phonological processing; some have used phonetic-radical similarity judgment (Cao et al., 2010) to examine orthographic processing, while some have used semantic relatedness judgment (Chou et al., 2009; Hu et al., 2010; Tan et al., 2001) to evaluate semantic processing. It is clear that amongst these studies, between-language comparisons have targeted different components of language processing using different approaches.

Although the studies reviewed had different experiment designs and samples, some findings seemed concordant. In particular, reading Chinese relative to English showed weaker activation in the left inferior parietal lobule, and greater activation in the left middle frontal gyrus and the right occipito-temporal cortex (Cao et al., 2015; Ge et al., 2015; Hu et al., 2010; Perfetti & Tan, 2013; Schlaggar & McCandliss, 2007; Tan et al., 2005; Zhu, Nie, Chang, Gao, & Niu, 2014). It has been interpreted that the left inferior parietal lobule is usually related to phonology assembly under the Grapheme-Phoneme-Conversion process, whereas assigning a syllable to an ideographic character is believed to be mediated by the left middle frontal gyrus (Bolger, Perfetti, & Schneider, 2005; Christine Brennan et al., 2013; Hu et al., 2010; Kuo et al., 2003; Siok, Niu, Jin, Perfetti, & Tan, 2008; Tan et al., 2005; Zhu et al., 2014); thus, the decreased recruitment of the left inferior parietal lobule and increased recruitment of the left middle frontal gyrus during Chinese relative to English recognition could be attributed to the higher ambiguity

of grapheme-to-phoneme mapping for Chinese than English. In addition, the right occipito-temporal cortex is thought to subserve the analysis of the complex visuospatial configurations of Chinese characters (e.g., left-right ‘叶’ [/ye4/ *leaf*]; top-down ‘古’ [/gu3/ *ancient*]; outside-inside ‘田’ [/tian2/ *cropland*]), and therefore is also noted to be specifically involved in Chinese processing (Cao et al., 2010; Siok et al., 2004; Wu, Ho, & Chen, 2012).

In the current literature, findings regarding Chinese versus English neural differences appear generally consistent as reviewed above. However, these findings are based on a qualitative summary of cross-study comparisons or a few within-study comparisons between Chinese and English. A quantitative approach, such as a meta-analysis, is needed to statistically synthesize how likely Chinese versus English semantic activations across studies are consistently located at specific coordinates. This approach allows Chinese and English to be quantitatively compared across studies, in contrast to the traditional between-language comparison within an empirical study. In addition, by integrating findings from multiple studies, results of meta-analysis might be statistically more powerful and conclusive than those of the single studies. Even though meta-analyses that identify the similarities and differences between Chinese and English neural systems are available, few have paid specific attention to semantic processing.

To probe the effect of language on phonological neural bases, Tan and colleagues (2005) utilized the activation likelihood estimation (ALE) method to quantitatively synthesize data from six studies with Chinese and 13 studies with alphabetic languages. Significant greater activation likelihood estimates were observed for Chinese relative to alphabetically written languages in the bilateral inferior occipital gyri, the right fusiform gyrus, and the left middle frontal gyrus, while alphabetically written languages compared to Chinese showed higher activation likelihood estimates in the left fusiform gyrus, the bilateral temporal gyri, the left supramarginal gyrus, and

the left inferior parietal lobule. In particular, the left middle frontal gyrus was thought to support addressed phonology in Chinese, whereas the left temporo-parietal cortex was interpreted to underpin the assembly of phonology in alphabetic languages (Bolger et al., 2005; Christine Brennan et al., 2013; Hu et al., 2010; Kuo et al., 2003; Siok et al., 2008; Tan et al., 2005; Zhu et al., 2014). Although Tan and colleagues (2005) evaluated phonological but not semantic processing using relatively small databases, this meta-analysis serves as an initial and pioneering attempt to use meta-analytic approach to investigate the influence of language on neural systems.

More recently, Zhu et al. (2014) produced two ALE maps in phonological processing in their meta-analysis, one for 11 character-language experiments (i.e., Chinese, Japanese kanji) and the other for eight alphabetic-language experiments (i.e., English, French). Consistent with Tan et al.'s results (2005), Zhu and his team found that logographic languages significantly activated the left middle-superior frontal lobe, the right middle occipital gyrus, and the left fusiform gyrus, whereas the alphabetic languages had significant activations in the left inferior frontal gyrus and left angular gyrus. Although these meta-analytic results plausibly replicate Tan et al.'s (2005), they are not based on direct comparisons between the two writing systems. In addition, the relatively small databases in this meta-analysis may also limit the explanatory power of the results.

To examine the neuroimaging results for word reading within and across writing systems, Bolger and colleagues (2005) used aggregated Gaussian-estimated sources (Chein, Fissell, Jacobs, & Fiez, 2002) to compile 25 studies for alphabetically written languages and nine studies for Chinese. The results suggest a commonality of the gross cortical regions involved as well as variations in the specific localization of each region across writing systems. As a generalized region for orthographic processing, the left occipito-temporal cortex (e.g., mid-fusiform

gyrus/visual word form area, anterior occipital area) showed strongly convergent activation across the writing systems. In contrast, the right occipito-temporal cortex was specialized for the visuospatial analysis for character writing system specifically. Compared to Tan et al.'s meta-analysis (2005) and Zhu et al.'s (2014), this meta-analysis extends the research scope beyond phonological processing to the more general-level word reading, thus likely enabling more studies to be included. However, the preceding similarity and difference across writing systems are essentially drawn from descriptive comparison rather than statistical comparison.

Apart from these three meta-analytic studies that have compared the neural activity between orthographic systems, the following section will present a review of two other meta-analyses that had emphasis on semantic neural network, which is the interest of the current thesis.

Binder and colleagues (2009) used ALE to identify reliably activated areas in 120 neuroimaging studies of semantic processing. These activations formed a distinct, left-lateralized network comprising three broad categories: (1) the posterior multimodal and heteromodal association cortex, including the angular gyrus, the middle temporal gyrus, and the fusiform gyrus; (2) the specific subregions of heteromodal prefrontal cortex, including the dorsal medial prefrontal cortex, the left inferior frontal gyrus, and the left ventral medial prefrontal cortex; and (3) the medial paralimbic regions with strong connections to the hippocampal formation, including the para-hippocampus and the posterior cingulate cortex. The involvement of the heteromodal cortex in semantic processing was thought to be related to its expansion in the human relative to the nonhuman primate brain, which may explain the unique human capacities in language, particularly in the fluid manipulation of semantic knowledge. This meta-analysis is conceivably a landmark in the semantic domain. It identified a large-scale architecture for

semantic brain networks with incorporation of the studies that utilized spoken or written word stimuli irrespective of language. It serves as a firm foundation for further examination of the specific semantic network for the Chinese language.

Subsequent to Binder and colleague's (2009) work, another meta-analysis was conducted specifically for Chinese processing (Wu et al., 2012). The ALE method was used to analyze eight studies of orthographic processing, 11 of phonological processing, and 15 of semantic processing in the Chinese language. Results showed that the left middle frontal gyrus, the left superior parietal lobule, and the left mid-fusiform gyrus were reliably activated among all three components of language processing, suggesting a common sub-network underlying the Chinese character process. It was also observed in the meta-analysis that although the overall networks for Chinese character processing were congruent with the previously-identified alphabetic language networks, the left middle frontal gyrus and the right fusiform gyrus were found to be additionally recruited for Chinese character processing. This study is the first meta-analysis that directly compared the neural networks for different language components for the Chinese language. The orthographic, phonological, and semantic networks obtained in this meta-analysis provide insightful information for future Chinese studies examining these language aspects. Although this paper also discussed possible similarity and differences between the findings of Chinese and previous findings of alphabetic languages, it did not make direct comparisons with alphabetically written languages.

From the above reports consisting of meta-analyses, visual analyses (eye balling), and literature review of various sample sizes and language components targeted, we can come to a similar conclusion: the findings plausibly point to a Chinese processing network that is slightly differentiated from that of alphabetically written languages, where the left inferior parietal lobule

is less recruited, and the right occipito-temporal cortex and left middle frontal gyrus are more engaged. However, this was not directly compared. Therefore, a meta-analysis that makes direct between-language comparisons using larger data sets is needed to consolidate this proposal.

To address this research gap, the current Study 1 conducted Activation Likelihood Estimation (ALE) meta-analyses to quantitatively compare 29 Chinese and 96 English semantic studies in the visual domain, as well as to synthesize 40 English semantic studies in the auditory domain. As the number of Chinese auditory semantic studies was too small to conduct a meta-analysis (i.e., 5, versus the required minimum of 17 in meta-analysis; Eickhoff et al., 2016), these Chinese studies were qualitatively summarized before being further qualitatively compared with the meta-analytic results of the 40 English auditory semantic studies. It was expected that in comparison with that of English, the visual semantic processing of Chinese would involve less activation in the inferior parietal lobule given the decreased regularity of sound-to-print mapping, while involving increased activity in the right occipito-temporal cortex and the left middle frontal gyrus for the visuospatial analysis of Chinese characters and lexical-level semantic integration, respectively. Based on the meta-analytic findings, a tentative auditory semantic model specifically for the Chinese language would then be proposed.

Methods

Literature Selection

With ‘(semantic or meaning) and (brain imaging or fMRI or PET or neuroimaging) and (Chinese or English)’ as keywords, neuroimaging articles published from 2000 to February 2017 were searched in the following databases: PubMed, Scopus, ScienceDirect, Web of Science, and Ebscohost. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) pipeline (Figure 2-1), 170 studies (Appendix 2-1) fulfilling the following criteria

were selected: (1) fMRI or PET study reporting complete coordinates in Talairach or Montreal Neurological Institute (MNI) space through whole-brain scanning; (2) study with at least one contrast examining the semantic-related activation; (3) study using word or sentence stimuli presented in written or spoken form, excluding studies using picture stimuli; (4) study recruiting healthy young adults (18-35 years old) who were native speakers of Mandarin Chinese or English, including late but not early bilinguals (Wu et al., 2012), and excluding those whose daily languages were other dialects (e.g., Cantonese) than Mandarin Chinese.

Figure 2-1. PRISMA flow chart of the literature search.

As shown in Appendix 2-1, the 23 simplified Chinese studies and six traditional Chinese studies were all included without differentiation in the visual domain. This was to maximize the data set and increase the statistical power. In addition, these within-language differences appear

to be relatively minor compared to the more pronounced between-language differences (Please refer to Page 9 for more information about the simplified and traditional Chinese).

To ensure that the coded foci were mainly associated with semantic processes, semantic-related tasks were adopted by most selected studies, such as semantic relatedness/association judgment for character/word pairs (e.g., Bedny & Thompson-Schill, 2006; Xiang et al., 2003), lexical decision of real or false characters/words (e.g., Shafto, 2012; Zhang et al., 2012), semantic categorization (e.g., living or not, dangerous or not, pleasant or not) based on character/word meaning (e.g., Ding et al., 2003; Visser, Jefferies, & Ralph, 2010), semantic fluency of generating as many characters/words in one semantic category as possible within a fixed time window (e.g., Birn et al., 2010; Tan et al., 2000), semantic plausibility/acceptance/meaningfulness/congruence judgment for sentences (e.g., Hindy, Altmann, Kalenik, & Thompson-Schill, 2012; Luke, Liu, Wai, Wan, & Tan, 2002), and passive sentence reading/listening with post-comprehension test (e.g., Tremblay & Small, 2011; Yang & Shu, 2014).

Of these 170 selected studies, there were 29 Chinese studies and 96 English studies in the visual domain, as well as five Chinese studies and 40 English studies in the auditory domain (Table 2-1). It is of note that the Chinese auditory semantic group consisting of only five studies was undersized compared to the required minimal data set size of 17 studies in a meta-analysis (Eickhoff et al., 2016). However, these five Chinese studies were still included for qualitative comparisons with the meta-analytic results of the 40 English auditory semantic studies. The limited number of Chinese auditory semantic studies was also an impetus to further examine this topic in later study (Study 3).

Meanwhile, in literature selection, the visual semantic studies using word stimuli were always twice as many as those using sentence stimuli for each language group, as illustrated in Table 2-1. This was to avoid the later comparison between Chinese and English data sets to be biased by distinct subset distributions between language groups (Turkeltaub & Coslett, 2010). It was also of note that the size of English data set (96 studies) was much larger than that of Chinese data set (29 studies). The current ALE algorithm was able to account for this discrepancy in data set sizes on a voxel-by-voxel basis (Eickhoff et al., 2011). The ALE algorithm simulated data by pooling the foci data sets and randomly dividing them into two new groupings of the same size as the original data sets, resulting in one simulated group with 29 randomly-chosen studies while the other including the remaining 96 studies. Subtraction was then conducted between the two simulated groups. After 10,000 permutations, 10,000 subtraction results jointly yielded a null distribution which served as a baseline to be compared with the true contrasted result between the actual 29 Chinese studies and the actual 96 English studies. This resulted in a voxel-wise p value image showing the significance level of the true contrast differentiated from the null distribution in every voxel. Therefore, unbalanced numbers of studies between Chinese and English groups should be a minor concern in the present study.

Table 2-1

The numbers of selected experiments

<i>Language</i>	<i>Visual</i>	<i>Auditory</i>
<i>Chinese</i>	29 (19 for words, 10 for sentences)	5 (4 for words, 1 for sentences)
<i>English</i>	96 (64 for words, 32 for sentences)	40 (24 for words, 16 for sentences)

Notably, the foci in the current meta-analysis were grouped by participant sample instead of by article, i.e., one foci group per sample rather than one foci group per article. This grouping approach is suggested by the non-additive method (Turkeltaub et al., 2012; Wagner, Sebastian, Lieb, Tüscher, & Tadić, 2014) to avoid underestimating or overestimating the contribution of any sample, considering that multiple samples may be employed by one article and one common sample is also possible to be shared by two studies. If multiple samples were employed by one article (e.g., Chee, Venkatraman, Westphal, & Siong, 2003; Chou et al., 2009), the foci activated by each sample were separately coded. If two studies were conducted by the same team, and at the same time the samples reported in these two studies had exactly the same demographic data such as sample size, average age, education length, and gender composition, the two studies were then considered to share an identical sample, such as Grossman et al.'s two studies (2002a, 2002b). In this example, activated foci from the two studies were grouped together, since both studies (Grossman et al., 2002a, 2002b) investigated English visual word processing. In contrast, in the case that two studies used one sample to examine different types of processing, as Xu et al. (2005) did in an English visual word experiment and an English visual sentence experiment, only the foci reported in the English visual sentence experiment was included considering English visual sentence studies relative to English visual word studies were less available in literature.

Data Analysis

The present meta-analyses were performed using a revised algorithm of Activation-Likelihood Estimation (ALE) analyses (Eickhoff, Bzdok, Laird, Kurth, & Fox, 2012; Eickhoff et al., 2009; Laird et al., 2005; Turkeltaub, Eden, Jones, & Zeffiro, 2002) implemented in GingerALE 2.3.6 to test for regional concordance across experiments. Coordinates reported in the Talairach space were first converted into the MNI space. Individual ALE analyses were

implemented for the Chinese visual semantic data set, English visual semantic data set, and English auditory semantic data set separately. Then foci included in Chinese visual semantic data set and English visual semantic data set were pooled together and subjected to another individual ALE analysis. All these individual ALE maps were thresholded at cluster level $p < .05$, with clusters generated under 1,000 permutations and a threshold of uncorrected $p < .001$ (Eickhoff et al., 2016). Afterward, the generated individual ALE maps from the Chinese visual semantic data set, English visual semantic data set, and the pooled data set were submitted together for contrast analysis, under a threshold of $p < .05$ (uncorrected) with 10000 permutations and a minimum cluster volume of 250 mm³. To make contrast results more robust, the resulted clusters stemming from less than two experiments were eliminated (Turkeltaub & Coslett, 2010; Wagner et al., 2014).

Results

Chinese Visual Semantic Activation

The visual semantic processing of Chinese showed activations in the left middle frontal gyrus (BA46), the bilateral insulae (BA13), the left inferior frontal gyrus (BA44/45/46/47/9), the left superior/medial frontal gyrus (BA8/6), the right lingual gyrus (BA18/17), and the left middle temporal gyrus (BA21) (Figure 2-2a1, Table 2-2a1).

English Visual Semantic Activation

The visual semantic processing in the English language displayed activations in the left middle frontal gyrus (BA46/6), the left inferior frontal gyrus (BA47/45/44), the left middle temporal gyrus (BA22/21/19/39), the left fusiform gyrus (BA37/20), the left angular gyrus (BA39), the left inferior parietal lobule (BA40), the left superior/medial frontal gyrus (BA8/6),

the right middle frontal gyrus (BA9), and the right precentral gyrus (BA6) (Figure 2-2a2, Table 2-2a2).

Difference and Similarity between Chinese and English Visual Semantic Activation

As compared to English visual semantic processing, the visual semantic processing of Chinese had greater activations in the right fusiform gyrus (BA18), the right lingual gyrus (BA18), the bilateral inferior frontal gyri (BA45), the bilateral insulae (BA13), the left superior frontal gyrus (BA8), the left middle frontal gyrus (BA9), and the left inferior frontal gyrus (BA9) (Figure 2-2b1, Table 2-2b1).

English relative to Chinese visual semantic processing elicited greater activations in the left angular gyrus (BA39), the left fusiform gyrus (BA20/37), the left superior temporal gyrus (BA22), the left inferior frontal gyrus (BA47), the bilateral posterior cingulates (BA30/23), and the left precuneus (BA23) (Figure 2-2b2, Table 2-2b2).

Conjunction analysis revealed that visual semantic processes in both languages recruited the left middle frontal gyrus (BA46), the left inferior frontal gyrus (BA9/44/45/46/47), the left superior/medial frontal gyrus (BA8/6), and the left middle temporal gyrus (BA21) (Figure 2-2b3, Table 2-2b3).

Figure 2-2. The overlaid results of meta-analyses. (a1) Chinese visual semantic activation (red), (a2) English visual semantic activation (green), (b1) Chinese > English visual semantic activation (red), (b2) English > Chinese visual semantic activation (green), (b3) the common activation in Chinese and English visual semantic processing (orange), and (c) English auditory semantic activation (blue). The images are displayed in the neurological convention, and the maps in b1-3 are thresholded at $p < .05$ (uncorrected), p -value permutations = 10000, and min volume = 250 mm³, whereas the maps in a1-2 and are significant at cluster level $p < .05$, with clusters generated under 1000 permutations and a threshold of uncorrected $p < .001$. MFG: middle frontal gyrus, IFG: inferior frontal gyrus; IPL: inferior parietal lobule; STG: superior temporal gyrus, MTG: middle temporal gyrus, O-T: occipito-temporal cortex.

Table 2-2

Peak coordinates within the significant clusters for (a) Chinese/English visual semantic processing, (b) the comparison between Chinese and English visual semantic processing, and (c) English auditory semantic processing

Volume (mm ³)	Region	BA	x	y	z	Max ALE
<u>(a1) Chinese visual semantic processing</u>						
8064	Left middle frontal gyrus	46	-48	24	24	0.028
	Left insula	13	-34	24	-2	0.022
	Left inferior frontal gyrus	44-47, 9	-42	36	-4	0.02
2352	Left superior frontal gyrus	8	-2	24	48	0.038
	Left medial frontal gyrus	6	0	8	52	0.015
1344	Right lingual gyrus	18, 17	22	-88	-10	0.02
1336	Right insula	13	38	26	-2	0.021
1184	Left middle temporal gyrus	21	-60	-42	-2	0.02
<u>(a2) English visual semantic processing</u>						
20000	Left middle frontal gyrus	46, 6	-48	22	20	0.058
	Left inferior frontal gyrus	47, 45, 44	-46	30	-14	0.056
13424	Left middle temporal gyrus	22	-58	-40	0	0.067
	Left fusiform gyrus	37, 20	-46	-58	-12	0.05
6896	Left middle temporal gyrus	19, 39	-50	-64	18	0.043
	Left angular gyrus	39	-40	-60	38	0.026
	Left inferior parietal lobule	40	-42	-54	40	0.025
5856	Left superior frontal gyrus	8, 6	-2	26	48	0.05
	Left medial frontal gyrus	8	-2	38	40	0.03
1864	Right middle frontal gyrus	9	54	24	26	0.031
	Right precentral gyrus	6	44	8	28	0.027
1672	Left posterior cingulate	30, 23	-8	-58	14	0.036
1160	Left middle temporal gyrus	21	-56	-6	-18	0.04

Volume (mm ³)	Region	BA	x	y	z	Max ALE
<u>(b1) Chinese visual semantic processing > English visual semantic processing</u>						
1240	Right fusiform gyrus	18	26	-93	-8	3.89
	Right lingual gyrus	18	26	-86	-6	3.54
928	Left inferior frontal gyrus	45	-36	29	0	2.95
	Left insula	13	-38	22	-2	2.71
864	Right inferior frontal gyrus	45	42	28	-2	2.85
	Right insula	13	44	20	-8	2.46
592	Left superior frontal gyrus	8	-2	22	48	2.35
384	Left middle frontal gyrus	9	-50	26	26	2.3
304	Left inferior frontal gyrus	9	-48	6	22	2.34
<u>(b2) English visual semantic processing > Chinese visual semantic processing</u>						
800	Left posterior cingulate	30	-6	-62	16	2.37
	Left precuneus	23	-2	-60	22	2.07
	Right posterior cingulate	23	4	-58	22	2.07
496	Left angular gyrus	39	-38	-60	44	2.41
464	Left fusiform gyrus	20, 37	-34	-40	-18	2.15
456	Left superior temporal gyrus	22	-54	-12	-12	2.31
272	Left inferior frontal gyrus	47	-50	30	-14	2.09
<u>(b3) The conjunction of Chinese & English visual semantic processing</u>						
5848	Left middle frontal gyrus	46	-48	24	24	0.028
	Left inferior frontal gyrus	9, 44-47	-42	36	-4	0.02
2024	Left superior frontal gyrus	8	-2	24	48	0.038
	Left medial frontal gyrus	6	0	8	52	0.015
1136	Left middle temporal gyrus	21	-60	-42	-2	0.02
<u>(c) English auditory semantic processing</u>						
8320	Left superior temporal gyrus	21, 41	-58	-14	-2	0.044
6320	Left inferior frontal gyrus	47	-46	28	-6	0.033
	Left middle frontal gyrus	46	-50	24	24	0.021
	Left insula	13	-36	22	14	0.021
4576	Right superior temporal gyrus	22	64	-6	-6	0.038

Volume (mm ³)	Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	Max ALE
3016	Right middle temporal gyrus	21	64	-30	0	0.021
	Left inferior temporal gyrus	20	-56	-54	-14	0.023
	Left fusiform gyrus	37	-46	-58	-12	0.019
1968	Left superior temporal gyrus	38	-50	14	-16	0.026
1336	Left supramarginal gyrus	40	-54	-52	28	0.018
	Left middle temporal gyrus	39	-42	-60	24	0.016

Note. *x*, *y*, *z* coordinates: MNI space; BA: Brodmann Area; ALE: Activation-Likelihood

Estimation. The meta-analysis in b1-3 was significant at $p < .05$ (uncorrected), p -value permutations = 10000, and min volume = 250 mm³; The meta-analyses in a1-2 and c were significant at cluster level $p < .05$, with clusters generated under 1000 permutations and a threshold of uncorrected $p < .001$.

English Auditory Semantic Activation

The auditory semantic processing in the English language involved the left superior temporal gyrus (BA21/41/38), the left inferior frontal gyrus (BA47), the left middle frontal gyrus (BA46), the left insula (BA13), the right superior temporal gyrus (BA22), the right middle temporal gyrus (BA21), the left inferior temporal gyrus (BA20), the left fusiform gyrus (BA37), the left supramarginal gyrus (BA40), and the left angular gyrus (BA39) (Figure 2-2c, Table 2-2c).

No individual ALE analysis was conducted for the Chinese auditory semantic data set due to the insufficient number of studies. Therefore, no contrast meta-analysis was performed between the Chinese and the English data sets in the auditory domain.

Discussion

Semantic processing involves semantic extract from the written or spoken form, which implies some extent of commonality across languages in the neurocognitive representation of semantic processing (Perfetti & Liu, 2005). On the other hand, the visual or auditory form of semantic representation usually varies according to different languages, suggesting the possible existence of cross-language differences in the semantic neural network (Bolger et al., 2005).

Difference and Similarity between Chinese and English Visual Semantic Activation

The present results provided evidence for both differences and similarities between Chinese and English neural networks for semantic processes in reading. With respect to the difference, the current results reinforce past findings of stronger activation in the left middle frontal gyrus but weaker activation in the left inferior parietal lobule during visual semantic processing of Chinese relative to English, which could potentially be related to the less consistent print-to-sound correspondence for Chinese. In addition, increased right but reduced left occipito-temporal activation were seen for Chinese visual semantic processing, possibly driven by the spatially- rather than linearly-configured Chinese characters (Cao et al., 2015; Ge et al., 2015; Hu et al., 2010; Perfetti & Tan, 2013; Schlaggar & McCandliss, 2007; Tan et al., 2005; Zhu et al., 2014). On the other hand, common activations were observed in the left middle temporal gyrus (BA21), the left middle frontal gyrus (BA46), the left ventral inferior frontal gyrus (BA45/47), and the left dorsal inferior frontal gyrus (BA44), areas thought to be responsible for lexicosemantic representation, lexical-level integration, semantic selection, and phonological/syntactic modulation, respectively (Binder et al., 2009; Friederici & Gierhan, 2013; Jung-Beeman, 2005; Price, 2012; Taylor, Rastle, & Davis, 2013).

The left middle frontal gyrus (BA9/46) was observed in both Chinese and English visual semantic processing. However, this region appeared to be more strongly activated by Chinese than English. Given the salient role of the left middle frontal gyrus in integrating phonological, orthographic, and semantic representations at the lexical/syllable level (e.g., print-to-sound mapping at whole word level or addressed phonology, print-to-meaning mapping) (Kuo et al., 2001; Perfetti et al., 2007; Siok et al., 2004; Tan et al., 2001), our results probably signify the greater demands of lexical-level integration in the visual semantic processing of Chinese as compared to English. In contrast, the sublexical-level transformation between graphemes and phonemes appears to be more needed in the visual semantic processing of English, in view of the stronger activation in the left inferior parietal lobule seen during English than Chinese processing (Booth et al., 2006; Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2005; Frost & Katz, 1992; Lee et al., 2007; Liu et al., 2009; Wu et al., 2009). These results jointly imply that both Chinese and English visual semantic processes are likely to involve phonological representations, as phonology mediates the establishment of mapping the visual print to the represented meaning during literacy acquisition (Perfetti & Dunlap, 2008; Perfetti & Liu, 2005).

The visual semantic processing of Chinese and English also exhibited preferential involvement of the right and left occipito-temporal cortex, respectively. This left and right dissociation might stem from the between-language differentiation in script configurations. The constituent letters in an English word are arranged in a consistent left-to-right sequence, as compared to the visuospatial radical layouts in Chinese characters (e.g., left-right ‘叶’ [/ye4/ *leaf*]; top-down ‘古’ [/gu3/ *ancient*]; outside-inside ‘田’ [/tian2/ *cropland*]) (Cao et al., 2010; Siok et al., 2004; Wu et al., 2012). Therefore, localized orthographic computation tuned by the left fusiform gyrus (BA20/37) could be more engaged in English visual semantic processing,

whereas holistic-level orthographic analysis at the right fusiform/lingual gyri (BA18) is more strongly involved in the visual semantic processing of Chinese (Cao et al., 2015; Hu et al., 2010; Perfetti & Tan, 2013; Tan et al., 2005; Zhu et al., 2014).

In addition to these language-specific regions, areas commonly activated in Chinese and English visual semantic processes were also identified. These areas included the left middle frontal gyrus (BA46), the left middle temporal gyrus (BA21), and the left inferior frontal gyrus (BA9/44/45/46/47). The left middle temporal gyrus is viewed as a principal hub for lexicosemantic storage (Binder et al., 2009; Price, 2012; Taylor et al., 2013). As for the left inferior frontal gyrus, there seems to be a dissociation of the ventral (BA45/47) and dorsal partition (BA44) for semantic selection and phonological/syntactic modulation, respectively (Devlin, Matthews, & Rushworth, 2003; Fiez, 1997; Friederici & Gierhan, 2013; Poldrack et al., 1999). In particular, the involvement of the left dorsal inferior frontal gyrus (BA44) in both Chinese and English visual semantic processes lends plausible support, again, for the likely presence of the phonologically mediated process during both Chinese and English reading. Overall, the consistent involvement of these areas in both Chinese and English visual semantic processes illuminates the stable roles of these regions in interpreting inputs and organizing conceptual representations for natural languages regardless of Chinese or English (Jung-Beeman, 2005).

A Preliminary Model for Chinese Visual Semantic Processing

The observed differences and similarities between Chinese and English visual semantic processing point to a Chinese semantic model in the visual domain, which includes the left ventral inferior frontal gyrus, the left middle frontal gyrus, the left middle temporal gyrus, and the bilateral occipito-temporal cortices. Although the current result of the Chinese visual

semantic activation only showed occipito-temporal involvement in the right but not the left hemisphere (Figure 2-2a1, Table 2-2a1), the unseen left counterpart is suspected to be obscured by the relatively stringent cluster-level thresholding (Eickhoff et al., 2012; Eickhoff et al., 2016). Given that the left occipito-temporal cortex is frequently reported in past meta-analyses as to Chinese reading (Bolger et al., 2005; Tan et al., 2005; Wu et al., 2012; Zhu et al., 2014), the left occipito-temporal cortex is also considered in our Chinese visual semantic model in addition to the right homologue.

However, it is unclear whether this model in the visual domain also applies to the auditory modality. In following segments, a parallel hypothetical Chinese semantic model in the auditory domain will be proposed based on the current meta-analytic results for English auditory semantic activation. In addition, a qualitative review of past findings from Chinese auditory semantic studies was conducted, as a quantitative meta-analysis for the Chinese auditory semantic data set was not possible due to the limited published empirical studies (i.e., 5, versus the required minimum of 17 in meta-analysis; Eickhoff et al., 2016).

English Auditory Semantic Activation

The meta-analytic result of English auditory semantic processing showed activations in the bilateral posterior superior temporal lobes (BA21/22/41) probably for auditory perception, in the left inferior parietal lobule (BA39/40) underpinning the grapheme-to-phoneme interaction, in the left ventral occipito-temporal cortex (BA20/37) for the fine-grained orthographic analysis, in the left middle temporal gyrus (BA21) underlying lexicosemantic representation, in the left anterior superior temporal lobe (BA38) that supports semantic associations, and also in the left ventral inferior frontal gyrus (BA47) for semantic retrieval (Awad, Warren, Scott, Turkheimer, & Wise, 2007; Fiez & Petersen, 1998; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Jobard,

Vigneau, Mazoyer, & Tzourio-Mazoyer, 2007; Poldrack et al., 1999; Price, 2000, 2010, 2012; Visser et al., 2010).

The activations in the posterior superior temporal lobe are noted to extend over both hemispheres and spread across BA41, BA22, and BA21. It is likely that the left and right superior temporal lobes are sensitive to linguistic voices and acoustic sounds respectively. The bilateral superior temporal gyri process audio stimuli with increasing complexity from BA41 to BA22 and then to BA21 (Price, 2012). The extensive activation of posterior superior temporal lobe reflects the intensity and variety of auditory processes that were required when listening to English. Activations in the temporal lobe were also observed in the left middle temporal gyrus (BA21) and the left anterior superior temporal gyrus (BA38), regions thought to be associated with word-level and sentence-level semantic processes, respectively. In addition to the temporal lobe, the left inferior parietal lobule (BA40/39) was also recruited, plausibly implying that written English forms might be automatically initiated when hearing English speech so as to facilitate semantic access (Stoeckel, Gough, Watkins, & Devlin, 2009). This also seems to be supported by the currently-observed activity of the left visual cortex (BA20/37) even during spoken English semantic processing where no text was visually presented.

A Preliminary Model for Chinese Auditory Semantic Processing

Analogous to that of English, the auditory semantic processing of Chinese was expected to involve the posterior superior temporal lobe possibly in both hemispheres, driven by the heavy and diverse demands of sound processing in the auditory modality. In addition, the left middle temporal gyrus and the left anterior superior temporal gyrus were also presumed to aid the semantic representations at the word level and sentence level, respectively. Considering the inconsistency of Chinese orthography, the activity of the left inferior parietal lobule, which

underlies the sublexical-level phoneme composition, was not expected; instead, the activity in the left middle frontal gyrus mediating the lexical-level integration was expected to be observed (Kuo et al., 2003; Zhu et al., 2014). The left ventral inferior frontal gyrus, an area supporting semantic selection, was expected to have an involvement in this semantic network. In particular, the left visual cortex was also expected, despite the absence of Chinese visual scripts in the auditory presentation. This could be because, as speculated for English semantic networks, the written form might be involved in the semantic processing of spoken language. In addition, the written form of Chinese compared to its spoken form is more reliable in cueing the semantic representation given the existence of homophones and semantic radicals. Thus, a greater precision of semantic retrieval might be achieved if the visual Chinese form could be re-mapped from the spoken form. Overall, the assumptions above will be further discussed below based on a qualitative review of past findings from five Chinese auditory semantic studies.

Of the five studies, four assess the semantic processing of spoken Chinese words, where activations are reported in the bilateral posterior superior temporal lobes (BA22), the left middle frontal gyrus (BA46), the left ventral inferior frontal gyrus (BA45/47), the left middle temporal gyrus (BA21), and the left occipito-temporal cortex (BA37/18). None of these four studies reported activation in the left inferior parietal lobule (BA39/40), plausibly consistent with our assumptions discussed. Activity in the right visual cortex is observed in the study that utilizes a lexical decision task (Xiao et al., 2005) or a dangerousness judgement task (Wu et al., 2009), but not in studies using semantic relatedness tasks (Liu et al., 2009; Zou et al., 2015), indicating that the extent to which Chinese spoken forms are visualized may vary according to the different tasks.

The only study evaluating the auditory semantic processing for Chinese sentences (Xu, Zhang, Shu, Wang, & Li, 2013) reported stronger activations in the left occipito-temporal cortex (BA20/37), the left middle temporal gyrus (BA21), and the left BA47 when listening to sentences consisting of randomly-selected words compared with sentences comprising syllables with misplaced consonants. However, given the difference between scrambled sentences and misplaced consonant sentences, these activations might be more attributable to the lexicosemantic processing rather than sentence-level semantic processing.

Although our assumptions regarding the Chinese auditory semantic model seem to be verified by findings of the five studies, this verification is rather limited for two reasons. First, despite the plausible evidence from linguistic and neuroimaging studies, the involvement of the Chinese visual form in Chinese auditory semantic processing still lacks direct evidence through intentional manipulation of visual information across conditions. Second, the neural network underlying Chinese auditory semantic processing is still far from being definite, as consensus cannot be reached from such a small number of studies with findings sensitive to task requirement.

Limitations

Although efforts have been made to optimize the methodology, limitations still exist. First, the tentative model proposed for Chinese auditory semantic processing is not quantitatively derived, as the insufficient number of Chinese auditory semantic studies did not allow a meta-analysis to directly compare across English and Chinese studies (i.e., 5, versus the required minimum of 17 in meta-analysis; Eickhoff et al., 2016). We hope that more Chinese auditory semantic studies will be available in the future to enable a stronger evidence-based auditory semantic model for Chinese.

Second, the visual semantic studies are numerally unequal between languages (29 for Chinese and 96 for English). However, absolute equivalence across languages is difficult to achieve in practice, and this discrepancy in data set sizes has been accounted for by the current ALE algorithm (Eickhoff et al., 2011). Meanwhile, efforts have also been taken to equate the distribution of word and sentence subsets within each language group (the size of word subset is always twice as large as that of sentence subset), so as to prevent the comparison between Chinese and English data sets being biased by inequivalent subset distributions between languages (Turkeltaub & Coslett, 2010). Thus, unbalanced numbers of studies between Chinese and English groups should be a minor concern in Study 1.

Last but not least, for those experiments using fixation or rest as a baseline, the contrast between task and baseline may have obscured the activation of interest in semantic processing. This is because fixation or rest may actually evoke semantic-like network activation (Binder et al., 1999) and residual irrelevant phonological and orthographic processes may be obtained after subtracting baseline from task, as these irrelevant processes are often incidental yet inevitable to semantic tasks but not so to fixation or rest conditions (Yang, McCandliss, Shu, & Zevin, 2009). Thus, efforts have been taken to maximize the essence of semantic processing and the number of studies included. In addition, care was taken to include semantic tasks that provided an alternative baseline (e.g., rhyming judgment) other than fixation or rest.

Summary

In the visual domain, a possible model for Chinese semantic processing has been proposed, which includes the bilateral occipito-temporal cortices, the left middle temporal gyrus, the left ventral inferior frontal gyrus, and the left middle frontal gyrus (Figure 2-2a1 and Table 2-2a1).

The corresponding model in the auditory domain is expected to be mostly parallel to that in the visual domain, with the addition of the more prominent involvement of the bilateral posterior superior temporal cortices and the likely lack of significant activation in the right occipito-temporal cortex. Thus, the Chinese auditory semantic model probably involves the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal gyrus, the left middle temporal gyrus, and the left occipito-temporal cortex (Figure 2-3).

Figure 2-3. The preliminary Chinese auditory semantic model proposed in Study 1. The images are displayed in the neurological convention. MFG: middle frontal gyrus, vIFG: ventral inferior frontal gyrus; aSTG: anterior superior temporal gyrus, MTG: middle temporal gyrus, pSTG: posterior superior temporal gyrus, O-T: occipito-temporal cortex. Using the MarsBaR toolbox, each region was created as an 8mm sphere centered at the peak coordinate that were identified from the meta-analysis result of Chinese visual or English auditory data set in Study 1 (Table 2-2a1 and Table 2-2c). Please see Page 89-90 for more details.

Implications for Study 2 and 3

The findings from the above meta-analysis and qualitative analysis supported a tentative model for Chinese auditory semantic processing to be proposed. However, its validity and reliability still need further verification.

First, although some linguistic and neuroimaging findings imply the possibility of the Chinese visual form to be involved in auditory semantic processing, it still lacks direct substantiation. To address this, a Chinese synonym judgment task was designed in Study 2, where two task conditions were manipulated to differ only by the orthographic information, and the task was carried out in both visual and auditory modalities. This task design allowed us to investigate the role of Chinese orthographic information in the auditory semantic processing in contrast with its role in the visual semantic processing.

Second, the preliminary model for Chinese auditory semantic processing is not solidly grounded on quantitative estimates, as meta-analysis is not considered valid for such a small data set with only five studies (A meta-analysis requires minimally 17 studies in a data set; Eickhoff et al., 2016). Thus, Study 3 aims to fill this gap by investigating the less-studied Chinese auditory semantic processing, and to test and refine the preliminary model proposed in Study 1 by focusing on word processing (Study 3a) and sentence processing (Study 3b), respectively. In addition, the regions involved in the preliminary model would also enable examination of functional connectivity between these regions in Study 3.

CHAPTER III: STUDY 2

Investigation of the Effect of Orthography on Chinese Auditory Semantic Processing: A Behavioral Study

Overview

In study 1, a tentative model was proposed for Chinese auditory semantic processing. However, the limited number of studies in Chinese auditory semantic processing did not allow the use of meta-analysis to quantitatively ascertain the validity of this network. Therefore, Study 2 and Study 3 attempt to supplement and refine this model using behavioral and neuroimaging investigations, respectively. In Study 1, the proposed model hypothesized the involvement of the occipito-temporal visual cortex in Chinese auditory semantic processing, based on the observed activation in the visual cortex in past Chinese auditory semantic studies as well as in the current meta-analysis results of the English auditory semantic data set (Table 2-2c). This implies that it is plausible that Chinese visual word forms could be activated during semantic retrieval from speech sounds where no print is physically presented. To further explore this possibility using empirical data, a Chinese synonym judgment task was designed in Study 2, where two of the four task conditions were manipulated to mainly differ by visual similarity and dissimilarity (the auditory-priming non-synonyms: e.g., ‘目的’ [/mu4 di/ *goal*] & ‘木头’ [/mu4 tou/ *wood*]; the visual- and auditory-priming non-synonyms: e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]). The task was conducted in both visual and auditory modalities, allowing for a more precise investigation of the role of Chinese visual word form in auditory semantic processing in contrast to its role in visual semantic processing. We hypothesized that if orthographic information did affect Chinese auditory semantic processing, performance in the auditory session would differ between the condition with visual priming and the condition without.

Introduction

In daily language communication, listening comprehension is usually more frequently utilized than reading comprehension (Price, 2012; Shafto, 2012). However, studies investigating auditory semantic processing were much fewer than those examining visual semantic processing, as shown earlier in Table 2-1. Essentially, the auditory semantic processing is particularly worth examining for the Chinese language, as the lexical access of spoken Chinese may need the visualization of Chinese word form due to the primacy of Chinese orthography over phonology in discerning homophones and extracting semantic clues (Huang & Hanley, 1995; McBride-Chang, Cho, et al., 2005). However, the role of the Chinese word form in auditory semantic processing has not been well investigated in empirical studies so far. Study 2 was thus conducted to address this.

To date, the automatic involvement of orthography in auditory semantic processing has been reported in several studies of alphabetic languages, including Portuguese (Ventura et al., 2004), French (Ziegler et al., 2008), Thai (Pattamadilok et al., 2008), and English (Chereau et al., 2007; Slowiaczek et al., 2003; Taft et al., 2008). These studies have collectively found that the recognition of a spoken word (e.g., tie) is faster if the word is primed orthographically (e.g., pie) than not (e.g., rye).

If the effect of orthography is present in alphabetic writing systems, one would expect a stronger effect of orthography on the Chinese language due to the following reasons. First, word meaning of Chinese is more precisely represented in the written rather than the spoken form due to the high occurrence of heterographic homophones as stated on Page 11. Second, some semantic clues are present in most visual Chinese characters. Originally, a number of Chinese characters (usually concrete characters) are pictographically derived from drawings or depictions

of the represented objects, such as the characters for a round sun (‘日’) and a crescent moon (‘月’); other characters (usually abstract characters) are formed by analogy or association, such as duplicating the character for person (‘人’) to represent ‘to follow’ or ‘from’ (‘从’) (Feng et al., 2001). Even now, these semantic clues are still embedded in semantic radicals for most Chinese characters (Feldman & Siok, 1999; Hoosain, 1991). For example, the left part of ‘树’ (/shu4/ *tree*) is its semantic radical ‘木’ (/mu4/ *wood*), where *tree* and *wood* are semantically related. These linguistic particularities of Chinese add up in a way such that orthography has dominance over phonology in Chinese lexical access (Perfetti & Zhang, 1991; Tan, Hoosain, & Peng, 1995; Weekes, Chen, & Lin, 1998; Wong & Chen, 1999; Zhou & Marslen-Wilson, 2009). Therefore, in terms of lexical access of spoken Chinese, visual Chinese forms may be automatically visualized to help extract semantic radicals and disambiguate homophonic competitors. However, there is still insufficient evidence to reach such a conclusion based on limited existing studies that evaluated the orthographic involvement in the spoken word recognition of Chinese (Zhou & Marslen-Wilson, 1995; Zou et al., 2012; Zou et al., 2015).

Among the three studies, a significant effect of orthography was only found in Zou et al.’s study in 2012, but not in Zou et al.’s study in 2015 nor in Zhou & Marslen-Wilson’s study (1995). However, a non-significant effect of orthography was observed in the latter two studies, where the response speed to ‘剧本’ (/ju4 ben3/ *play script*) was non-significantly facilitated by the additional visual priming to auditory priming (e.g., ‘剧烈’ [/ju4 lie4/ *violent*] = ‘惧怕’ [/ju4 pa4/ *fear*]). Notably, neither of these two studies were specifically designed to examine the effect of orthography on Chinese auditory semantic processing. Zhou and Marslen-Wilson (1995) aimed to assess the role of morphological structure in processing Chinese compounds,

while Zou et al. (2015) intended to examine the neural mechanism of Chinese morphological processing. Hence, inferences could only be made about the presence or absence of an effect of orthography in these three studies as below.

Although Zhou & Marslen-Wilson (1995) and Zou et al. (2012) both applied lexical decision tasks, a significant effect of orthography was only found in the latter but not the former study. It is speculated that the inconsistent results are plausibly driven by the lexical decision task used. First, it was unclear to what extent semantic processing was involved in these lexical decision tasks. Native Chinese participants might only need to process up to the phonological-level instead of going further into orthographic or semantic mapping to accomplish the auditory lexical decision task, as the participants could simply respond based on their familiarity to the target sounds. Second, while both the semantically-related primes (e.g., ‘剧场’ [ju4 chang3/ *theatre*] primed ‘剧本’ [ju4 ben3/ *play script*]) and the semantically-unrelated primes (e.g., ‘惧怕’ [ju4 pa4/ *fear*] primed ‘剧本’ [ju4 ben3/ *play script*]) were included in Zhou & Marslen-Wilson’s study (1995), all the primes in Zou et al.’s study (2012) were semantically unrelated to the targets (e.g., ‘面包’ [mian4 bao1/ *bread*] primed ‘面孔’ [mian4 kong3/ *face*], or ‘灯光’ [deng1 guang1/ *illumination*] primed ‘登山’ [deng1 shan1/ *mountain climbing*]). This might prompt the participants in Zou et al.’s study (2012) to implicitly develop strategic responses with greater reliance on orthographic or phonological information rather than semantic information, which may eventually lead to the significant effect of orthography observed in Zou et al.’s study (2012).

It is also interesting to note that although two studies were conducted by the same group using similar spoken word stimuli, only the study using lexical decision task had a significant effect to suggest orthographic processing (Zou et al., 2012) and not the study with the

morphological relatedness task (Zou et al., 2015). In addition to the task difference, both studies did not control for possible confounds such as word frequency and word class. It was also not clear whether reaction time was recorded from the onset, the end, or any other time point during the presentation of each audio stimulus, as participants may not precisely recognize a spoken word until enough amount of the word has been heard. Given these issues, it is difficult to assess whether the significant or non-significant effect of orthography observed in these two studies was biased by the lack of control of the above confounds and/or by the insufficient essence of semantic processing in the lexical decision task used in their 2012 study.

To address these issues, a well-controlled synonym judgment task was developed in Study 2 to prompt participants to make responses using semantic-level processing. The visual, phonological, and semantic similarity between paired words were manipulated, so that two of the four task conditions only differed in visual similarity while equated in phonological and semantic similarity (i.e., *the condition of visual- and auditory-priming non-synonym*: 目的 [/mu4 di/ goal] & 目录 [/mu4 lu4/ catalog]; *the condition of auditory-priming non-synonym*: 木头 [/mu4 tou/ wood] & 目的 [/mu4 di/ goal]). Moreover, we had both visual and auditory sessions to allow the effect of orthography to be directly compared between the visual and auditory domains. Similar to past studies, words rather than sentences were used as stimuli to avoid additional confounds introduced by sentences, such as prosody and grammar. In addition, some potential confounds such as frequency, word class, and cohort density were ruled out during the task design or the data analysis. We hypothesized that during the auditory session, participants would respond faster to the condition with additional visual priming than the condition without. In contrast, when the words were visually presented, response speed was not expected to differ between the two conditions.

Methods

Participants

Forty-eight young adults (mean age = 26.4 years, SD = 3.0 years, range = 19-33 years; 24 females) from mainland China participated in the experiment. All participants were native speakers of Mandarin Chinese and used simplified Chinese characters in their daily reading and writing. They were highly proficient in Chinese reading (mean proficiency = 6.69, SD = 0.55, range = 5-7) and listening (mean proficiency = 6.67, SD = 0.60, range = 5-7) measured with a self-report proficiency on a 7-point Likert scale (1 = extremely unskilled, 2 = quite unskilled, 3 = slightly unskilled, 4 = neither skilled nor unskilled, 5 = slightly skilled, 6 = quite skilled, 7 = extremely skilled). All participants were right-handed based on the Edinburgh Handedness Inventory (mean handedness score = 86.0, SD = 16.4, range = 42.9-100) (Oldfield, 1971). None of the participants had a history of psychiatric or neurological disorders. Information such as age, gender, handedness, psychological health, and language background was collected using a demographic questionnaire (Appendix 3-1) before the commencement of the task. The Experiment was approved by the Institutional Review Board at Nanyang Technological University in Singapore, and informed consent was obtained prior to the start of the experiment (Appendix 3-3).

Procedure

A synonym judgment task was administered separately in a visual and an auditory session. The sequence of the two sessions was counterbalanced amongst participants. During each session, participants had to accomplish a six-trial practice before proceeding to the 40-trial formal experiment. Each trial started with a blue cross in the center of the screen (in the visual session) or a 700 Hz beep (in the auditory session), presented for one second to signal the start of

a trial, followed by a pair of two-character compound words which were consecutively presented for 1s each with a 0.2s inter-stimulus-interval between them (Figure 3-1). Written words in 80-size NsimSun font were created as '*.bmp' format images for the visual session; while spoken words in the auditory session were delivered in a female voice synthesized by Interphonic5.0 at 16,000 Hz audio rate and 16-bit audio size in the '*.wav' format. In both sessions, the participants had to indicate after the presentation of the second word whether the two paired words were synonymic or not by a button-press. Therefore, the first word in each pair was the prime for the second word, which was the target. Reaction time was recorded from the onset of the target. The next trial would only start after a response was recorded.

Figure 3-1. The timing of a trial in the visual session (left panel) and the auditory session (right panel). The example given was from the 'No priming synonym' condition: 目的 (/mu4 di/ goal) & 动机 (/dong4 ji1/ motivation).

There were four conditions as listed in Table 3-1. (1) The prime and target shared a common character and thus having similar visual forms, sounds, and meanings (*visual- and auditory-priming synonym*: e.g., 目的 [/mu4 di/ goal] & 目标 [/mu4 biao1/ target]). (2) The

prime and target had different visual and spoken forms but similar meanings (*no priming synonym*: e.g., 目的 [/mu4 di/ goal] & 动机 [/dong4 ji1/ motivation]). (3) The prime and target had similar visual and spoken forms but different meanings despite sharing a common character (*visual- and auditory-priming non-synonym*: e.g., 目的 [/mu4 di/ goal] & 目录 [/mu4 lu4/ catalog]). (4) The prime and target had different visual forms and different meanings but similar sounds, with one character in each word homophonic (*auditory-priming non-synonym*: e.g., 目的 [/mu4 di/ goal] & 木头 [/mu4 tou/ wood]).

Table 3-1

Examples of the four conditions in the synonym judgment task

<i>Task condition</i>	<i>Prime</i>	<i>Target</i>
<i>Visual- and auditory-priming synonym</i>	目的 (/mu4 di/ goal)	目标 (/mu4 biao1/ target)
<i>No priming synonym</i>	动机 (/dong4 ji1/ motivation)	目的 (/mu4 di/ goal)
<i>Visual- and auditory-priming non-synonym</i>	目的 (/mu4 di/ goal)	目录 (/mu4 lu4/ catalog)
<i>Auditory-priming non-synonym</i>	木头 (/mu4 tou/ wood)	目的 (/mu4 di/ goal)

Note. Pronunciation and meaning follow each word in the parentheses.

We used two-character compounds rather than single-character words due to the greater availability and lower ambiguity of compound words. According to a statistical analysis of modern Chinese (Dictionary, 1986), two-character compound words make up about 73.6% in a corpus of 1.31 million words, whereas one-character words are only about 12%. Thus, there are much more two-character compound words to choose from to construct the stimuli. In addition, two-character compound words are more distinguishable than single-character words in the

auditory presentation for having a lower incidence of homophones (Zhou & Marslen-Wilson, 1995). For example, when hearing the sound of a single character /mu4/, participants would possibly extract ‘木’ (*wood*), ‘目’ (*eye*), ‘牧’ (*shepherd*), ‘慕’ (*admire*), ‘暮’ (*dusk*), and so on; in contrast, the sound of a two-character compound word /mu4 di/ maps to ‘目的’ (*goal*) in a largely unique manner without much ambiguity. Apart from this, it was also noteworthy that the four conditions all shared a common word (e.g., ‘目的’). The two synonymic words of this common word (e.g., ‘目标’ and ‘动机’) were chosen from two synonym dictionaries (Zhao & Li, 2009; Zhang, 2010) and then assigned as *the visual- and auditory-priming synonym*, and *the no priming synonym* accordingly. The other two non-synonymic words (e.g., ‘目录’ and ‘木头’) were generated as *the visual- and auditory-priming non-synonym* and *the auditory-priming non-synonym*, respectively. Among these four conditions, the two non-synonym conditions are of major interest, since performance differences between these two conditions might largely stem from the differences in orthographic information, allowing us to investigate the involvement of orthography in Chinese semantic processing. The other two synonym conditions serve only as fillers to balance the numbers of the synonym conditions and non-synonym conditions. In addition to these four conditions, the other four conditions, *auditory-priming synonym*, *visual-priming synonym*, *visual-priming non-synonym*, and *no priming non-synonym*, are also theoretically possible but was not included in the task design, given the difficulty of finding enough existing words for the first three conditions.

In order to ensure that the participants would truly consider the selected paired words in synonym conditions as ‘synonymic’ but those in non-synonym conditions as ‘non-synonymic’, the word pairs were piloted with 30 Chinese participants (mean age = 23.5 years, SD = 3.5 years, range = 19-30 years; 15 females; mean handedness score = 86.6, SD = 13.1, range = 63.6-100;

mean reading proficiency = 6.67, SD = 0.55, range = 5-7; mean listening proficiency = 6.83, SD = 0.46, range = 5-7) to assess the synonymic degree for each selected word pair using a 7-point Likert scale (1 = surely non-synonymic, 2 = should be non-synonymic, 3 = probably non-synonymic, 4 = hard to decide, 5 = probably synonymic, 6 = should be synonymic, 7 = surely synonymic). Results showed that participants perceived the paired words in the two synonym conditions (mean synonymic degree = 5.6, SD = 0.7) to be significantly more synonymic than those in the two non-synonym conditions (mean synonymic degree = 1.1, SD = 0.2), $t(96.113) = 51.730, p < .001$. The two focused conditions were equivalently judged as ‘non-synonymic’ without significant rating difference, $t(156) = 1.339, p = .183$. Although the synonymic degree varied between responses, other stimulus properties, such as stroke number, word frequency, and spatial configuration, were comparable across responses and across conditions of interest (Table 3-2, Appendix 3-2). This may restrain participants from making responses based on these stimulus features other than semantic relatedness.

Table 3-2

Summary of the stimulus properties across conditions

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>	<i>Synonym versus non-synonym</i>	<i>Differences between the two non-synonym conditions</i>
<i>Synonymic degree (1-7)</i>	-	5.5	5.7	1.2	1.0	$t(96.1) = 51.730$, $p < .001$	$t(156) = 0.407$, $p = .183$
<i>Stroke number</i>	16.5	16.4	16.6	17.3	16.1	$t(195) = -0.315$, $p = .753$	$t(195) = 1.260$, $p = .209$
<i>Word frequency (per million)</i>	5910	4510	9540	5330	3320	$t(67.6) = 1.426$, $p = .158$	$t(63.4) = 1.319$, $p = .192$
<i>Spatial configuration</i>							
<i>1st character, Left-right (N.)</i>	19	20	22	20	16	$X^2(1) = 0.462$, $p = .497$	$X^2(1) = 0.444$, $p = .505$
<i>2nd character, Left-right (N.)</i>	15	19	16	16	19	$X^2(1) = 0$, $p = 1$	$X^2(1) = 0.257$, $p = .612$
<i>1st character, Top-down (N.)</i>	10	14	10	8	14	$X^2(1) = 0.087$, $p = .768$	$X^2(1) = 1.636$, $p = .201$
<i>2nd character, Top-down (N.)</i>	12	12	13	14	10	$X^2(1) = 0.020$, $p = .886$	$X^2(1) = 0.667$, $p = .414$
<i>1st character, Single (N.)</i>	6	4	5	6	7	$X^2(1) = 0.727$, $p = .394$	$X^2(1) = 0.077$, $p = .782$
<i>2nd character, Single (N.)</i>	7	4	6	2	8	$X^2(1) = 0$, $p = 1$	$X^2(1) = 3.6$, $p = .058$
<i>1st character, Half-surrounding (N.)</i>	5	2	3	5	3	$X^2(1) = 0.692$, $p = .405$	$X^2(1) = 0.5$, $p = .48$
<i>2nd character, Half-surrounding (N.)</i>	6	4	5	6	2	$X^2(1) = 0.059$, $p = .808$	$X^2(1) = 2.0$, $p = .157$

Note. Stimulus properties such as the ‘stroke number’ and ‘spatial configuration’ were referenced from the online Chinese dictionary

via <http://xh.5156edu.com/>

Experiments were programmed using E-prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). The 40 trials in each session were evenly distributed for the four conditions (10 trials for each condition), the two responses (20 trials for the positive and negative responses each), the position of the common word in each pair (20 trials having the common word as the prime, e.g., ‘目的’ before ‘目标’; 20 trials having the common word as the target, e.g., ‘目的’ after ‘动机’), and also the common syllable position (i.e., whether a word pair was chosen from a set of five words with four word members overlapping in the first or second syllable. Twenty trials came from the word set with four constituent words shared the first syllable, e.g., 动机 /dong4 ji1/ and 目的 /mu4 di/ from the word set of 目的 /mu4 di/, 目标 /mu4 biao1/, 目录 /mu4 lu4/, 木头 /mu4 tou/, and 动机 /dong4 ji1/; twenty trials came from the word set with four constituent words shared the second syllable, e.g., 按照 /an4 zhao4/ and 拍照 /pai1 zhao4/ from the word set of 依照 /yi1 zhao4/, 拍照 /pai1 zhao4/, 按照 /an4 zhao4/, 笼罩 /long3 zhao4/, and 根据 /gen1 ju4/. ²). The presentation of word sets was counterbalanced to prevent participants from developing response strategies based on regularities in the stimulus grids that may be noticed over time. In addition, to avoid familiarity effect, each word was displayed only once in each session, where the four word pairs sharing a common word were pseudo-randomly assigned to four between-subject parallel forms, and no word pair appeared simultaneously in the visual and auditory sessions for any parallel form. In each session of a given parallel form, the 40 trials were

² The paired words were consistent in the position of the common syllable. No paired words had opposite positions for the common syllable (counter-example: ‘照’ in ‘照耀’ and ‘按照’), since inconsistent positions may inhibit the effect of orthography (Ding, Peng, & Taft, 2004).

presented in the same randomization order for all participants, with the first three trials uniformly set as filler conditions to familiarize the participants with the task.

Data Handling

Reaction time has been considered as a sensitive measure of processing complexity and effortfulness (Harald Baayen & Milin, 2010; Lachaud & Renaud, 2011; Whelan, 2008), and has been frequently used as a dependent variable in past studies (Zhou & Marslen-Wilson, 1995; Zou et al., 2012; Zou et al., 2015). In the current study, reaction time was also used as an indicator of the expected orthographic analysis in Chinese auditory semantic processing. The reaction times in the visual and auditory sessions were separately processed, as they were recorded from the onset of each target, and thus a sequentially-unfolding spoken word compared to a simultaneously-presented written word might need longer reaction time to allow for sufficient amount of the audio clip to be heard (Harley, 2013; Whitney, 1998). Only the reaction times in the correctly-responded trials were computed. Thus, out of all the 960 reaction time values in each session (10 trials per condition * 2 conditions of interest * 48 participants), only 922 and 919 values were processed for the auditory and the visual sessions, respectively. Before the data were entered into statistical testing, these values were transformed and trimmed to fulfill the normality assumption of statistical tests following the steps below.

As illustrated in Figure 3-2a, the group distributions of the raw reaction times were skewed for all the combinations of condition (visual priming vs. no visual priming) by common syllable position (1st vs. 2nd syllable) by session (visual vs. auditory). This is not surprising, as reaction time distribution is very likely to be skewed by extreme values, where extreme values may arise from a swift but unintended muscle twitching upon seeing or hearing a target, or from

participants' hesitation or lapsed concentration in some trials, especially during a task without time limit as the present task.

To normalize these skewed distributions, inverse, logarithm, square root, and cube root transformations were all attempted. Among them, the inverse transformation appeared to outperform others, by which the transformed data distributions were the closest approximation of normality with relatively symmetric shapes (Figure 3-2bcde). Thus, inverse transformation was chosen for the current data transformation.

To exclude the reaction time extremes that could not be solved by inverse transformation, individual extremes were identified after inverse transformation using Boxplot, where those inverse reaction times at least three times the interquartile range above the 3rd quartile or below the 1st quartile were detected within each participant and then excluded from further data processing (Figure 3-3). After the removal, no further extremes were detected for any participant.

Figure 3-2. Each participant's extremes of the inverse-transformed reaction times (inverse RTs) were marked in asterisks within the red quadrilateral for the auditory session (left panel) or asterisks within the red circle for the visual session (right panel).

Figure 3-3. The Histograms for the distributions of (a) the raw reaction times, (b) the inverse-transformed reaction times, (c) the log-transformed reaction times, (d) the square roots of the reaction times, and (e) the cube roots of the reaction times in each combination of the condition (visual priming vs. no visual priming) by common syllable position (1st vs. 2nd syllable) by session (auditory vs. visual).

After the exclusion of individual extreme observations, the inverse-transformed reaction times in each condition (visual priming vs. no visual priming) by common syllable position (1st vs. 2nd syllable) by session (visual vs. auditory) were averaged in two ways, one for by-participants means across trials and the other for by-items means across participants. This allowed for two separate statistical tests to be conducted subsequently. Shapiro-Wilk test of normality showed that these means were normally distributed without extremes detected in both auditory and visual sessions, by participants or by items (Table 3-3a).

The by-participants and by-items means of the inverse reaction times were then back-transformed to test the distribution normality for the back-transformed reaction times. Results showed that most distributions were no longer normal after the back transformation (Table 3-3b), suggesting the need for the later parametric statistical tests to be conducted on the inverse means rather than the back-transformed means, regardless of by participants or by items.

Descriptive Analysis

The inverse reaction time means per condition per session were then back-transformed for plotting and easier interpretation purposes. In addition, participants' accuracy per condition per session was also displayed descriptively although not analyzed statistically, so as to provide some basic information of participants' accuracy and task difficulty. Notably, the accuracy was computed on all the trials within a given condition and given session, regardless whether the corresponding reaction times were excluded due to incorrect responses or extreme values.

Table 3-3

The Shapiro-Wilk normality tests for the (a) means of the inverse reaction times, and (b) back-transformed means of the inverse reaction times in each session, by participants or by items

		<u>By participants</u>		<u>By items</u>	
		Auditory	Visual	Auditory	Visual
<u>(a) Means of the inverse reaction times</u>					
Condition	Visual priming	$D(96) = .992,$ $p = .863$	$D(96) = .995,$ $p = .974$	$D(40) = .983,$ $p = .787$	$D(40) = .958,$ $p = .148$
	No visual priming	$D(96) = .988,$ $p = .539$	$D(96) = .980,$ $p = .163$	$D(40) = .965,$ $p = .248$	$D(40) = .977,$ $p = .568$
Common syllable position	1st syllable	$D(96) = .982,$ $p = .217$	$D(96) = .988,$ $p = .569$	$D(40) = .983,$ $p = .811$	$D(40) = .949,$ $p = .171$
	2nd syllable	$D(96) = .992,$ $p = .862$	$D(96) = .977,$ $p = .190$	$D(40) = .979,$ $p = .635$	$D(40) = .944,$ $p = .146$
<u>(b) Back-transformed means of the inverse reaction times</u>					
Condition	Visual priming	$D(96) = .899,$ $p < .001$	$D(96) = .858,$ $p < .001$	$D(40) = .901,$ $p = .002$	$D(40) = .910,$ $p = .004$
	No visual priming	$D(96) = .908,$ $p < .001$	$D(96) = .815,$ $p < .001$	$D(40) = .920,$ $p = .008$	$D(40) = .985,$ $p = .849$
Common syllable position	1st syllable	$D(96) = .903,$ $p < .001$	$D(96) = .818,$ $p < .001$	$D(40) = .924,$ $p = .010$	$D(40) = .961,$ $p = .179$
	2nd syllable	$D(96) = .889,$ $p < .001$	$D(96) = .865,$ $p < .001$	$D(40) = .909,$ $p = .004$	$D(40) = .868,$ $p < .001$

Statistical Analysis

The current study intended to evaluate how reaction time differed between the condition with visual priming and the condition without, where condition was a within-participant and between-item factor of interest. In addition, several variables of non-interest were also taken into account to rule out their potential confounding effects. These included the common syllable

position, the within-pair similarity in word class, the prime and the target word frequencies for both sessions, as well as the cohort density only for the auditory but not the visual session. Further elaboration on the rationale for including these predictors of non-interest is provided below.

‘Cohort density’ refers to the number of existing two-character words that share the same first syllable with a given two-character target word. Based on the cohort theory (Marslen-Wilson, 1987; Marslen-Wilson & Welsh, 1978) and the shortlist model (Norris, 1994), cohort density may have an influence on participants’ reaction time to spoken words (Magnuson, Dixon, Tanenhaus, & Aslin, 2007). For example, ‘目的’ (/mu4 di/ *goal*) has a large number of cohort members that start with the same first syllable /mu4/, such as ‘牧羊’ (/mu4 yang2/ *shepherd*), ‘目前’ (/mu4 qian2/ *at present*), ‘木瓜’ (/mu4 gua1/ *papaya*), ‘墓场’ (/mu4 chang3/ *cemetery*), ‘募捐’ (/mu4 juan1/ *to solicit contributions*), ‘慕名’ (/mu4 ming2/ *to admire somebody’s reputation*), and ‘幕后’ (/mu4 hou4/ *behind the scenes*). In contrast, the cohort density of the word ‘笼罩’ (/long3 zhao4/ *to envelop*) is only three, where only three items share the first syllable /long3/ with ‘笼罩’, which are ‘垄断’ (/long3 duan4/ *enjoy market dominance*), ‘笼络’ (/long3 luo4/ *to win somebody over*), and ‘笼统’ (/long3 tong3/ *general*). In this case, a longer time might be needed to disambiguate ‘目的’ than to disambiguate ‘笼罩’ when these targets were presented aurally. However, the cohort density might have little effect on the reaction time in the visual session, where word forms were seen all at once without ambiguity. Therefore, the cohort density was only controlled for in the auditory but not the visual session. In the current study, the SUBTLEX-CH corpus (Cai & Brysbaert, 2010) was utilized to sum up the cohort density for the target word in each auditory trial. This corpus contains 46.8 million

characters and 33.5 million words that were coded from film subtitles and television program subtitles. Only the words appearing in more than one film or television program were counted as cohort members in the current study, as rarely-used words might not occur to participants to interfere with their task performance (Whitney, 1998).

As shown in Table 3-2, the t-test result showed that word frequencies did not differ significantly across conditions. However, the prime word frequency and the target word frequency were still taken as covariates to partial out their potential confounding effects on the condition factor of interest, as reaction time is very sensitive to word frequency (Cai & Brysbaert, 2010; Feng et al., 2001; Harley, 2013; Jared & Seidenberg, 1991; Marslen-Wilson, 1987; Whitney, 1998). Word frequency here was referenced from the natural logarithm of word count in SUBTLEX-CH, a corpus that has been validated to provide good frequency estimates of daily written and spoken language exposure (Cai & Brysbaert, 2010).

Whether the prime and target were from the same word class or not (i.e. the within-pair similarity in word class, or word class similarity) was likely to cue participants to develop strategic-based rather than semantic-related responses. Thus, this factor was also controlled for in both sessions, where SUBTLEX-CH was used to extract the dominant word class for each word.

As stated earlier, the 20 word pairs overlapping in the first syllable and the other 20 pairs sharing the second syllable were alternated in stimulus presentation to discourage participants' strategic responses. In addition, the potential confounding effect from this factor was still ruled out in the data-analysis phase, as this factor was found to influence priming effects (Dumay et al., 2001; Slowiaczek & Hamburger, 1992; Zhou & Marslen-Wilson, 1995).

To examine the effect of condition on reaction time while controlling for the above variables of non-interest, the linear mixed model was chosen for two reasons. First, this model

could account for both categorical confounds (factors, e.g., common syllable position) and continuous confounds (covariates, e.g., target word frequency). Second, this model allowed for a covariate (e.g., target word frequency) to change with different conditions for each participant, which fitted our data structure. As mentioned earlier, separate linear mixed models were conducted for the by-participants and by-items data sets. As of major interest, the by-participants linear mixed model aimed to reveal whether the results were generalizable to a larger participant population. In contrast, the linear mixed model by items served only as a supplementary analysis to help further explore the data generalization to a more exhaustive stimulus list (Baayen, Davidson, & Bates, 2008).

In addition to the preceding normality assumption, the linear mixed model also assumed the independence between factors and covariates (Verbeke, 1997). To test for this independence assumption, all the possible two-way factor-covariate interactions and factorial interactions were submitted together with the factors and covariates into the linear mixed model using SPSS 23.0. The results showed no significant interactions in either session, irrespective of by participants or by items (Table 3-4), suggesting the independence assumption was satisfied. Therefore, the linear mixed models were adjusted with only the factors and covariates entered while all interactions were removed.

Table 3-4

The two-way interactions between each factor and each covariate in each session

	<i>Auditory session</i>		<i>Visual session</i>	
	<i>By participants</i>	<i>By items</i>	<i>By participants</i>	<i>By items</i>
Condition *	$F(1,197) = 0.628,$	$F(1,64) = 2.264,$	$F(1,179) = .813,$	$F(1,67) = .205,$
Common syllable position	$p = .429$	$p = .137$	$p = .526$	$p = .652$
Condition *	$F(1,91) = 2.666,$	$F(1,64) = .053,$	$F(1,171) = 2.383,$	$F(1,67) = .109,$
Prime word frequency	$p = .106$	$p = .819$	$p = .096$	$p = .742$
Condition *	$F(1,96) = 2.791,$	$F(1,64) = .344,$	$F(1,178) = 0.318,$	$F(1,67) = .028,$
Target word frequency	$p = .098$	$p = .560$	$p = .573$	$p = .867$
Condition *	$F(1,98) = 2.851,$	$F(1,64) = 0.279,$	$F(1,175) = 2.730,$	$F(1,67) = .492,$
Word class similarity	$p = .094$	$p = .599$	$p = .102$	$p = .485$
Condition *	$F(1,90) = 3.046,$	$F(1,64) = .044,$	N.A.	N.A.
Cohort density	$p = .084$	$p = .835$		
Common syllable position	$F(1,90) = 2.837,$	$F(1,64) = .751,$	$F(1,137) = .111,$	$F(1,67) = 1.281,$
* Prime word frequency	$p = .096$	$p = .389$	$p = .739$	$p = .262$
Common syllable position	$F(1,87) = 3.146,$	$F(1,64) = 3.389,$	$F(1,174) = 2.980,$	$F(1,67) = 0.079,$
* Target word frequency	$p = .080$	$p = .070$	$p = .126$	$p = .779$
Common syllable position	$F(1,87) = 2.559,$	$F(1,64) = .331,$	$F(1,179) = 0.039,$	$F(1,67) = 3.338,$
* Word class similarity	$p = .113$	$p = .567$	$p = .843$	$p = .072$
Common syllable position	$F(1,91) = 2.616,$	$F(1,64) = 1.048,$	N.A.	N.A.
* Cohort density	$p = .109$	$p = .310$		

Results

The back-transformed reaction time and raw accuracy in each condition of each session are shown in Figure 3-4.

Figure 3-4. The back-transformed reaction time (RT; left panel) and raw accuracy (ACC; right panel) in the condition with visual priming (in blue) and the condition without visual priming (in green) for the auditory and the visual sessions; ***, $p < .001$.

The results showed that after accounting for the variables of non-interest (common syllable position, prime word frequency, target word frequency, within-pair similarity in word class, and cohort density), effects of condition were significant in the auditory session, $F(1,147) = 14.864$, $p < .001$, Cohen's $D = .556$, power = .901 ($\alpha = .05$), by participants, and $F(1,73) = 7.182$, $p = .009$; Cohen's $D = .300$, power = .237 ($\alpha = .05$), by items, with faster responses to *the visual- and auditory-priming non-synonym* (back-transformed RT = 1311ms) than *the auditory-priming non-synonym* (back-transformed RT = 1439ms). In contrast, for the visual session, effects of condition were not significant after controlling for the variables of non-interest (common syllable position, prime word frequency, target word frequency, and within-pair similarity in word class), $F(1,141) = 0.943$, $p = .333$, Cohen's $D = .140$, power = .095 ($\alpha = .05$),

by participants, or $F(1,74) = 1.686$, $p = .198$, Cohen's $D = .145$, power = .064 ($\alpha = .05$), by items (Table 3-5a). No variables of non-interest were significant in either session, by participants or by items (Table 3-5b).

Table 3-5

The effects of the (a) condition and (b) variables of non-interest on the inverse-transformed reaction times in each session, by participants or by items

	<i>Auditory session</i>		<i>Visual session</i>	
	<i>By participants</i>	<i>By items</i>	<i>By participants</i>	<i>By items</i>
<i>(a) Visual priming condition vs. No visual priming condition</i>				
	$F(1,147) = 14.864$,	$F(1,73) = 7.182$,	$F(1,141) = 0.943$,	$F(1,74) = 1.686$,
	$p = .000$;	$p = .009$;	$p = .333$;	$p = .198$;
	Cohen's $D = .556$;	Cohen's $D = .300$;	Cohen's $D = .140$;	Cohen's $D = .145$;
	power = .901	power = .237	power = .095	power = .064
	($\alpha = .05$)	($\alpha = .05$)	($\alpha = .05$)	($\alpha = .05$)
<i>(b) Variables of non-interest</i>				
<i>Common syllable position</i>	$F(1,147) = 0.509$,	$F(1,73) = .640$,	$F(1,143) = 1.045$,	$F(1,74) = 0.203$,
	$p = .477$	$p = .426$	$p = .308$	$p = .654$
<i>Prime word frequency</i>	$F(1,175) = 0.000$,	$F(1,73) = 0.072$,	$F(1,141) = 1.384$,	$F(1,74) = 0.039$,
	$p = .991$	$p = .789$	$p = .241$	$p = .844$
<i>Target word frequency</i>	$F(1,144) = 2.162$,	$F(1,73) = 3.690$,	$F(1,154) = 0.842$,	$F(1,74) = 0.139$,
	$p = .144$	$p = .099$	$p = .360$	$p = .711$
<i>Word class similarity</i>	$F(1,140) = 0.329$,	$F(1,73) = 0.071$,	$F(1,146) = 2.942$,	$F(1,74) = 0.496$,
	$p = .567$	$p = .791$	$p = .088$	$p = .484$
<i>Cohort density</i>	$F(1,141) = 0.036$,	$F(1,73) = 0.850$,	N.A.	N.A.
	$p = .849$	$p = .360$		

Note. Effect size (Cohen's D) was calculated using the formula provided by Rosenthal (1991); statistical power was computed using the formula provided by Scherbaum and Ferreter (2009).

Discussion

In the current study, longer reaction time was shown for the auditory-priming non-synonym (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]) than for the visual- and auditory-priming non-synonym (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]) in the auditory session, whereas no difference was found between these two conditions in the visual session. This suggests the involvement of orthography in Chinese auditory semantic processing.

Significant Effect of Orthography in the Auditory Modality

In the auditory session where no characters were visually presented, the speed of synonym judgement was faster when a common character was shared between the paired words (e.g., ‘目’ /mu4/ in ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]) as compared with when no common character was shared (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]).

Visual similarity or dissimilarity between paired words is likely to have contributed to this difference in response, as the number of strokes, character configuration, presenting order, word frequency, word class, common syllable position, and cohort density were deliberately controlled for *a priori* in stimulus selection and presentation setup, and also after-the-fact during the data-analysis phase (Table 3-2 & Table 3-5b). Therefore, this reaction time difference may indicate the influence of the written Chinese form on auditory semantic processing, where no Chinese characters are visually presented. As mentioned earlier, due to the advantage of Chinese orthography over phonology in differentiating homophones and providing semantic cues (Perfetti & Liu, 2005; Treiman et al., 1981; Zhou & Marslen-Wilson, 1995), spoken Chinese words might need to be mentally visualized as written forms for the precision of semantic access. Such visualization processes appear to be easier for the paired words with an overlapping character (e.g., ‘目的’ & ‘目录’) compared to those without (e.g., ‘目的’ & ‘木头’). Therefore, the longer

processing time needed is possibly the result of heavier visualization loads for the latter than the former condition in the auditory session. As most existing Chinese studies have not found the significant effect of orthography (Zhou & Marslen-Wilson, 1995; Zou et al., 2012; Zou et al., 2015), the current finding is plausibly one of the first evidence to substantiate the effect of orthography in auditory lexicosemantic processing specifically for the Chinese language.

Non-significant Effect of Orthography in the Visual Modality

In the visual session, the reaction time was not significantly different for the auditory-priming non-synonym (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]) and the visual- and auditory-priming non-synonym (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]), which is consistent with prior findings (Zhou, Marslen-Wilson, Taft, & Shu, 1999). Unlike the auditory session, characters in the visual session do not need to be visualized from the heard syllables. Thereby, consistency between the print and meaning is overt in the visual session, where the print is presented visually. For example, the print-related but semantic-unrelated word pairs (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]) may have higher print-to-meaning inconsistency and thus need more processing time to activate wider network for semantic retrieval compared to the word pairs that were consistently unrelated in both print and meaning (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]). On the other hand, synonym judgment might be faster for the non-synonyms that were primed both visually and aurally (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]) than those only primed aurally (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]). All these may eventually contribute to the equivalent reaction time for the two conditions in the visual session. This appears to replicate the findings from a visual lexical decision study of Chinese (Cheng & Shih, 1988) as well as a visual naming

study of Chinese (Pollatsek, Tan, & Rayner, 2000). It has been found in these studies that when primes are both homophonic and orthographically similar to targets (e.g., ‘诚’/cheng2/*honest* & ‘城’/cheng2/*city*), recognition by phonology is sufficient (e.g., /cheng2/), thus dampening the orthographic similarity effect (e.g., ‘诚’ & ‘城’). Accordingly, in the current study, the paired words already shared one common syllable in each condition (e.g., /mu4/), beyond which, whether the common syllable represented the same written form in the paired words (e.g., both ‘目’) or not (e.g., ‘目’ & ‘木’) might not produce any additive effect for performance in the visual semantic task.

Taken together, the current auditory and visual results contribute to our understanding of the Chinese semantic processing particularly in the auditory domain, which has been relatively neglected in the literature relative to the visual domain but is, in fact, more frequently utilized in daily language communication (Price, 2012; Shafto, 2012). Our finding is likely amongst the first behavioral evidence to deduce the involvement of orthography in spoken Chinese semantic processing (RT: ‘visual- and auditory-priming non-synonym’ < ‘auditory-priming non-synonym’ in the auditory session). Meanwhile, the non-significant effect of orthography on Chinese visual semantic processing (RT: ‘visual- and auditory-priming non-synonym’ = ‘auditory-priming non-synonym’ in the visual session) may imply that the effect of orthography may be conditional upon factors such as the input modality and the phonological/orthographic/semantic relations between paired words.

Limitations

Efforts have been taken to tease apart confounds from the effect of orthography of interest, as stated in the preceding section. However, limitations still exist.

First, the role of orthography needs to be further verified and the possible strategic responses could be better avoided, if the other four conditions (auditory-priming synonym, visual-priming synonym, visual-priming non-synonym, and no priming non-synonym) could be included. Ideally, with these additional four conditions, the role of orthography could be further clarified not only by the current contrast ('visual- and auditory-priming non-synonym' versus 'auditory-priming non-synonym'), but also through several other between-condition comparisons (e.g., 'visual- and auditory-priming synonym' versus 'auditory-priming synonym', 'no priming synonym' versus 'visual-priming synonym', and 'visual-priming non-synonym' versus 'no priming non-synonym'). Furthermore, the independent effect of orthography and its combined effect with phonology/meaning could be examined as well. In addition, with the other four conditions (auditory-priming synonym, visual-priming synonym, visual-priming non-synonym, and no priming non-synonym), the structure of conditions would be more symmetric between synonyms and non-synonyms, and thus some potential strategic responses in the current design (e.g., the paired words without auditory priming were always synonyms) could largely be avoided. However, due to the linguistic nature of Chinese, limited word pairs could be located in the conditions of the auditory-priming synonym, visual-priming synonym, and visual-priming non-synonym despite their theoretical possibility. Task manipulations could be optimized to consider this in future studies.

Second, some other confounds may also need to be factored out in stimulus selection, presentation setup, and data analysis. The potential confounds in the stimulus selection include word association (how likely participants would think of the target if they have just seen/heard the prime), word collocation (how likely the prime and target would follow each other in a sentence), the morphological transparency of each compound word (the degree of semantic

overlap between compound words and their constituent characters), the semantic transparency of each character (whether each character is semantically related to its semantic radical), and so forth (Hsiao & Shillcock, 2006; Zhou & Marslen-Wilson, 2009). In addition, given the effect of orthography by items was statistically under powered (Cohen's $D = .300$, power = .237), future studies may need to consider including a larger number of stimuli to observe the effect that is generalizable to the stimulus population. As for the presentation setup, strategic expectations could be better controlled if future studies could consider using a shorter inter-stimulus-interval, employing a time-limit setup for responses (e.g., 5s), and applying the reversed button-press for half trials (Chereau et al., 2007). During the data processing, future research may consider the frequency of each cohort member (Luce & Pisoni, 1998) and use 'gating' to identify the recognition point of each spoken word (Marslen-Wilson, 1987). Controlling for these confounds in future research may lessen the chance of obtaining spurious results that are caused by strategic processing of primes and targets (Norris, McQueen, & Cutler, 2002).

Third, the involvement of visual information in Chinese auditory semantic processing might be more directly demonstrated if comparisons are made between the literate and illiterate (Castro-Caldas et al., 1998). However, this may introduce some new problems, considering the illiterate may develop a differentiated neuro-architecture not comparable to that of the literate. Having said this, it may still be a worthwhile point for future research to start with.

Summary

Findings in Study 2 are likely amongst the first behavioral evidence from which to infer the involvement of orthography in spoken Chinese semantic processing. It was found that after controlling for several confounds, processing time was longer for auditory-priming non-synonyms than for visual- and auditory-priming non-synonyms in the auditory session, possibly

due to the heavier visualization load in the former condition due to its lack of visual priming. In contrast, without such visualization needed in Chinese reading, the effect of orthography disappeared in Chinese visual semantic processing. These results imply that the effect of orthography might be conditional upon factors such as the input modality and the phonological/orthographic/semantic relation between paired words.

Implications for Study 3

Findings in Study 2 provided deeper insight into the visual cortex involvement in the Chinese auditory semantic model which was preliminarily postulated in Study 1. In the following study (Study 3), this model is further tested and refined using neuroimaging data sets, where the involvement of the occipito-temporal visual cortex is also investigated.

CHAPTER IV: STUDY 3

Validation of the Proposed Chinese Auditory Semantic Model: fMRI Studies

(Study 3 has been partly presented as a poster in *the 2016 Organization for Human Brain*

Mapping Annual Conference, Geneva, Switzerland, 26th -30th June, 2016)

Overview

A tentative Chinese auditory semantic model was proposed in Study 1. However, the limited studies in the literature prevented further quantitative meta-analysis to be conducted to provide more conclusive evidence to support the model. Meanwhile, word and sentence comprehension are previously suggested to have dissociated anatomical substrates (Marco Catani, 2017; Mesulam, Thompson, Weintraub, & Rogalski, 2015). However, such specificity of word-level and sentence-level network could not be verified by the meta-analytic results in Study 1. Thus, Study 3 aims to fill this gap to test whether and how word-level (Study 3a) and sentence-level (Study 3b) Chinese auditory semantic processing fit into the proposed model, respectively.

Two archival fMRI data sets were collected from a group of native Mandarin Chinese speakers performing two auditory semantic tasks. In one, participants decided whether the heard word described a living creature bigger than a cat, and in the other, participants passively listened to sentences under conditions that approximated natural listening. The former and the latter data sets are separately examined in Study 3a and Study 3b instead of being combined into one study or contrasted with each other. This is because the two tasks are inherently and structurally incomparable in several dimensions other than the material level itself (words vs. sentences), such as response requirement, involvement of syntax, word number, and high/low baseline. To examine the possible connections amongst the regions of the proposed network, functional connectivity analysis was conducted in addition to the whole-brain activation analysis in Study 3a and Study 3b. Meanwhile, we also would like to follow up on the behavioral evidence shown in Study 2 where slowed reaction time was thought to reflect the orthographic analysis in Chinese auditory semantic processing. If orthography indeed affects the semantic

processing of spoken Chinese, we would expect to see the presence of activation in the occipito-temporal visual cortex in Study 3.

STUDY 3a: WORD-LEVEL VALIDATION

Introduction

In daily communication using spoken language, one of the core processes is understanding the words heard. It is particularly interesting to identify how the brain processes the semantic information heard in the Chinese language as semantic radicals apparently do not aid in this process. To our knowledge, this issue has only been investigated in four studies to date (Liu et al., 2009; Wu et al., 2009; Xiao et al., 2005; Zou et al., 2015). Based on a review of these studies as well as a meta-analysis of other relevant studies, a Chinese auditory semantic model was preliminarily proposed in Study 1, which included the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex. In the current chapter, we will revisit these four past studies within the framework of this preliminary model. Based on the possible research gaps in these four studies, we developed a study from archival data to test the proposed model.

The earliest study among these four (Xiao et al., 2005) found that the bilateral occipital-temporal cortices (BA37) and the bilateral middle temporal gyri (BA21) had greater activity when making auditory lexical decision to real disyllabic Chinese words (e.g., ‘太阳’/tai4 yang2/*sun*) than to false words (e.g., ‘领村’/ling3 cun1/). It is surprising to capture the lexical effect in the bilateral occipital-temporal visual cortices, as no visual word forms were physically presented. The authors thereafter argued that this finding would reflect the automatic activation of Chinese visual characters when corresponding phonological representations were activated, which coincides with our findings in Study 2. In addition to the bilateral visual cortices, the

bilateral middle temporal gyri were also seen in the real- > false-word contrast. This possibly indicates the greater lexicosemantic representations in real words than false words. Despite the recruitment of the middle temporal gyrus, it is still difficult to estimate to what extent this lexical decision task involved semantic-related activation. As participants were not explicitly required to make decisions based on the semantic quality of the heard words, the false words can be rejected simply due to the unfamiliar phonology without the necessity to exploit semantic-level processing (James, 1975). Essentially, Xiao and colleagues (2005) also claimed that the research focus of their study was phonologic forms but not semantic representations of Chinese two-character words.

More recently, similar findings are observed in two studies (Liu et al., 2009; Zou et al., 2015) using similar task paradigms, where auditory meaning relatedness judgment compared to tone baseline evoked greater activations in the bilateral posterior temporal lobes (BA22 in Liu et al., 2009; BA48 in Zou et al., 2015), the left occipito-temporal cortex (BA18 in Liu et al., 2009; BA37 in Zou et al., 2015), and the left ventral frontal lobe (BA47 in Liu et al., 2009; BA45 in Zou et al., 2015). Both studies ascertained the significance of the left pars triangularis (ventral inferior frontal gyrus) in Chinese auditory lexicosemantic processing. It has also been interpreted in these two studies that the recruitment of the left occipito-temporal cortex was driven by the interaction of orthographic and phonological representations during spoken Chinese word recognition. This reinforced our findings in Study 2 from a neurobiological perspective. The activated regions in these two studies were within the network that was identified in our preliminary model. However, the statistical power of the region-of-interest (ROI) results in Zou et al.'s study (2015) could be stronger if the ROIs were defined from an independent study rather than from the same study.

In addition to regional activation pattern, interregional connectivity network underpinning Chinese auditory lexicosemantic processing was examined in Wu et al.'s study (2009) using multivariate independent component analysis (ICA). While the regional activation results seen in the occipito-temporal cortex (right lingual gyrus, BA18) and the left ventral frontal lobe (BA45/47) were consistent with Liu et al.'s (2009) and Zou et al.'s (2015), several intensely-connected networks were identified within the extensive fronto-temporal cortex when contrasting Chinese auditory semantic dangerousness judgment (e.g., ‘手枪’/shou3 qiang1/ *gun*) to a rest baseline. This highlights the significance of the fronto-temporal co-activation in Chinese auditory lexicosemantic processing. However, it was also recognized by Wu et al. (2009) that the networks were extracted in a relatively broad manner, without being further separated into more precise sub-networks such as interlinks between two paired regions. Nevertheless, this study broadens our understanding of the complex neuro-mechanism underlying Chinese auditory lexicosemantic processing, which is not only mediated by isolated brain regions but also dependent on the interactions of several areas in a parallel distributed hierarchy.

Apart from Wu et al.'s study (2009), most other studies examining the effective/functional connectivity underlying Chinese lexicosemantic processing utilize visually-rather than aurally-presented tasks. For example, Fan and colleagues (2012; 2010) used dynamic causal modeling (DCM) and found that semantic relatedness judgment of visual Chinese characters appeared to be modulated by several interregional connections. The bidirectional connectivity between the left ventral inferior frontal gyrus and the left middle temporal gyrus suggests that the ventral inferior frontal gyrus may assist to retrieve semantic knowledge stored in the left middle temporal gyrus, while the connection from the left fusiform gyrus to the left middle temporal gyrus signals the bottom-up influences of orthography on semantic

representations. It thus implicates that the left middle temporal gyrus may serve as an interface to integrate top-down controlled and bottom-up automatic processes.

In addition to those studies tapping task-based effective/functional connectivity, the anatomical connectivity underlying the Chinese semantic system has also been examined using diffusion tensor imaging (Han et al., 2013). In this study, reduced fractional anisotropy and greater lesion percentage in the left inferior fronto-occipital fasciculus correlated with more severe semantic deficits in Chinese patients, irrespective of factors such as the input modality (visual vs. auditory), output modality (verbal vs. non-verbal), patients' overall cognitive state, whole lesion volume, type of brain damage, and grey matter involvement. This suggests that the Chinese semantic system is likely to be regulated by the inferior fronto-occipital fasciculus connecting the posterior lateral temporal cortex to the frontal cortex and underscores the significance this fiber tract to semantic processing in Chinese.

As mentioned earlier, there existed complications that limited the implication of these past studies for the current investigation. For example, Xiao et al.'s study (2015) utilized a lexical decision task that may not intensely engage semantic network; the ROIs in Zou et al.'s study (2015) were not *a priori* but instead were defined using conjunction results in their own study; limited studies investigated the ROI-to-ROI functional connectivity underlying Chinese lexicosemantic processing in the auditory modality. Given this, an empirical investigation is needed to evaluate the Chinese auditory lexicosemantic activations by employing a task that explicitly requires semantic-based responses, and at the same time to examine functional connectivity between *a priori* ROIs. To achieve this, Study 3a utilized an fMRI data set, where native Mandarin Chinese participants judged whether a heard Chinese word denoted a living creature bigger than a cat. *A priori* regions of interest (ROIs) were created based on the meta-

analytic synthesis in Study 1, and functional connectivity between these ROIs was computed.

Based on the preliminary model postulated in Study 1, it is hypothesized that activations will be observed in the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex. Functional connectivity is also expected within this predefined Chinese auditory semantic network.

Methods

Participants

An archival neuroimaging data set of 26 native speakers of Mandarin Chinese was employed in this study. The study was conducted in Taiwan and all participants used traditional Chinese characters in their everyday reading and writing. None of them had a history of neurological diseases or psychiatric disorders, and the participants had received 17.6 years of education ($SD = 2.2$ years, range = 13-23 years) on average. All participants gave informed consent approved by the Institutional Review Board at National Taiwan University Hospital before the experiment.

Three male participants were excluded due to the poor image quality. The remaining 23 right-handed participants (12 females; mean age = 25.7 years, $SD = 4.2$ years, range = 19-35 years; mean handedness score = 87.8, $SD = 17.6$, range = 42.8-100) were included in data analysis.

Procedure

A blocked design auditory semantic-tone task, which was adapted from Binder and colleagues' (1997), was applied in Study 3a. In the semantic condition, the participants were instructed to judge whether a heard two-syllabic Chinese noun described a living creature bigger

than a cat. Two- instead of one-character nouns were adopted to lessen the incidence of homophones and then to avoid the potential semantic confusion arising from irrelevant homophones. As a baseline, the tone condition required the participants to determinate whether there were two high tones (750 HZ) amongst a sequence of three to seven tones (either 250HZ or 750HZ).

After performing a ten-trial practice outside the scanner, participants were administered the formal task in one run while being scanned. The run consisted of ten 30s blocks that alternated between the semantic condition and the tone condition, forming five cycles each comprising one semantic and one tone block (Figure 4-1). Each block had ten 3s trials. In each trial, after an auditory stimulus was played, participants were required to respond with a button press using their right hand before the next trial started.

Figure 4-1. The condition sequence in the run in Study 3a.

Image Acquisition

The current experiment applied functional magnetic resonance imaging (fMRI). This technology is non-invasive and replicable with good spatial resolution down to millimeters and fair temporal resolution within a few seconds. Given that neural activity is coupled with cerebral blood flow, fMRI measures neural activity by detecting changes in the oxygen level in blood.

That is, when blood flow to a brain region increases, neural activity of this region is also presumed to increase.

In Study 3a, participants were imaged in a 3 Tesla Siemens Trio MRI scanner with a 12-channel head coil at National Taiwan University Hospital. The echo planar imaging (EPI) sequence was used to obtain functional images: repetition time (TR) = 2000 ms, echo time (TE) = 24 ms, flip angle (FA) = 90 °, field of view (FOV) = 240 mm, matrix size = 64 × 64, voxel size = 3.8 mm x 3.8 mm x 3.8 mm, slice thickness = 3.8 mm, and 34 axial slices aligned to the anterior-posterior commissure plane with a total of 150 images per task. A T2-weighted image was acquired with TR = 5920 ms, TE = 102 ms, FA = 150°, FOV = 250mm, matrix size = 256 × 256, voxel size = 1 mm x 1 mm x 3.9 mm, slice thickness = 3.9 mm, and 34 axial slices. A high resolution T1-weighted 3D Magnetization-Prepared RAPid Gradient-Echo (MPRAGE) whole-brain scan was also acquired using TR = 1380 ms, TE = 2.6 ms, FA = 15°, FOV = 250 mm, matrix size = 256×256, and voxel size = 1mm x 1mm x 1mm, slice thickness = 1 mm.

Image Analysis

The neuroimaging data were subjected to a three-stage preprocessing (Ashburner, 2007) implemented in Statistical Parametric Mapping 8 (SPM8; Department of Cognitive Neurology, London, UK). The first stage was conducted for each individual participant, where all structural and functional images were reoriented to an origin at the anterior commissure, followed by a slice timing correction of the functional images to the middle slice (Sladky et al., 2011), a realignment of the functional images to the first volume, a co-registration of the T1 MPRAGE image to the mean functional image, and a segmentation of the T1 MPRAGE image into gray matter (GM), white matter (WM), and cerebrospinal fluid (CSF). This first stage generated a GM template and a WM template for each participant. The GM and WM templates from all

participants were superimposed together in the second stage, to generate a group template and a flow field for each participant. The group template and individual flow field were utilized for the normalization and smoothing of each participant in the last stage. Individual functional images and GM image were normalized to Montreal Neurological Institute (MNI) space and smoothed with a Gaussian kernel of 8 mm full-width at half-maximum (FWHM). While the first preprocessing stage went through conventional preprocessing, the second and third stages undertook Diffeomorphic Anatomical Registration using Exponentiated Lie algebra (DARTEL) preprocessing instead for improved normalization (Klein et al., 2009; Yassa & Stark, 2009). After the three stages of preprocessing, whole brain activations in the semantic > tone contrast were obtained for each participant using the first-level analysis in SPM8. At second-level analysis, group activation across all participants was computed for the semantic > tone contrast using a one-sample t-test.

In addition to the whole-brain analyses, ROIs were also created for the examination of the possible functional connections between them. Based on the tentative Chinese auditory semantic model proposed in Study 1, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal gyrus, the left middle temporal gyrus, the bilateral posterior superior temporal gyri, and the left occipito-temporal cortices were selected as *a priori* ROIs. The center coordinates of the left middle frontal gyrus (BA46), the left ventral inferior frontal gyrus (BA47), and the left middle temporal gyrus (BA21) were identified from the meta-analysis result of Chinese visual semantic data set in Study 1 (Table 2-2a1). The center coordinates of the left posterior superior temporal gyrus (BA41), the right posterior superior temporal gyrus (BA22), the left anterior superior temporal gyrus (BA38), and the left occipito-temporal cortex (BA20) were identified from the meta-analysis result of English auditory

semantic data set in Study 1 (Table 2-2c). Using the MarsBaR toolbox (Brett, Anton, Valabregue, & Poline, 2002), the ROIs of the left posterior superior temporal gyrus, the right posterior superior temporal gyrus, the left anterior superior temporal gyrus, and the left occipito-temporal cortex were defined as 8mm spheres centered at (-58, -14, -2), (64, -6, -6), (-50, 14, -16), and (-56, -54, -14), respectively. The ROIs of the left middle frontal gyrus, left ventral inferior frontal gyrus, and the left middle temporal gyrus were defined as 8mm spheres centered at (-48, 24, 24), (-42, 36, -4), and (-60, -42, -2), respectively.

Functional connectivity between every pair of these predefined ROIs was calculated in the semantic > tone contrast by CONN 17b (<https://www.nitrc.org/projects/conn>) implemented in SPM8. ROI-to-ROI functional connectivity indicates the level of linear association of the blood oxygen level-dependent (BOLD) time series between each pair of ROIs (Friston, 2002; Stevens, 2009). When distributed brain ROIs display strongly correlated patterns of neural activity change, it is taken as evidence that these ROIs are functionally connected (Fingelkurts, Fingelkurts, & Kähkönen, 2005). After ‘setup’ and ‘denoising’ phases, the first (individual) level analysis generates files for all the possible participant/condition/ROI combinations. In the second (group) level analysis, by specifying Fisher z-transformed correlation coefficient values for between-condition and between-ROI contrasts, the corresponding participant/condition/ROI files yielded in the first-level would be extracted together for group-level correlation analyses accordingly. It is believed that the ROI-to-ROI functional connectivity represents the best approach to directly reveal brain connectivity (Sala-Llonch, Bartres-Faz, & Junque, 2015; Smith et al., 2013). Here, our study utilized the most updated version (17b) of the CONN toolbox at the time when this analysis was conducted, where the component-based noise correction (CompCor)

method is implemented to improve the analysis sensitivity, selectivity, and interscan reliability (Whitfield-Gabrieli & Nieto-Castanon, 2012).

Results

Two out of the 23 participants had missing behavioral data. Another two participants had only their practice performance available, with above 70% accuracy for both of them. Of the remaining 19 participants, 11 participants had technical issues with the performance data recorded. They had 10-50% trials with undefined 's' responses rather than the expected 'yes' or 'no' responses. This is presumably caused by the task programming that the 'yes' and 'no' were not exclusively set as the only two allowable response types, which permitted some actual responses to be erroneously overwritten by scanning pulses. Given this, the trials with 's' responses were taken as missing trials rather than incorrect trials and then were excluded from the actual computation of accuracy and reaction time. In addition to the 's' trials, missing responses were found in all the 19 participants that ranged from 6% to 56% of the trials. However, the recorded trials (excluding the 's' trials) regardless of their correctness were verified to be distributed throughout the entire run for each of the 19 participants, indicating that these 19 participants were most likely engaged in the whole run without being pronouncedly distracted towards the end of the run. The main purpose of the behavioral data were to act as a reassurance that the participants were attending to the task during the scan. The performance data were not entered into any analysis. Thus, we conducted some data checks below to ensure activation maps between participants with full behavioral data recording did not differ from participants with partial data recorded.

The ten participants with more than 50% trials recorded and higher than 70% accuracy in the recorded trials were grouped together, while the remaining 13 participants were taken as

another group for having more problematic behavioral data. Independent sample t-test was conducted between the imaging data of these two groups, and no difference in neural activations was found between groups with a threshold of $p < .001$ uncorrected, minimum 20 voxels. This suggests that the 13 participants with problematic response recording are likely to be equally involved in the semantic-tone task as the ten participants with better behavioral data quality, and thus their imaging data should be a valid representation of the targeted semantic aspect. In addition, the behavioral data is not needed for analysis. Therefore, all the 23 participants were included in imaging analyses to obtain a reasonable sample size with adequate statistical power.

As illustrated in Table 4-1 and Figure 4-2, whole brain analysis of the 23 participants showed that the semantic > tone condition had greater cortical activations in the left superior/medial frontal gyrus (BA8/10), the left supplementary motor area (BA6), the right cerebellum (Crus I/II), the left middle occipital gyrus (BA19), the left superior parietal lobule (BA7), the right superior temporal gyrus (BA38/48), the left hippocampus (BA20), the left pars triangularis (BA48), the left middle frontal gyrus (BA44/9), the left inferior temporal gyrus (BA20), the left fusiform gyrus (BA20), the left middle temporal gyrus (BA21), and the left pars orbitalis (BA47), thresholded at $p(FWE) < .05$, cluster size ≥ 10 voxels. The relatively conservative threshold of $p(FWE) < .05$ could diminish false-positive rates, while a cluster extent threshold of 10 voxels may avoid false alarms of overly small and unreliable effects. This threshold has recently been demonstrated to be valid and has the potential to produce replicable and dependable results (Eklund, Nichols, & Knutsson, 2015; Eklund, Nichols, & Knutsson, 2016). Corresponding brain regions and Brodmann areas (BAs) of resulted coordinates were identified using respective templates in MRICron toolbox (<https://www.nitrc.org/projects/mricron>).

Figure 4-2. The whole brain activation maps in the semantic > tone contrast, $p(FWE) < .05$, cluster size ≥ 10 voxels. O-T: occipito-temporal cortex, MTG: middle temporal gyrus, vIFG: ventral inferior frontal gyrus, MFG: middle frontal gyrus, aSTG: anterior superior temporal gyrus, SPL: superior parietal lobule

Table 4-1

Peak coordinates within the significant clusters of the whole brain activation in the semantic > tone contrast

Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>Cluster size</i>	<i>T</i>
Left superior frontal gyrus	9, 10	-15	53	34	59	9.41
Left superior/medial frontal gyri, Left supplementary motor area	8, 6	-8	27	61	94	7.94
Right cerebellum (Crus I/II)	--	42	-68	-34	32	8.39
Left middle occipital gyrus	19	-30	-76	38	94	8.02
Left superior parietal lobule	7	-27	-72	46	32	7.83
Right superior temporal gyrus	38	53	11	-15	11	7.94
Left hippocampus	20	-27	-11	-11	28	7.81
Right superior temporal gyrus	48	61	-4	-4	16	7.68

Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>Cluster size</i>	<i>T</i>
Left ventral inferior frontal gyrus (pars triangularis)	48	-46	23	27	60	7.54
Left middle frontal gyrus	44, 9	-49	15	38	27	7.09
Left inferior temporal gyrus	20	-38	-23	-23	22	7.43
Left fusiform gyrus	20	-34	-30	-19	18	6.44
Left middle temporal gyrus	21	-49	-34	-8	16	6.95
Left ventral inferior frontal gyrus (pars orbitalis)	47	-34	19	-15	14	6.84

Note. *x*, *y*, *z* coordinates: MNI space; BA: Brodmann Area. Cluster criterion: $p(FWE) < .05$, cluster size ≥ 10 voxels.

Significant functional connectivity in the semantic > tone contrast was found between the left ventral inferior frontal gyrus and the right posterior superior temporal gyrus, $t(22) = 3.18$, $p = .004$, between the left middle frontal gyrus and the right posterior superior temporal gyrus, $t(22) = 2.81$, $p = .010$, and also between the left ventral inferior frontal gyrus and the left middle frontal gyrus, $t(22) = 2.32$, $p = .030$, under a threshold of $p < .05$ (Table 4-2, Figure 4-3).

Table 4-2

Significant ROI-to-ROI functional connectivity in the semantic > tone contrast

ROI-to-ROI Connectivity	<i>t</i>(22)	<i>p</i>
Left ventral inferior frontal gyrus – right posterior superior temporal gyrus	3.18	.004
Right posterior superior temporal gyrus – left middle frontal gyrus	2.81	.010
Left ventral inferior frontal gyrus – left middle frontal gyrus	2.32	.030

Note. Threshold: $p < .05$.

Figure 4-3. Significant ROI-to-ROI functional connectivity in the semantic > tone contrast, $p < .05$. vIFG: ventral inferior frontal gyrus, MFG: middle frontal gyrus, pSTG: posterior superior temporal gyrus.

Discussion

The current Study 3a aims to examine the model proposed in Study 1 and how it applies to the Chinese auditory semantic processing at the word level using a semantic-tone task. Based on the proposed model, the word-level Chinese auditory semantic network was hypothesized to involve the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal

gyrus, and the left occipito-temporal cortex. This hypothesis is generally supported by the whole-brain activation and functional connectivity results as demonstrated below.

Consistency of Activation Results to the Proposed Model

Based on the whole-brain results in the current Study 3a, lexicosemantic > tone processing was seen to engage several regions within the proposed model, including the left occipito-temporal cortex (BA19/20), the left middle temporal gyrus (BA21), the right anterior superior temporal cortex (BA38/48), the left ventral inferior frontal gyrus (BA47), and the left middle frontal gyrus (BA44/9). The bilateral posterior superior temporal cortices that were originally hypothesized in the proposed model were not observed, while activations outside the proposed network were noted in the left superior parietal lobule (BA7), the left sensorimotor area (BA6/8/9/10), and the right cerebellum (Crus I/II).

Within the proposed model, activations in the left occipito-temporal cortex were observed in the left fusiform gyrus (BA20), the left inferior temporal gyrus (BA20), and the left middle occipital gyrus (BA19). Past studies have suggested that BA20 is more associated with orthographic representation at the higher-order linguistic level, rather than the non-linguistic visual imagery of the heard object, as visual feature extract is usually regulated by the primary visual cortex, BA17, an area posterior to BA20 (Atlas, 2013; Cohen et al., 2002; Harley, 2013; Kosslyn et al., 1999; Price, 2012; Wise & Price, 2006; Wu et al., 2012). Hence, the observed activation in the left BA20 is believed to reflect the orthographic analysis involved in spoken Chinese lexicosemantic processing rather than task-induced visual imagery. This suggests the possibility of visualization processes when listening to Chinese words, given that the Chinese visual form has greater clarity, reliability, and precision than that of the spoken form in discriminating homophones and semantic decoding. This replicates past findings (Liu et al.,

2009; Wu et al., 2009; Xiao et al., 2005; Zou et al., 2015) and also lends neurobiological support to the finding of Study 2, that orthographic information may be processed even upon hearing a word without the necessity of seeing it.

In addition to the left occipito-temporal cortex, temporal lobe activations that were hypothesized in the proposed model were also observed. It included the left middle temporal gyrus, a repository site of lexicosemantic representations (Binder et al., 2009; Friederici, 2012), as well as the right anterior superior temporal cortex (BA38/48), an area underlying basic syntactic construction such as category registration (Friederici, 2012; Herrmann, Maess, Hahne, Schröger, & Friederici, 2011; Seyedehrezvan Farahibozorg1, 2017; Wise & Price, 2006). It is of note that the anterior superior temporal lobe observed in the current Study 3a was located in the right rather than left hemisphere. Likewise, the right anterior superior temporal lobe has also been reported in Wu et al.'s study (2009), which used a semantic dangerousness task that required word categorization (dangerous or not). This is not surprising based on previous findings (Friederici, 2012; Herrmann et al., 2011), where word category information was believed to be registered in the anterior superior temporal gyrus bilaterally.

In the frontal lobe, activations were shown in the left ventral inferior frontal gyrus, an area supporting controlled retrieval of stored semantic representations, as well as the left middle frontal gyrus, a region thought to be specialized for lexical coordination in the Chinese language (Lee, Booth, Chen, & Chou, 2011; Liu et al., 2009; Liuzzi et al., 2017; Poldrack et al., 1999).

Overall, the occipito-temporo-frontal involvement is consistent with the proposed model, and may subserve the precise extract/categorization of the biological (i.e., living or not) and physical (i.e., bigger than a cat or not) features of the incoming spoken word under the modulation of the higher-order frontal lobe.

Other than the expected findings above, the hypothesized activity to be seen in the bilateral posterior superior temporal lobes failed to surpass the threshold of $p(\text{FWE}) < .05$ in the semantic > tone contrast. It is plausible that activity in these auditory regions was probably obscured by the tone baseline, as the posterior temporal speech areas are very likely to be intensely elicited by non-speech sounds such as the tones in the current study ((Binder et al., 1999)Price, 2012(Cabeza & Kingstone, 2006)).

Regions outside our proposed model were also observed. The activation seen in the left superior parietal lobule was likely involved due to visuospatial analysis that was needed in the semantic but not the tone condition, where the size of the object indicated by a heard noun had to be analyzed and compared with the size of a cat. This implication is based on the role of this area in visuospatial analysis of objects (Haxby et al., 1991), visual search, and spatial selective attention (Booth et al., 2003).

It is also interesting to note that the left sensorimotor cortex had consistent activation in the Chinese visual semantic meta-analysis in Study 1 as well as in the current Study 3a. However, this region was not considered in our proposed model, in that its activity appears to be less relevant to the semantic-related processing of interest. In Study 3a, the recruitment of the left sensorimotor cortex is more likely to be attributed to the covert articulation of the heard words that were automatically induced in the semantic but not tone condition. Activity in the left sensorimotor cortex is unlikely due to motoric processes for button responses, as the motoric activity evoked by the button-press appears to be cancelled out after contrasting the semantic condition to the tone baseline.

In addition to the cerebral activations stated above, cerebellar activity in the right posterolateral cerebellum (Crus I/II) was also observed. Past empirical and meta-analytic studies

have accumulated evidence for the preferential sensitivity of the anterior and posterior cerebellum to sensorimotor functions and higher-order cognitive processes, respectively (Chen & Desmond, 2005; E, Chen, Ho, & Desmond, 2014; Stoodley & Schmahmann, 2009). Thus, the current observation of the posterolateral cerebellum in the semantics > tones contrast likely implies its involvement in the higher-order language functioning. Interestingly, in contrast to the left lateralization of cerebral network underlying language processing, the present results showed cerebellar activity in the right hemisphere, reflecting crossed cerebro-cerebellar projections as reported by past studies (E et al., 2014; Stoodley & Schmahmann, 2009). In addition, the right Crus I/II has been suggested to subserve linguistic predictability, error adjustment, and phonological but not orthographic or semantic processing (E et al., 2014; Lesage, Hansen, & Miall, 2017). Thus, the current observation of the right Crus I/II activities was likely associated with the phonological decoding of the word heard as well as participants' prediction of the characteristics of the upcoming word heard (e.g., whether it denotes a living thing bigger than a cat) but not directly involved with semantic processing.

Overall, activations consistent with the proposed model were found in the left occipito-temporal cortex, the left middle temporal gyrus, the right anterior superior temporal gyrus, the left ventral inferior frontal gyrus, and the left middle frontal gyrus, beyond the influence of task requirement. Due to sensitivity to task properties, minor inconsistencies are also noted between the proposed model and the bilateral posterior superior temporal lobes, the left superior parietal lobule, the left sensorimotor cortex, and the right cerebellum (Crus I/II). These inconsistent regions are mostly situated in the dorsal stream except for the cerebellar regions (Hickok & Poeppel, 2000; Rauschecker, 1998; Scott & Wise, 2004; Wise et al., 2001), supporting the view that the degree of activity in the auditory dorsal stream is more sensitive to task variation

compared to the auditory ventral stream (Hickok & Poeppel, 2007). As these inconsistent regions were mostly attributable to the task administered rather than lexicosemantic processing, these regions do not invalidate the proposed model.

The Functional Connectivity Pattern within the Predefined Network

To isolate the auditory semantic processing of interest from irrelevant processes driven by task demands, and also to reveal potential interactions between the regions of the Chinese auditory semantic network, functional connectivity was examined within the network that was predefined in the meta-analysis of Study 1. Results showed that the semantic relative to tone condition had greater connectivity between the right posterior superior temporal gyrus, the left middle frontal gyrus, and the left ventral inferior frontal gyrus. This indicates an intensely interconnected subnetwork amongst these three regions plausibly related to the facilitation of the sensori-to-semantic transformation. It is thought that the right auditory cortex may be engaged with coordination of the complexity of acoustic features (e.g., pitch frequencies, spectral properties) that is greater in spoken words than tones, while the left middle frontal gyrus is involved in integrating word form and meaning at the lexical level (Price, 2012). The activity seen in the right posterior superior temporal gyrus and the left middle frontal gyrus in tandem with the left ventral inferior frontal gyrus, could possibly be related to the retrieval of the targeted meaning from a spoken word at greater precision. These three regions may serve as nodes to link and converge information from discrete brain sites, providing support for a Chinese auditory semantic network of regions that are highly interconnected.

As reviewed earlier, the left posterior temporal lobe and the left frontal lobe have been demonstrated to be anatomically connected via the inferior fronto-occipital fasciculus to support the normal Chinese semantic functioning (Han et al., 2013), and also functionally interconnected

to subserve Chinese visual lexicosemantic processing (Fan & Chou, 2012; Fan et al., 2010; Wu et al., 2009). In contrast to the intra-hemispheric connections reported in these previous studies, the current study observed connectivity between the left frontal lobe and the right posterior temporal lobe across the two hemispheres. The involvement of the right rather than left posterior temporal lobe may again be linked to the non-linguistic acoustic differences between the current semantic and the tone conditions, such as the pitch frequencies (e.g., contour or level) and spectral properties (e.g., wide or narrow). According to the cortical asymmetry model (McGettigan & Scott, 2012), the right temporal lobe is more sensitive to certain aspects of the acoustic signal compared to the left temporal lobe. Therefore, the currently seen inter-hemispheric connectivity between the left frontal lobe and the right posterior temporal lobe may arise from the fact that the task was presented aurally, and also from considerable acoustic differences between the semantic and tone conditions. Nevertheless, the current finding may still provide the first evidence for the significance of the fronto-temporal connectivity in sensori-to-semantic transformation during Chinese lexicosemantic processing, specifically in the auditory domain.

Based on the current results, the significant activation and functional connectivity between the left middle frontal gyrus and the left ventral inferior frontal gyrus highlight these to be core regions for Chinese auditory lexicosemantic processing. Although the right posterior superior temporal cortex was not significantly activated in the whole-brain functional map, it was functionally connected with the left frontal regions during auditory semantic processing. This was likely because acoustic processing alone may not be sufficient to facilitate the performance of the auditory semantic-tone task, where the task performance may need the coordination of acoustic processing with higher-order semantic integration/selection. Apparently, the

interregional functional connectivity reveals some unique neural mechanisms not observable through activation patterns. This ascertains the need to consider the function of an area within the neural network of which it is a part (Hickok & Poeppel, 2007; Price, 2012), so as to better understand how different brain regions interact with one another in the attempt to comprehend spoken Chinese words.

Limitations

Despite careful considerations of possible confounds, our study is not without limitations. Our task used a tone condition as the baseline. One could argue that the resultant semantic > tone contrast may not tightly target the auditory semantic network of interest given the existence of other differences between the semantic and tone conditions, such as pitch frequencies (e.g., contour or level), spectral properties (e.g., wide or narrow), and whether the stimulus was linguistic (e.g., phonological processing involved or not). This semantic-tone task was adapted from Binder and colleagues' (1997), where the original task was devised to elicit auditory semantic network while controlling for automatic nonlinguistic processing such as involuntary sensorimotor, attentional activities, and executive functioning in the tone baseline (Binder et al., 1997; Binder et al., 1995; Demonet et al., 1992; Yang et al., 2009). Previous studies using this task paradigm also showed a robust and reliable activation of the auditory semantic network (Binder et al., 1999; Cabeza & Kingstone, 2006; Perani et al., 1996; Price, Wise, & Frackowiak, 1996). Nevertheless, future studies may consider designing a more comparable baseline in investigations of auditory lexicosemantic processing.

The missing behavioral data as a result of technical difficulties was not ideal. It prevented further analyses of behavior-brain correlation, behavior-brain regression, and ANCOVA with accuracy/latency as a covariate were not conducted. However, these analyses appear to be less

necessary for Study 3a, where all participants were young adults with relatively low variability in performance. Nevertheless, analysis on the remaining recorded trials showed that they were distributed throughout the entire run, partially ascertaining participants' sustained attentiveness and engagement in the task performance. There was also no significant difference in neural activity between the participants who had more or less missing behavioral data, which may imply that the functional data were not likely to be different between these participants. As such, all the 23 participants were included for image analysis to ensure adequate sample size and statistical power.

Lastly, we only investigated functional connectivity in this study and was not able to determine the directional influence from one region to another. Thus, the potential bottom-up and top-down processes could not be differentiated based on the current connectivity results. However, we did not conduct effective connectivity analysis as it required a well-defined model for model comparisons. It is difficult to ascertain such a model given the limited existing studies. Hopefully, more studies evaluating the Chinese auditory semantic network will be available in the future to help determine a well-defined network model that will allow effective connectivity to be examined.

Summary of Study 3a

The Chinese auditory semantic network proposed in Study 1 is generally supported by Study 3a. Results showed that activations within the proposed network were observed in the left occipito-temporal cortex, the left middle temporal gyrus, the right anterior superior temporal gyrus, the left ventral inferior frontal gyrus, and the left middle frontal gyrus. The bilateral posterior superior temporal lobes that were expected in the proposed network did not show significant activations. This is possibly obscured by the auditory processing of the tone baseline,

as the bilateral auditory areas appear not to be linguistic specific but are instead responsive to nonlinguistic tones as well (Price, 2012). Nevertheless, co-activity between the right posterior superior temporal cortex and frontal areas was noted in functional connectivity results, indicating the involvement of the posterior superior temporal cortex in Chinese auditory lexicosemantic processing.

In summary, the semantic network of spoken Chinese words is thought to involve the regions of the proposed model, including the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex. Within this Chinese auditory lexicosemantic network, the right posterior superior temporal gyrus, the left middle frontal gyrus, and the left ventral inferior frontal gyrus were identified as an interconnected subnetwork using functional connectivity analysis. This verifies the significance of the fronto-temporal connectivity in Chinese lexicosemantic network specifically in the auditory domain.

STUDY 3b: SENTENCE-LEVEL VALIDATION

Introduction

Everyday interpersonal communication mostly emphasizes speech comprehension. Speech is usually relayed in sentences, which comprise sets of words but convey meanings far more abundant than the simple sum of the constituent words. Spoken sentence comprehension thus relies not only on the identification of individual spoken words, but also on the contextual information giving rise to the expected meanings. These meanings of individual spoken words in a sentence are determined by the words preceding and following it, and the frequency of such occurrence (Li, 2002). In a Chinese sentence, the lack of grammatical inflections such as word category, case, number, and person (Xu, 1997; Ye, Luo, Friederici, & Zhou, 2006) therefore places greater reliance on the word order in Chinese sentence comprehension. Every word in a sentence must be placed in an appropriate sequence to be compatible with the remaining words in the sentence; changing one word or the position of the word sometimes may completely alter the sentence meaning (Comrie, 1989; Perfetti & Adlof, 2012; Whaley, 1996). It is thus interesting to understand how the brain allows a Chinese listener to sequentially bind the isolated words into a coherent sentence so that additional information not contained in the single words could be delivered.

Based on the Chinese auditory semantic model proposed in Study 1, sentence processing is expected to involve the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex. However, the only study that assessed Chinese auditory semantic processing using sentence stimuli (Xu et al., 2013) appeared

not to be ideal enough to examine this proposed model. In Xu et al.'s study (2013), listening to the scrambled sentence composed by randomly-selected words compared with the sentence consisting of misplaced-consonant syllables elicited stronger activations in the left occipito-temporal cortex (BA37/20), the left middle temporal gyrus (BA21), and the left ventral inferior frontal gyrus (BA47), which appears to partly support our proposed Chinese auditory semantic model. However, this activation pattern is essentially more representative for lexicosemantic processing rather than for sentence-level semantic processing, although sentence-level stimuli were utilized in this study (Xu et al., 2013). The aim of Xu et al.'s study (2013) was to investigate whether lexical meaning can be accessed in pitch-flattened (monotone) sentences in tonal languages like Mandarin Chinese. Therefore, the contrast of scrambled sentences and misplaced consonant sentences was used as a 'localizer' to localize regions responsible for accessing meaning to words but not to sentences, supposing word intelligibility was the major difference between these two types of sentences: scrambled sentences were syntactically anomalous and unintelligible at the sentence level, while the consonant replacement led to syntactic anomaly and unintelligibility at the levels of both words and sentences. Given the actual differences between the two conditions, the compatibility of sentence-level processing with our tentative model still remains unanswered.

There is limited literature about language networks for spoken Chinese sentence comprehension, and even less knowledge is available for the interregional connectivity pattern underpinning this process. It is not far-fetched to presume that the underlying anatomical networks for Chinese semantic processing (Han et al., 2013) also support Chinese auditory sentential comprehension. Thus, the semantic processing of spoken Chinese sentences would

likely involve the left inferior fronto-occipital fasciculus via the posterior lateral temporal cortex and frontal cortex as indicated for semantic comprehension.

As with anatomical connectivity, only one study has investigated functional connectivity underlying Chinese sentential semantic processing (Li, Jiang, Yu, & Zhou, 2014). However, sentence stimuli in this study were presented visually instead of aurally. Results showed that the incongruent > congruent contrast produced stronger functional connectivity between the left/right ventral inferior frontal gyrus and several inhibitory-related regions such as BA40 and BA46, suggesting that the comprehension system attempted to suppress or replace the semantically-violated word in a given incongruent sentence (e.g., ‘连这么大的声音张都能听清楚，太敏锐了。’ /lian2 zhe4 me da4 de1 sheng1 yin1 zhang1 dou1 neng2 ting1 qing1 chu3, tai4 min3 rui4 le/ *Even such a loud sound can be heard by Zhang; he has a sharp hearing.*). However, the authors did not examine congruent > incongruent conditions, which could provide more information regarding semantic comprehension without conflict. Nevertheless, the finding from this study is valuable to the understanding of the functional connectivity specific to Chinese sentence comprehension.

Given the limited investigation into the semantic neuro-mechanisms underlying spoken Chinese sentence processing, Study 3b is conducted to fill this research gap. We used an archival fMRI data set collected from 22 native Mandarin Chinese participants performing a forward-backward passive listening task. This task paradigm allows us to identify the sentential semantic component through the forward > backward contrast, since the sentence-level semantic information that was intact in the forward condition was largely eliminated in the backward baseline. Based on the preliminary model proposed in Study 1, whole-brain activation results could be hypothesized to involve the bilateral posterior superior temporal lobes, the left middle

frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the left occipito-temporal cortex. To identify the interconnections within the Chinese auditory semantic network proposed in Study 1, ROI-to-ROI functional connectivity patterns would also be examined. Based on these investigations, the preliminary model can be further refined to include auditory comprehension of Chinese spoken sentences.

Methods

Participants

The same group of the 26 native speakers of Mandarin Chinese in Study 3a performed an auditory passive listening task in Study 3b. The three male participants excluded from Study 3a were also excluded from Study 3b due to poor image quality. Another male participant was excluded due to missing data from the follow-up sentence comprehension test and his engagement in the passive listening task could not be verified. The remaining 22 right-handed participants (12 females; mean age = 25.7 years, SD = 4.3 years, range = 19-35 years; mean handedness score = 87.2, SD = 17.8, range = 42.8-100) were included in subsequent data analysis.

Procedure

A blocked design passive listening task that was adapted from Maldjian et al. (2002) was employed. Participants were instructed to listen to a short story played for 30 sec in the forward block, and listened to the same text played backwards for another 30 sec in the backward block. It is of note that the audio in the backward condition was a complete reversal of the forward audio. Thus, the backward audio was not comprehensible at either the lexical or the sentential level. Five forward blocks and five backward blocks were alternated in one run (Figure 4-4).

This task was considered to provide a well-matched between-condition comparison, as both forward and backward conditions had the same spectral information profile and acoustic stimulation but mainly differed in their meaningfulness. Although no response was required for the task, participants' concentration on the task was assessed by a follow-up comprehension test after the scan, which included ten questions requiring responses of 'right' or 'wrong' with no response time-limit.

Figure 4-4. The condition sequence in the run in Study 3b.

Image Acquisition

Participants were imaged in a 3 Tesla Trio MRI scanner with a 12-channel head coil at National Taiwan University Hospital. Imaging acquisition parameters were the same as those described in the Image-Acquisition section in Study 3a.

Image Analysis

SPM8 was employed for the imaging analyses. The neuroimaging data went through the same preprocessing steps as in Study 3a, as specified in the Image-Analysis section (Page 88-89). After preprocessing, whole brain activation maps in the forward > backward contrast were obtained for each participant. Group activations across all participants were computed in the forward > backward contrast using a one-sample t-test.

Using the same set of ROIs detailed in Study 3a, functional connectivity between every pair of the ROIs was calculated in the forward > backward contrast by CONN 17b (<https://www.nitrc.org/projects/conn>) implemented in SPM8.

Results

In the comprehension test that followed the passive listening task, the 22 participants had a mean accuracy of 86% (SD = 0.08, range = 70-100%) and a mean reaction time of 2,863 ms (SD = 2,593 ms, range = 1,413-12,504 ms). This accuracy ascertained participants' attentiveness and engagement in the passive listening task, so that the neuroimaging results are supposed to reflect the neural network that supports speech comprehension rather than perception.

Table 4-3 and Figure 4-5 shows the whole brain activity maps of the 22 participants, where forward condition had greater activations than backward condition in the left superior temporal gyrus (BA38), the right superior temporal gyrus (BA22), the left middle temporal gyrus (BA21), the right middle temporal gyrus (BA38), the left supplementary motor area (BA6), and left precentral gyrus (BA6), at $p(FWE) < .05$, cluster size ≥ 10 voxels. This threshold has been shown to minimize false-positive rates as well as to produce replicable and dependable results (Eklund et al., 2015; Eklund et al., 2016). Corresponding brain regions and Brodmann areas (BAs) of resulted coordinates were identified using respective templates in MRICron toolbox (<https://www.nitrc.org/projects/mricron>).

No significant functional connectivity was observed between any pair of ROIs in the forward > backward contrast, at a threshold of $p < .05$.

Figure 4-5. The whole brain activation maps in the forward > backward contrast, $p(FWE) < .05$, cluster size ≥ 10 voxels. MTG: middle temporal gyrus, aSTG: superior temporal gyrus, pSTG: posterior superior temporal gyrus

Table 4-3

Peak coordinates within the significant clusters of the whole brain activation in the forward > backward contrast

Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	Cluster size	<i>T</i>
Left superior temporal gyrus	38	-57	8	-15	283	11.53
Left middle temporal gyrus	21	-65	-8	-11	20	9.65
Left supplementary motor area	6	-8	8	61	13	8.67
Right middle temporal gyrus	38	57	11	-19	31	8.18
Left precentral gyrus	6	-42	0	46	16	7.97
Right superior temporal gyrus	22	57	-19	-4	24	7.72

Note. *x*, *y*, *z* coordinates: MNI space; BA: Brodmann Area. Cluster criterion: $p(FWE) < .05$, cluster size ≥ 10 voxels.

Discussion

The current Study 3b examined on how the model proposed in Study 1 applied to the Chinese auditory semantic processing at the sentence level using a passive listening task. Based on the proposed model, Chinese auditory sentential semantic network was hypothesized to involve the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, the left middle temporal gyrus, and the occipito-temporal cortex. The current whole-brain results suggest the involvement of all the above regions except the occipito-temporal cortex in the sentence-level Chinese auditory semantic model, which will be discussed below.

Consistency of Activation Results to the Proposed Model

Activations within the regions of the proposed network were observed in the bilateral middle temporal gyri (BA21/38), the left anterior superior temporal gyrus (BA38), and the right posterior superior temporal gyrus (BA22). No significant activity was found in the left middle frontal gyrus, left ventral inferior frontal gyrus, and occipito-temporal cortex, areas that were originally hypothesized in our proposed model. Meanwhile, unexpected activity of the left sensorimotor area (BA6) was noted, which was likely attributed to the covert articulatory repetition during the forward but not backward audio listening.

Within the model, the bilateral middle temporal gyri as the lexicosemantic hubs were probably recruited for the lexicosemantic processing involved in the forward but not the backward condition (Humphries, Binder, Medler, & Liebenthal, 2007). In contrast to the middle temporal gyrus which underpins lexicosemantic storage, the left anterior temporal lobe (BA38) is usually involved in grouping words into a larger unit for sentence-level comprehension (Awad et al., 2007; Jobard et al., 2007). The role of the anterior temporal lobe in semantic associations is

supported by a meta-analysis of 164 semantic-related neuroimaging studies (Visser et al., 2010), where this region is identified to be steadfastly activated in past studies to aid combinational semantic representation, above and beyond the influences of stimuli or tasks (e.g., passive listening, passive reading, semantic judgment). In addition to the function of sentential semantic composition, the current involvement of the left anterior temporal lobe (BA38) may also be related to its role in building basic syntactic structure such as quantifier or prepositional phrases (Bornkessel & Schlesewsky, 2006; Brennan et al., 2012; Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Hickok & Poeppel, 2007; Saur et al., 2008; Wise & Price, 2006). Structurally, partial segregation within the left anterior temporal cortex has been reported in the literature (Humphries, Binder, Medler, & Liebenthal, 2006), where the most anterior portion of it responds to basic syntactic manipulations, and a posterior partition is likely to represent the syntactic and semantic interactions. This functional and structural evidence points to a combinatorial role of the left anterior temporal lobe in compositional semantic operations as well as in the basic syntactic building.

The observed activity of the right posterior superior temporal cortex may arise from prosodic computation as well as complex syntactic analysis. On the one hand, this area is recruited probably to cope with greater prosodic processes involved in the intelligible speech than unintelligible backward sounds (McGettigan & Scott, 2012; Xu et al., 2005; Zatorre & Belin, 2001). On the other hand, processing complex syntax might also contribute to the greater activation in the right posterior superior temporal cortex in the forward > backward contrast (Friederici, 2012; Friederici, Makuuchi, & Bahlmann, 2009).

It is known that Chinese sentences do not entail grammatical inflections that mark word category (e.g., happy, happiness), case (e.g., I wish, he wishes), number (e.g., cat, cats), time

tense (e.g., is, was, been), person (e.g., he, him), and so on. (Xu, 1997; Ye et al., 2006). Thus, the semantic access of Chinese sentences may require emphasis on the serial word order imposed by syntactic structure, where every word in a sentence must be embedded in an appropriate position and compatible with the words preceding and following it; scrambling the word order will alter the sentence meaning in its entirety (Comrie, 1989; Perfetti & Adlof, 2012; Whaley, 1996).

Therefore, the syntactic analysis represented in the posterior superior temporal lobe is probably at a relatively complex level, such as sequencing compositional audio words and updating context accordingly. This is contrasted to the above left anterior temporal lobe which regulates basic syntactic building. The respective parts of the left anterior temporal lobe and posterior superior temporal cortex in basic syntactic building and complex syntactic analysis likely imply that grammatical processing is not localized to one single region, but rather is instantiated in a network involving the anterior and the posterior temporal systems (Caplan, Hildebrandt, & Makris, 1996; Hickok & Poeppel, 2004).

Our study also revealed null findings in several regions hypothesized in the proposed model. These regions included the occipito-temporal cortex, the left middle frontal gyrus, and the left ventral inferior frontal cortex. The lack of activity in the occipito-temporal visual cortex possibly implied that the homophone disambiguation during Chinese sentence listening may require less visualization of heard speech when the scaffold of sentence context and syntax is available. Although the left occipito-temporal cortex was reported in Xu et al.'s study (2013), it could not be taken as evidence for the involvement of orthography in Chinese sentence listening. This is because the contrast of scrambled > misplaced consonant sentences in Xu et al.'s study (2013) was more likely to target lexicosemantic rather than sentence-level semantic processing despite the use of sentence stimuli. Interestingly, the lack of significant occipito-temporal

activations in the current sentence-level study is contrasted to the observed activation in the occipito-temporal cortex in Study 3a where word stimuli were used. Taken together, these findings suggest that the orthographic involvement in Chinese auditory semantic processing, which was found in Study 2, may be more applicable to word-level rather than sentence-level processing.

The apparent lower need for speech-to-print conversion in spoken Chinese sentences may also contribute to the lack of significant activation seen in the left middle frontal gyrus, given the possible role of this region in assigning the represented syllable to a Chinese character (Hu et al., 2010; Siok et al., 2008). On the other hand, given the lack of significant activations in the left ventral inferior frontal cortex in addition to this left middle frontal gyrus, the general absence of significant left inferior/middle frontal activations is more likely to be attributed to the task effect (Cabeza & Kingstone, 2006). Listening to normal sentences with no behavioral response requirement might invoke a relatively low cognitive load in the forward condition as in the backward baseline. Thus, subtracting the neural activity of backward from forward condition is likely to cancel out the expected left inferior/middle frontal activations, given the possible role of the left frontal lobe in cognitive control processes (Brass, Derrfuss, Forstmann, & von Cramon, 2005; Derrfuss, Brass, Neumann, & von Cramon, 2005; Koechlin, Ody, & Kouneiher, 2003).

Overall, activations consistent with the proposed network were observed in the bilateral middle temporal gyri, the left anterior superior temporal gyrus, and the right posterior superior temporal gyrus. Within the proposed network, the lack of significant activation in the occipito-temporal cortex implies that visualization of the sentences heard may be less necessary to the listening comprehension of Chinese sentences due to the availability of contextual and grammatical scaffolding in sentences. Thus, the current study would not suggest the inclusion of

the occipito-temporal cortex in the adjusted network at the sentence level. In contrast, inconsistencies were observed between the proposed network and recruitment of the left middle frontal gyrus, the left ventral inferior frontal gyrus, and left sensorimotor cortex, which could be a result of task sensitivity. Hence, the sentence-level Chinese auditory semantic network is still thought to involve the left middle frontal gyrus and the left ventral inferior frontal gyrus while not involve the left sensorimotor area. These findings help develop the model to differentiate sentence-level semantic processing to include the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, and the left middle temporal gyrus from the word level processing that additionally included the occipital-temporal gyrus.

The Functional Connectivity Pattern within the Predefined Network

Within the predefined Chinese auditory semantic network, none of the ROI-to-ROI functional connectivity was significant in the forward > backward contrast. The null result is likely because the higher-order interregional coordination was less needed by the forward condition where no responses were required. It is also possible that participants may be in a semi-resting state when listening to the backward speech, as the stimuli were incomprehensible. This may allow self-thoughts or contemplation to occur, which might induce semantic-like co-activation in the backward baseline, obscuring the functional connectivity patterns that might be present for the forward > backward contrast. However, these are speculations which would require further studies with more precise task paradigms to isolate sentence-level semantic processing mechanisms.

Limitations

The current study employed an archival data set that may lead to some concerns for the validity of the task paradigm for examining auditory sentence comprehension. It is plausible that linguistic components other than sentential semantic processing of interest differed between the current forward and backward conditions. These aspects of non-interest included syntactic parsing, prosody, word segmentation, word recognition, lexical access, and temporal sequence, and thus could partially confound activations supposedly observed for sentential semantic processing. However, the forward and the backward sounds seemed to be comparable in low-level spectral information profile and acoustic stimulation, allowing for the sentential-level semantic and syntactic aspects to be mainly distinguished after the forward > backward comparison. Nevertheless, future studies may still consider using a more closely matched baseline such as ‘musical rain,’ which is also scrambled and unintelligible, but with fine-temporal dynamics better matched to the normal speech.

Summary of Study 3b

The preliminary Chinese auditory semantic model proposed in Study 1 is generally supported by the sentence-level activation pattern in Study 3b, where activations were observed in the right posterior superior temporal gyrus, the left anterior superior temporal gyrus, and the left middle temporal gyrus. Inconsistencies between the proposed network and several regions were also noted. The supposed activations in the left middle frontal gyrus and left ventral inferior frontal gyrus were not significant, likely due to task effect rather than the sentential semantic processing of interest. Thus, the sentence-level Chinese auditory semantic network is still thought to involve the left middle frontal gyrus and left ventral inferior frontal gyrus. In contrast, the lack of occipito-temporal activity is more likely associated with the sentence-level

processing, and thus this region may be less crucial to the Chinese auditory semantic processing at the sentence level. Overall, our findings suggest a differentiated model for Chinese auditory sentential-level semantic processing that involves the bilateral posterior superior temporal lobes, the left middle frontal gyrus, the left ventral inferior frontal gyrus, the left anterior superior temporal cortex, and the left middle temporal gyrus, excluding the occipito-temporal cortex which was found in the word-level processing in Study 3a.

Summary of Study 3a and Study 3b

Based on the results in Study 3a and Study 3b, the Chinese auditory semantic model proposed in Study 1 is examined and further refined to the word-level and sentence-level processing, respectively. In Chinese auditory lexicosemantic processing, the neural network can be differentiated into a word-level processing network that includes the left occipito-temporal cortex, the left middle temporal gyrus, the bilateral posterior superior temporal lobes, the left anterior temporal lobe, the left ventral inferior frontal gyrus, and the left middle frontal gyrus, as well as a sentence-level processing network that may have similar regions except the occipito-temporal visual cortex. In addition, within the Chinese auditory semantic network predefined in Study 1, the right posterior superior temporal gyrus, the left middle frontal gyrus, and the left ventral inferior frontal gyrus were found to be an interconnected subnetwork to facilitate Chinese auditory lexicosemantic processing in Study 3a.

CHAPTER V: GENERAL DISCUSSION

During semantic comprehension, listening has primacy over reading in the history of humankind as well as an individual's lifetime, and is also more frequently utilized in everyday language communication. To date, most existing models of auditory semantic processing are based on alphabetically written languages like English. It is unclear whether and how these models are compatible with character-based Chinese language, given the linguistic differences between Chinese and English. While the semantic representation in English seems to be more easily retrieved from the spoken than written form, visual Chinese forms are presumably less ambiguous and more suggestive to semantic access than auditory forms, due to the existence of pervasive homophones and semantic radicals in the Chinese language. It is thus meaningful to propose an auditory semantic model specifically for the Chinese language.

The current thesis aimed towards this goal by assessing the behavioral and neural correlates of Chinese auditory semantic processing in three studies. Study 1 postulated a tentative neurocognitive model specifically for Chinese auditory semantic processing. Using a meta-analytic approach, past findings were quantitatively collated to characterize the similarities and differences between Chinese and English semantic neuro-networks. A preliminary model specific to Chinese auditory semantic processing was then proposed. Study 2 attempted to supplement this model from a behavioral perspective and evaluated whether orthographic representation was involved in Chinese auditory semantic processing in the absence of the visual form. This is contrasted with a baseline of orthographic involvement in Chinese visual semantic processing. Study 3 further refined the proposed network model, where two separate neuroimaging data sets were employed to test the model specialization for words (study 3a) and sentences (study 3b), respectively. Overall, this series of research provides meta-analytic, behavioral, and neurobiological evidence for a preliminary Chinese auditory semantic model.

Their corroborative findings may advance our understanding of the linguistic, behavioral, and neurobiological correlations underlying Chinese auditory semantic processing.

Summary of the Findings of Each Study

The meta-analysis in Study 1 helped set the stage for the proposal of Chinese semantic model. The ALE meta-analysis of the existing literature computed which cortical regions had significant involvement in Chinese relative to English visual semantic processing. Through this analysis, we were able to identify overlapping networks between Chinese and English visual semantic processing (Table 2-2b3, Figure 2-2b3), and delineate a visual semantic network specialized for Chinese (Table 2-2a1, Figure 2-2a1). This preliminary model for Chinese semantic processing in the visual domain included the right occipito-temporal cortex, the left middle temporal gyrus, the left ventral inferior frontal gyrus, and the left middle frontal gyrus. Analogously, the corresponding model in the auditory domain was proposed to be likely parallel to that in the visual domain, with the addition of the bilateral posterior superior temporal cortices but not the right occipito-temporal cortex as the information was not visually presented as seen in Figure 2-3 and Figure 5-1a.

Next, to ascertain the involvement of the visual cortex activation reported in Chinese auditory semantic studies, Study 2 was conducted to investigate the role of Chinese visual form in auditory semantic processing. Forty-eight native speakers of Mandarin Chinese performed a synonym judgment task in both visual and auditory sessions, where task conditions were manipulated so that two of the four conditions in each session only differed in orthographic similarity. After controlling for several possible confounds, the auditory-priming non-synonym (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]) had a longer processing time than the visual- and auditory-priming non-synonym (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/

catalog]) in the auditory session, possibly resulting from the heavier visualization load in the former condition due to its lack of visual priming. In contrast, without such visualization needed in Chinese reading, the effect of orthography appeared to be absent from Chinese visual semantic processing. These results were likely amongst the first behavioral evidence for us to directly infer the involvement of Chinese visual form in auditory semantic processing, where no visual print was physically presented.

To further test the specificity of the proposed model to word-level (Study 3a) and sentence-level (Study 3b) processing, respectively, two archival fMRI data sets acquired from one group of Mandarin Chinese native speakers were utilized in Study 3. While Study 3a administered an auditory semantic-tone task using words as stimuli and requiring responses from the participants, participants in Study 3b passively listened to a series of sentences with no responses required. Based on the whole-brain activation results, the proposed model showed differential networks for word- (Study 3a) and sentence-level (Study 3b) processing. Consistent with the originally proposed model, the word-specific model appears to involve the left occipito-temporal cortex, the left middle temporal gyrus, the bilateral posterior superior temporal lobes, the anterior superior temporal lobe, the left ventral inferior frontal gyrus, and the left middle frontal gyrus (Figure 5-1b). As for sentence-level processing, all the regions specified in the proposed model are thought to be involved except for the occipito-temporal visual cortex (Figure 5-1c), as bottom-up visualization process seems to be less needed due to the availability of top-down contextual control in sentence processing.

To identify the possible interconnections amongst the regions of the proposed network, functional connectivity was conducted between the ROIs that were predefined in Study 1. Results in Study 3a showed that the right posterior superior temporal gyrus, the left middle

frontal gyrus, and the left ventral inferior frontal gyrus were intensely interconnected within the proposed network, probably to subserve Chinese auditory lexicosemantic processing. In contrast, no significant functional connectivity was observed during Chinese auditory sentential semantic processing in Study 3b, likely due to the low-demanding task conditions. This calls for future studies of functional connectivity to utilize a more active task with a more comparable baseline.

Figure 5-1. Visual comparisons between (a) the preliminary Chinese auditory semantic network proposed in Study 1, (b) the word-level network suggested by Study 3a, and (c) the sentence-level network suggested by Study 3b. The images are displayed in the neurological convention. MFG: middle frontal gyrus, vIFG: ventral inferior frontal gyrus; aSTG: anterior superior temporal gyrus, MTG: middle temporal gyrus, pSTG: posterior superior temporal gyrus, O-T: occipito-temporal cortex. Using the MarsBaR toolbox, each region was created as an 8mm sphere centered at the peak coordinate that were identified from the meta-analysis result of Chinese visual or English auditory data set in Study 1 (Table 2-2a1 and Table 2-2c). Please see Page 89-90 for more details.

A Preliminary Chinese Auditory Semantic Model

Findings from Study 1 to 3 converge to a plausible Chinese auditory semantic model, which shows slight specialization for word-level and sentence-level processing, respectively (Figure 5-1b&c). The word-specific and sentence-specific models are both thought to involve the left middle temporal gyrus, the left anterior temporal lobe, the bilateral posterior superior temporal lobes, the left ventral inferior frontal gyrus, and the left middle frontal gyrus. In

addition to these regions, the left occipito-temporal cortex appears to be additionally involved in word-level but not sentence-level processing.

By relocating the above Chinese model back to the whole picture incorporative of various writing systems, the current Chinese model seems to largely replicate the models that are mainly grounded on alphabetic writing systems (Table 2-2b3 and Figure 2-2b3). However, Chinese semantic processing appears to elicit little dorsal-stream activation in the left inferior parietal lobule while have greater recruitment of the left middle frontal gyrus in the ventral stream as compared to the networks seen in alphabetic languages (Table 2-2b and Figure 2-2b). This neurobiological difference is construed to be wired by the specific linguistic nature of Chinese (Ehrich, 2009). Unlike English processing that involves the left inferior parietal lobule in sound assembly from the constituent phonemes, Chinese is characterized as assigning a syllable to a given character with the involvement of the left middle frontal gyrus (Perfetti & Liu, 2005; Tan et al., 2005; Wang et al., 2015).

Interestingly, the dissociation of the left and right occipito-temporal cortices observed in the English and Chinese visual semantic meta-analyses (Table 2-2b, Figure 2-2b) appears to be absent from the respective language models in the auditory modality. Within the auditory domain, when spoken Chinese is presented in sentences, the occipito-temporal cortex may not be induced in either hemisphere, based on the current observation in Study 3b (Table 4-3, Figure 4-5). This possibly implies that the disambiguation of homophones during Chinese sentence listening may not require much visualization of the heard speech into the written form, owing to the scaffold of sentence context and syntax. In contrast, when spoken Chinese is presented at the word level, the occipito-temporal cortex is more likely to be activated in the left than right hemisphere, in view of past findings (Liu et al., 2009; Wu et al., 2009; Xiao et al., 2005; Zou et

al., 2015) as well as the current finding in Study 3a (Table 4-1, Figure 4-2). It suggests that the left occipito-temporal cortex is needed to discern the character meaning from the homophonic candidates during Chinese word listening (Hsiao & Cottrell, 2009). Furthermore, the left-hemispheric preference of the occipito-temporal activation in Chinese word listening also resembles that of English (Table 2-2c, Figure 2-2c), indicating the possibility of orthographic involvement in spoken word recognition in both languages. The possible interaction between sound and print during semantic processing is also plausibly evidenced by the observed activation in left inferior parietal lobule in English auditory semantic model as well as in the left middle frontal gyrus in Chinese auditory semantic model. In addition, behavioral evidence from study 2 that provided a more direct evaluation of the effect of orthography on Chinese spoken word comprehension, showed that the auditory semantic processing was faster when paired words were visually similar (e.g., ‘目的’ [/mu4 di/ *goal*] & ‘目录’ [/mu4 lu4/ *catalog*]) than dissimilar (e.g., ‘木头’ [/mu4 tou/ *wood*] & ‘目的’ [/mu4 di/ *goal*]). Integrating findings from Study 2 and 3 strongly suggest that orthographic processing is more likely to be involved in the auditory semantic processing of Chinese words than sentences.

Limitations and Future Directions

Limitations specific to each study have been stated in the corresponding chapters. The discussions below mainly focus on the threats of validity in the three studies that would lead to gaps in the model to be verified in the future.

First, the internal consistency within the entire thesis might be limited by the disparate methodologies, disparate samples, and disparate tasks employed in Study 1, Study 2, and Study 3. For example, Study 1 included the participant samples from the simplified-Chinese background as well as those from the traditional-Chinese background, while participants were

purely simplified-Chinese users in Study 2 and all traditional-Chinese users in Study 3.

Disregarding the differentiation of simplified- and traditional-Chinese in written languages, the first spoken language of all the samples in Study 1-3 was uniformly Mandarin Chinese. Given that spoken Chinese was more emphasized in the current thesis compared to written Chinese, visual differences between traditional and simplified Chinese should be less of a concern; meanwhile, the script differences within a language should be relatively minor as compared to the more pronounced differences between languages. Nevertheless, related confounds may still have been introduced. Future large-scale studies may need to consider improving the internal consistency by applying a consistent participant sample and a consistent task paradigm within one coherent project.

Second, causal relationship between brain and cognition needs to be understood, so as to further verify whether activations in the bilateral posterior superior temporal gyri and the left occipito-temporal cortex are necessary for Chinese auditory semantic processing before final determination of whether to include these regions in the model. In the current investigation, these regions do not seem to be directly associated with semantic processing, but are inferred to be crucial to the process of decoding semantic representation from verbal stimuli, given the role of the posterior superior temporal gyri and the occipito-temporal cortex in phonological and orthographic processes, respectively (Price, 2012). Meanwhile, the current evidence also seems not powerful enough to interpret or suggest the laterality of activations in these regions.

Although we tried to make inferences regarding these issues, such inferences were largely based on brain-to-cognition associations revealed by fMRI. The actual causality between these regions and Chinese auditory semantic processing still needs to be identified by other technologies such as transcranial magnetic stimulation (TMS). TMS is a non-invasive brain stimulation technique

that can provide a transient and reversible “lesion” at a more focal region, can be used as a complementary tool to interrupt the neural activity in a specific region for characterization of behavioral effects (Matthews et al., 2003). With TMS, future studies may try to transiently interrupt the activity of the left occipito-temporal cortex, for example, to assess whether response is slowed and/or accuracy is decreased during Chinese auditory semantic processing, and then to determine whether the left occipito-temporal cortex should be considered in the Chinese auditory semantic model.

Third, the functional connectivity within the Chinese auditory semantic network, particularly which at the sentence level, was still not fully clarified by the current thesis. This was likely related to the baseline condition that did not match closely enough to the task condition. To achieve greater validity and reliability of the functional connectivity analysis, future studies may attempt to utilize a task where the semantic component of interest is more precisely localized in the task > baseline contrast.

The above limitations may not cover all the possible weaknesses existing in the current thesis, but they might provide some worthy points of consideration for future research.

Conclusions

Findings in all three studies provide mutually corroborating evidence that stems from meta-analytic, behavioral, and neuroimaging perspectives, and jointly establish a Chinese auditory semantic model, with the involved regions slightly specialized for the word-level and sentence-level processes, respectively. In Chinese auditory lexicosemantic processing, the neural network is thought to include the left occipito-temporal cortex, the left middle temporal gyrus, the left anterior superior temporal lobe, the bilateral posterior superior temporal lobes, the left ventral inferior frontal gyrus, and the left middle frontal gyrus. In contrast, Chinese auditory

sentence comprehension may involve a network comprising the left middle temporal gyrus, the left anterior temporal lobe, the bilateral posterior superior temporal lobes, the left ventral inferior frontal gyrus, and the left middle frontal gyrus.

The current Chinese model appears to be generally consistent with alphabetic writing systems, with minor specificity noted. The auditory semantic processing of Chinese appears less relevant to the left inferior parietal lobule underlying the sublexical-level processing while more associated with the lexical-level processing by the left middle frontal gyrus. In addition, the occipito-temporal visual cortex seems to be involved in spoken Chinese lexicosemantic processing as observed in Study 3a. This result, together with the finding in Study 2, converges to the involvement of orthography in Chinese auditory lexicosemantic processing despite the absence of characters visually presented. From the linguistic perspective, these findings likely reflect that Chinese visual characters, being evolved from semantic-represented drawings, are inherently more advantageous over spoken forms in supplying semantic clues and differentiating homophones during the lexical access of Chinese (Perfetti & Dunlap, 2008).

This model based on the intact Chinese semantic system may serve as a baseline for us to further understand Chinese semantic dementia and some possible interventions. For instance, if orthographic information does influence Chinese auditory semantic processing as revealed in the present thesis, it would be worth inspecting whether the Chinese patients with alexia also have some listening comprehension challenge in addition to the reading comprehension deficiency, or whether the neural basis of auditory semantic processing is different between the literate and illiterate. Clinically, by integrating fMRI with other techniques such as TMS, we could further verify whether there is a need for neurosurgeons to consider the particularity of Chinese model

or the nuances between Chinese and English networks during the pre-surgical planning for Chinese speaking population.

Findings in the current thesis helped to deepen our understanding of how the auditory semantic nature of Chinese influences the behavioral and neural mechanisms it engages. Based on the limited evidence available in the literature and our current investigations, a preliminary Chinese auditory semantic model is proposed for future research to reference from and improve upon.

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Appendix 2-1. *Summary of the studies selected for the meta-analysis.*

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Booth et al., 2006	Simplified Chinese	Visual	Word	Meaning association judgment tasks – rhyming judgment	MNI	13	2
Chee et al., 2001	Simplified Chinese	Visual	Word	Semantic judgments - font size judgment	Talairach	9	4
Ding et al., 2003	Simplified Chinese	Visual	Word	Semantic classification- fixation	Talairach	6	4
Dong et al., 2005	Simplified Chinese	Visual	Word	Semantic association task - fixation	Talairach	12	21
Gao et al., 2015	Simplified Chinese	Visual	Word	Semantic relatedness judgment – Korean similarity judgment	MNI	36	16
Li et al., 2004	Simplified Chinese	Visual	Word	Noun lexical decision- fixation; Verb lexical decision- fixation; Ambiguous lexical decision- fixation	Talairach	8	65
Lin et al., 2015	Simplified Chinese	Visual	Word	Lexical decision (real characters) – lexical decision (pseudocharacters)	MNI	12	3
Liu et al., 2008	Simplified Chinese	Visual	Word	Semantic association – line judgment	MNI	16	12
Luo et al., 2003	Simplified Chinese	Visual	Word	Semantic judgment task - fixation	Talairach	10	8
Tan et al., 2000; 2001	Simplified Chinese	Visual	Word	Covert semantic generation (precise meanings) – fixation; Covert semantic generation (vague meanings) – fixation; Covert semantic generation (two-character words) – fixation; Semantic relatedness decision - fixation	Talairach	6	92
Wang et al., 2016	Simplified Chinese	Visual	Word	Lexical decision (real characters) – lexical decision (stroke patterns)	MNI	16	9
Xiang et al., 2003	Simplified Chinese	Visual	Word	Semantic relatedness discrimination tasks - fixation	Talairach	6	12
Yang & Shu, 2014	Simplified Chinese	Visual	Word	(Hand verb + tool verb hand part + tool verb tool	Talairach	20	29

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
				part) passive reading > rest			
Zhang et al. 2004	Simplified Chinese	Visual	Word	Semantically relatedness judgment (high conflict) - semantically relatedness judgment (neutral); Semantically relatedness judgment (low conflict) - semantically relatedness judgment (neutral); semantically relatedness judgment (high conflict) - semantically relatedness judgment (low conflict)	Talairach	20	9
Zhang et al. 2012	Simplified Chinese	Visual	Word	Lexical decision (word) – lexical decision (non-word)	Talairach	14	6
Zhao et al., 2014	Simplified Chinese	Visual	Word	Semantic association judgment – homophone judgment	MNI	18	1
Chou et al., 2009	Traditional Chinese	Visual	Word	Semantic-related word pairs - semantic-unrelated word pairs	MNI	31	5
	Traditional Chinese	Visual	Word	Semantic-related word pairs - semantic-unrelated word pairs	MNI	32	8
Liu et al., 2006	Traditional Chinese	Visual	Word	Semantic judgment - orthographic judgment	Talairach	12	1
Huang et al. 2012a	Simplified Chinese	Visual	<i>Sentence</i>	Semantically plausible sentences comprehending – unpronounceable Sanskrit characters	Talairach	14	20
Huang et al. 2012b	Simplified Chinese	Visual	<i>Sentence</i>	Unexpected semantic acceptable judgment – expected semantic acceptable judgment	Talairach	23	5
Wang et al., 2015	Simplified Chinese	Visual	<i>Sentence</i>	Naturalistic Story Reading > rest	MNI	16	10
Zhao et al., 2013; 2014	Simplified Chinese	Visual	<i>Sentence</i>	Novel comprehension – conventional comprehension; Novel comprehension – rest; Conventional comprehension -rest	MNI	17	37
Zhou et al. 2011	Simplified Chinese	Visual	<i>Sentence</i>	New related two-part saying – new unrelated two-part saying	MNI	10	9

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Zhu et al. 2009	Simplified Chinese	Visual	<i>Sentence</i>	Sentence semantic acceptable judgment - fixation	Talairach	16	12
Zhu et al. 2012	Simplified Chinese	Visual	<i>Sentence</i>	Silent reading for comprehension – fixation; Semantic congruent judgment - fixation	MNI	27	10
Ahrens et al. 2007	Traditional Chinese	Visual	<i>Sentence</i>	Conventional metaphor sentence reading – literal sentence reading	Talairach	8	1
Luke et al. 2002	Traditional Chinese	Visual	<i>Sentence</i>	Semantic plausibility judgment task – font size judgment task	Talairach	7	23
Mo et al. 2005	Traditional Chinese	Visual	<i>Sentence</i>	Semantic knowledge retrieval of living things – nonletter character strings; Semantic knowledge retrieval of nonliving things – nonletter character strings	Talairach	8	15
Liu et al. 2008	Simplified Chinese	<i>Auditory</i>	Word	Semantic association – tone judgment	MNI	16	12
Wu et al. 2009	Simplified Chinese	<i>Auditory</i>	Word	Auditory word semantic judgment task – silence	Talairach	14	15
Xiao et al. 2005	Simplified Chinese	<i>Auditory</i>	Word	Lexical decision (real word) – lexical decision (pseudoword)	Talairach	14	3
Zou et al., 2016	Simplified Chinese	<i>Auditory</i>	Word	morphological judgment > tone judgment	MNI	17	71
Xu et al. 2013	Simplified Chinese	<i>Auditory</i>	<i>Sentence</i>	Scrambled sentences - Consonant misplaced sentences	Talairach	18	4
Assaf et al., 2006	English	Visual	Words	Correct recall/association > no-recall/no-association	Talairach	18	13
Atkins & Reuter-Lorenz, 2011	English	Visual	Words	Related lure > unrelated lure	MNI	20	6
Bedny & Thompson-Schill, 2006	English	Visual	Words	Semantic related words > visually similar nonwords	MNI	13	6
Binder et al., 2003	English	Visual	Words	Lexical decision: words > nonwords	Talairach	24	26

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Binder et al., 2005	English	Visual	Words	Reading: Regular/irregular > Nonword	Talairach	24	48
Binder et al., 2005b	English	Visual	Words	Lexical decision: concrete/abstract > nonwords	Talairach	24	63
Birn et al., 2009	English	Visual	Words	Overt fluency: category > letter	Talairach	14	5
Bonner et al., 2013	English	Visual	Words	Real words > pseudowords	MNI	20	25
Bozic et al., 2007	English	Visual	Words	Lexical decision > fixation	Talairach	15	18
Bright et al., 2004	English	Visual	Words	Lexical decision/semantic categorization > letter strings	Talairach	38	7
Carota et al., 2012	English	Visual	Words	Word comprehension > hashmark viewing	MNI	18	75
Chee et al., 2003	English	Visual	Words	Semantic associative judgment > size judgment	Talairach	12	7
Chee et al., 2003	English	Visual	Words	Semantic associative judgment > fixation (block)	Talairach	8	7
Chee et al., 2003	English	Visual	Words	Semantic associative judgment > fixation (event-related)	Talairach	12	10
Clark & Wagner, 2003	English	Visual	Words	Phonological decision: English > foreign Finnish	MNI	20	9
Coderre et al., 2016	English	Visual	Words	Semantic categorization (words) > semantic categorization (nonwords)	MNI	15	0
Copland et al., 2003	English	Visual	Words	Lexical decision on target: unrelated prime > related prime	Talairach	12	3
Copland et al., 2007	English	Visual	Words	Lexical decision on target: unrelated prime > related prime	MNI	14	3
Davis et al., 2004	English	Visual	Words	Synonym-monitoring task > letter string	MNI	12	9
de Chastelaine & Rugg, 2014	English	Visual	Words	Semantic relatedness judgment > rest	MNI	18	6

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Devereux et al., 2013	English	Visual	Words	Word category judgment > fixation	MNI	14	13
Devlin et al., 2002	English	Visual	Words	Lexical decision > letter detection	MNI	12	6
Devlin et al., 2002	English	Visual	Words	Semantic categorization > letter categorization	MNI	8	7
Devlin et al., 2002	English	Visual	Words	Semantic categorization > letter categorization	MNI	8	27
Devlin et al., 2003	English	Visual	Words	Semantic decision > Phonological decision	MNI	12	5
Devlin et al., 2004	English	Visual	Words	Lexical decision on target: unrelated prime > consonant letter strings	MNI	12	11
Gaillard et al., 2003	English	Visual	Words	Covert semantic fluency > silent rest	Talairach	29	14
Giesbrecht et al., 2004	English	Visual	Words	Semantic relatedness judgment: unrelated > related	MNI	10	8
Glezer et al., 2009	English	Visual	Words	Semantic categorization: different prime > same prime	Talairach	14	3
Gold & Rastle, 2007	English	Visual	Words	Lexical decision: lexical-semantic priming	Talairach	16	1
Gourovitch et al., 2000	English	Visual	Words	Overt fluency: category > letter	Talairach	18	7
Graves et al., 2010	English	Visual	Words	Classification judgment (forward) > (reversed)	Talairach	22	12
Grossman et al., 2002b & c	English	Visual	Words	Verb & noun pleasantness judgment > pronounceable pseudoword/pseudofont stimuli	Talairach	16	6
Kemmerer et al., 2008	English	Visual	Words	Semantic similarity judgment > Wingdings similarity judgment	MNI	16	77
Klepousniotou et al., 2013	English	Visual	Words	Semantic relatedness judgment > baseline	MNI	15	26
Kraut et al., 2002	English	Visual	Words	Object activation/semantic association > baseline	Talairach	11	12
Kraut et al., 2002	English	Visual	Words	Category association > baseline	Talairach	10	1

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Kuperberg et al., 2008	English	Visual	Words	Lexical decision/relatedness judgment > fixation; unrelated > related	Talairach	16	9
Lau et al., 2013	English	Visual	Words	Associated word pairs > unrelated word pairs	MNI	28	4
Longe et al., 2007	English	Visual	Words	Pleasantness judgment: Stems + inflections (Nouns + Verbs) > Baseline	Talairach	12	13
Mechelli et al., 2000	English	Visual	Words	Passive reading : Words > Pseudowords	Talairach	6	1
Moseley & Pulvermuller, 2014 & Moseley et al., 2012	English	Visual	Words	Passive reading > visual baseline/hash mark	MNI	18	47
Muller et al., 2003	English	Visual	Words	Semantic match judgment > visual match judgment	Talairach	9	14
O'Hare et al., 2008	English	Visual	Words	Lexical decision: unrelated prime > related prime	MNI	17	9
Pilgrim et al., 2002	English	Visual	Words	Semantic categorisation > letter detection	MNI	14	16
Postle et al., 2008	English	Visual	Words	Passive reading > hash mark	MNI	18	6
Pulvermüller & Hauk, 2006	English	Visual	Words	Semantic relatedness judgment > strings of hash marks	Talairach	14	4
Raposo et al., 2006	English	Visual	Words	Semantic categorisation: unrelated > identity	Talairach	15	12
Roskies et al., 2001	English	Visual	Words	Synonym > rhyme	Talairach	20	22
Scott et al., 2003	English	Visual	Words	Semantic decision > syllable decision	Talairach	9	7
Simmons et al., 2005	English	Visual	Words	Semantic similarity > sign similarity	Talairach	15	7
Skipper & Olson, 2014	English	Visual	Words	Words comprehension > nonwords spelling	MNI	19	52
Smith et al., 2012	English	Visual	Words	Property-verification task (word) > letter-verification task (nonword)	MNI	14	8

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Stein et al., 2009	English	Visual	Words	Meaning known detection > fixation	Talairach	10	23
Tyler et al., 2004	English	Visual	Words	Words (Nouns + Verbs) relatedness judgment > Letter Strings	MNI	12	18
Vigliocco et al., 2014	English	Visual	Words	Lexical decision: words > pseudowords	MNI	20	7
Visser et al., 2010	English	Visual	Words	Semantic categorisation > control categorisation	MNI	11	5
Wagner et al., 2001	English	Visual	Words	Semantic relatedness judgment: Weak > Strong, 4 targets > 2 targets	MNI	14	18
Wang et al., 2015	English	Visual	Words	Lexical decision > rest	MNI	16	17
Welcome & Joanisse, 2012	English	Visual	Words	Word meaning > word rhyming/case	Talairach	20	7
Wright et al., 2008	English	Visual	Words	Semantic one-back judgment > identity one-back judgment	MNI	16	2
Xu et al., 2002	English	Visual	Words	Category judgment > unpronounceable letter strings	Talairach	18	5
Yang & Zevin, 2014	English	Visual	Words	Lexical decision > symbol detection	Talairach	16	10
Yee et al., 2010	English	Visual	Words	Property judgment > fixation	MNI	18	7
Prat et al., 2011	English	Visual	<i>Sentences</i>	Opposite context > supporting context	MNI	24	12
Boulenger et al., 2009	English	Visual	<i>Sentences</i>	Sentence comprehension > hashmarks strings	MNI	18	11
Chen et al., 2008	English	Visual	<i>Sentences</i>	Plausibility judgment: Predicate Metaphor > Non-motive Sentences	Talairach	14	1
D'Arcy et al., 2004	English	Visual	<i>Sentences</i>	Sentence-pair matching: incongruent/congruent > rest	Talairach	10	7
Desai et al., 2013	English	Visual	<i>Sentences</i>	Covert meaningfulness decision (metaphor/idiom > abstract)	Talairach	27	7

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Diaz & Hogstrom, 2011	English	Visual	<i>Sentences</i>	Sentence relatedness judgment: incongruent > congruent	MNI	16	3
Diaz et al., 2011	English	Visual	<i>Sentences</i>	Valence assessment > nonword sentences	MNI	16	17
Glaser et al., 2013	English	Visual	<i>Sentences</i>	Low semantic interference sentences > high semantic interference sentences	MNI	12	2
Goldberg et al., 2007	English	Visual	<i>Sentences</i>	Property verification > letter detection	Talairach	14	4
Grossman et al., 2007	English	Visual	<i>Sentences</i>	Property judgment > baseline	Talairach	25	23
Hindy et al., 2012	English	Visual	<i>Sentences</i>	Sentence plausibility judgment > fixation	Talairach	16	6
Hindy et al., 2012	English	Visual	<i>Sentences</i>	Sentence plausibility judgment > fixation	Talairach	16	4
Humphreys & Gennari, 2014	English	Visual	<i>Sentences</i>	Sentence comprehension > rest	MNI	17	8
Husband et al., 2011	English	Visual	<i>Sentences</i>	Acceptability judgment: coercion > control	Talairach	19	5
Keidel et al., 2011	English	Visual	<i>Sentences</i>	Functional-shifted sentences > non-shifted sentences	Talairach	17	5
Kiehl et al., 2002	English	Visual	<i>Sentences</i>	Sentence meaningfulness judgment: incongruent > congruent	Talairach	28	12
Kuperberg et al., 2006	English	Visual	<i>Sentences</i>	Highly related > intermediately related > unrelated	Talairach	15	17
Kuperberg et al., 2008	English	Visual	<i>Sentences</i>	Sentence acceptness judgment: syntactic violation > pragmatic violation > animacy violation	Talairach	16	25
Mason & Just, 2007	English	Visual	<i>Sentences</i>	Sentences comprehension judgment: ambiguous > unambiguous	MNI	12	6
McMillan et al., 2012	English	Visual	<i>Sentences</i>	Undetermined > determined explicit decision/ passive reading	MNI	16	29
Newman et al., 2010	English	Visual	<i>Sentences</i>	Unrelated > related probe	MNI	20	11

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Peele et al., 2009	English	Visual	<i>Sentences</i>	Inconsistent critical features > consistent critical features	MNI	25	29
Robertson et al., 2000	English	Visual	<i>Sentences</i>	Passive viewing sentences > nonletter character strings	Talairach	8	16
Schafer & Constable, 2009	English	Visual	<i>Sentences</i>	Noun phrase formation > fixation	Talairach	16	8
Schmidt & Seger, 2009	English	Visual	<i>Sentences</i>	All sentences (literal, easy-familiar, easy-unfamiliar, difficult-unfamiliar) > non-word sentences	Talairach	10	3
Sheldon & Moscovitch, 2012	English	Visual	<i>Sentences</i>	Semantic fluency > visual motor baseline	Talairach	16	11
Stringaris et al., 2006	English	Visual	<i>Sentences</i>	Semantic relatedness judgment: metaphor > literal	Talairach	12	8
Stringaris et al., 2007	English	Visual	<i>Sentences</i>	Meaningfulness judgment: literal > nonmeaning	Talairach	11	4
Tyler et al., 2008	English	Visual	<i>Sentences</i>	Pleasantness judgment: Phrases (Nouns + Verbs) > Baseline	MNI	15	3
Wang et al., 2015	English	Visual	<i>Sentences</i>	Naturalistic Story Reading > rest	MNI	16	13
Xu et al., 2005	English	Visual	<i>Sentences</i>	Sentence passive reading > letter strings	MNI	22	17
Yang et al., 2009	English	Visual	<i>Sentences</i>	Sentence valence judgment: novel metaphor > conventional metaphor > literal > redundant	Talairach	18	26
Basho et al., 2007	English	<i>Auditory</i>	<i>Words</i>	Semantic fluency > baseline	Talairach	12	6
Beeson et al., 2003	English	<i>Auditory</i>	<i>Words</i>	Generative writing > writing alphabet	MNI	12	29
Bilenko et al., 2008	English	<i>Auditory</i>	<i>Words</i>	Lexical decision: unambiguous unrelated > ambiguous related	Talairach	16	7
Binder et al., 2000	English	<i>Auditory</i>	<i>Words</i>	Word listening > tone listening	Talairach	28	8

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Booth et al., 2002	English	<i>Auditory</i>	Words	Meaning > rhyming	MNI	13	5
Bozic et al., 2010	English	<i>Auditory</i>	Words	Gap detection: words > music rain	MNI	12	21
Bozic et al., 2013	English	<i>Auditory</i>	Words	Gap detection: words > music rain	MNI	18	16
Donnelly et al., 2011	English	<i>Auditory</i>	Words	Semantic decision > tone decision	Talairach	52	8
Grindrod et al., 2008	English	<i>Auditory</i>	Words	Triplet priming lexical decision: unrelated > concordant	Talairach	15	5
Hwang et al., 2009	English	<i>Auditory</i>	Words	Categorized word generation > repeat 'nothing'	Talairach	13	6
Lee & Dapretto, 2006	English	<i>Auditory</i>	Words	Semantic relatedness judgment: nonliteral > literal	Talairach	12	3
Leff et al., 2008	English	<i>Auditory</i>	Words	Gender judgment: (Idioms + Rearranged Idioms) > Time Reversed Idioms	MNI	26	3
Minicucci et al., 2013	English	<i>Auditory</i>	Words	Lexical decision (competitor) > lexical decision (no competitor)	Talairach	17	3
Noppeney & Price, 2002	English	<i>Auditory</i>	Words	Semantic decision > reversed word gender decision	Talairach	12	7
Noppeney & Price, 2003	English	<i>Auditory</i>	Words	Semantic decision > reversed word gender decision	Talairach	9	7
Orfanidou et al., 2006	English	<i>Auditory</i>	Words	Lexical decision: words > pseudowords	MNI	13	34
Poeppl et al., 2004	English	<i>Auditory</i>	Words	Lexical decision > categorical perception/frequency-modulated sweeps	Talairach	10	25
Rissman et al., 2003	English	<i>Auditory</i>	Words	Lexical decision > tone baseline	Talairach	15	19
Ruff et al., 2008	English	<i>Auditory</i>	Words	Semantic judgment: unrelated > related	Talairach	15	1
Shafto et al., 2012	English	<i>Auditory</i>	Words	Lexical decision (words) > music rain	MNI	14	21
Sharp et al., 2010	English	<i>Auditory</i>	Words	Semantic decision > phonological decision	MNI	12	10

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Wible et al., 2006	English	<i>Auditory</i>	<i>Words</i>	Semantic priming lexical decision: unrelated > related	Talairach	13	5
Wong et al., 2007	English	<i>Auditory</i>	<i>Words</i>	Pitch same-different judgment: speech > sinewave	Talairach	17	6
Zhuang et al., 2011	English	<i>Auditory</i>	<i>Words</i>	Lexical decision (words) > silence	MNI	14	16
Bekinschtein et al., 2011	English	<i>Auditory</i>	<i>Sentences</i>	Ambiguous > unambiguous sentences	MNI	12	2
Cooper et al., 2011	English	<i>Auditory</i>	<i>Sentences</i>	Passive listening > baseline	Talairach	12	10
Halai et al., 2015	English	<i>Auditory</i>	<i>Sentences</i>	passive listening (intelligible speech) > passive listening (rotated speech)	MNI	20	13
Hamberger et al., 2013	English	<i>Auditory</i>	<i>Sentences</i>	Covert description naming > passive listening	Talairach	12	6
Humphries et al., 2006	English	<i>Auditory</i>	<i>Sentences</i>	Meaningfulness judgment: congruent/random > pseudoword	MNI	21	12
Just et al., 2004	English	<i>Auditory</i>	<i>Sentences</i>	Sentence reality judgment > fixation	MNI	10	21
Kuperberg et al., 2000	English	<i>Auditory</i>	<i>Sentences</i>	Sentence meaningfulness judgment: normal sentences > word strings	Talairach	9	11
Maguire & Frith, 2004	English	<i>Auditory</i>	<i>Sentences</i>	Name detection in facts/controls > syllable detection	MNI	12	11
Moore-Parks et al., 2010	English	<i>Auditory</i>	<i>Sentences</i>	Sentence congruousness judgment > reversed speech	Talairach	16	9
Rodd et al., 2005	English	<i>Auditory</i>	<i>Sentences</i>	Passive listening > noise	MNI	15	4
Rodd et al., 2010	English	<i>Auditory</i>	<i>Sentences</i>	Sentences comprehension judgment > noise	MNI	14	13
Rodd et al., 2012	English	<i>Auditory</i>	<i>Sentences</i>	Sentences comprehension judgment > silence or noise	MNI	15	16
Thierry et al., 2003	English	<i>Auditory</i>	<i>Sentences</i>	Semantic decision: words > sounds	Talairach	12	4

<i>Study</i>	<i>Language</i>	<i>Modality</i>	<i>Level</i>	<i>Contrast</i>	<i>Atlas</i>	<i>N of subjects</i>	<i>N of Foci</i>
Tracy et al., 2003	English	<i>Auditory</i>	<i>Sentences</i>	Narrative text only > rest	Talairach	15	2
Tremblay & Small, 2011	English	<i>Auditory</i>	<i>Sentences</i>	Passive listening > rest	Talairach	21	9
Vitello et al., 2014	English	<i>Auditory</i>	<i>Sentences</i>	Semantic relatedness: ambiguous > unambiguous sentences	MNI	20	3

Appendix 3-1. *The demographic questionnaire (in Chinese) and its English translation.***被试基本信息表（样本）**

被试号码（由主试填写） _____

您以下填写的个人信息将严格保密、只作研究之用。在答题过程中有任何疑问，您都可以随时提问。谢谢！

1. 年龄：_____
2. 性别：男_____ 女_____
3. 12岁之前居住最久的城市：_____
4. 您曾经被诊断过注意、阅读、口语障碍或其他神经障碍么？如果有请您写下来

5. 您会多少种语言？请勾选您在阅读和听这些语言时的熟练程度。

		极不熟练	很不熟练	较不熟练	中等水平	较为熟练	很熟练	极为熟练
母语：_____	读							
	听							
第二语言（如果有）：_____	读							
	听							
第三语言（如果有）：_____	读							
	听							

6. 您习惯用哪只手：左_____ 右_____

请勾选出您在下列活动中使用手/脚/眼的偏好。有些活动可能同时需要两双手，在这种情况下，题目所指的那只手会在括号里标明。‘从未用左’和‘从未用右’是指您只有在被强迫的情况下才会使用。请您尽力不要遗漏下列任何一个问题，除非您从未从事过该类活动。

活动	只用左从未用右	喜欢用左	无偏好	喜欢用右	只用右从未用左
写字					
画画					
扔东西					
拿剪刀					
拿牙刷					
拿菜刀					
拿勺子					
拿扫把（位置偏上的那只手）					
擦火柴（拿火柴的那只手）					
开盒子（拧盖子的那只手）					
踢球用的脚					
单眼看东西（如相机）					

Basic demographic information form (example)

Participant ID (official use only) _____

All data are confidential, and will not be used in a manner that identifies you. If you have questions concerning any of the items, please do not hesitate to ask us about them. Thanks!

7. Age: _____
 8. Gender: male _____ female _____
 9. The city you lived the longest before 12 years old: _____
 10. Do you have diagnosed problems in attention, reading, oral language, or any other neurological or psychiatric disorders? Please specify if yes:

11. How many language(s) can you speak? Please tick your reading and listening proficiency levels of it/them.

		Extremel y unskilled	Quite unskille d	Slightly unskille d	Neither skilled nor unskille d	Slightl y skilled	Quite skille d	Extremel y skilled
1 st language: _____	Reading							
	Listenin g							
2 nd language (if any): _____	Reading							
	Listenin g							
3 rd language (if any): _____	Reading							
	Listenin g							

12. Your handedness: left _____ right _____

Please indicate your preferences in the use of hands/feet/eyes in the following activities by putting √ in the appropriate column. Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. 'Never used right/left' means you do not use it unless you are forced. Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

Activities	Only use left and never used right	Prefer to use left	No preference	Prefer to use right	Only use right and never used left
Writing					
Drawing					
Throwing					
Scissors					
Toothbrush					
Knife (without fork)					
Spoon					
Broom (upper hand)					
Striking Match (match)					
Opening box (lid)					
Which foot do you prefer to kick with?					
Which eye do you use when using only one? (e.g., camera)					

Appendix 3-2. *The synonym judgment task stimuli and the properties of each word stimulus.*

	Common word	Visual- and auditory-priming synonym	No priming synonym	Visual- and auditory-priming non-synonym	Auditory-priming non-synonym
2nd*	按照	依照	根据	拍照	笼罩
Stroke number	22	21	21	21	24
Synonymic degree		6.23	6.17	1.03	1
Pronunciation	An4 zhāo4	Yi1 zhāo4	Gen1 jū4	Pai1 zhāo4	Long3 zhāo4
Spatial configuration	Left-right; Top-down	Left-right; Top-down	Left-right; Left-right	Left-right; Top-down	Top-down; Top-down
2nd	产生	发生	出现	学生	上升
Stroke number	11	10	13	13	7
Synonymic degree		3.83	5	1.13	1.17
Pronunciation	Chan3 shēng1	Fa1 shēng1	Chu1 xián4	Xue2 shēng1	Shang4 shēng1
Spatial configuration	Single; Single	Single; Single	Single; Left-right	Top-down; Single	Single; Single
2nd	促进	增进	推动	引进	无尽
Stroke number	16	22	17	11	10
Synonymic degree		5.77	6.03	1.53	1
Pronunciation	Cu4 jìn4	Zeng1 jìn4	Tui1 dòng4	Yin3 jìn4	Wu2 jìn4
Spatial configuration	Left-right; Half-surrounding	Left-right; Half-surrounding	Left-right; Left-right	Left-right; Half-surrounding	Single; Top-down
2nd	整理	打理	收拾	道理	婚礼
Stroke number	27	16	15	23	16
Synonymic degree		4.97	6.17	1	1
Pronunciation	Zheng3 lǐ3	Da3 lǐ3	Shou1 shì	Dao4 lǐ3	Hun1 lǐ3
Spatial configuration	Top-down; Left-right	Left-right; Left-right	Left-right; Left-right	Half-surrounding; Left-right	Left-right; Left-right
2nd	迅速	快速	敏捷	减速	色素
Stroke number	16	17	22	21	16
Synonymic degree		6.03	5.73	1.03	1
Pronunciation	Xun4 sù4	Kuai4 sù4	Min3 jié2	Jian3 sù4	Se4 sù4
Spatial configuration	Half-surrounding;	Left-right; Half-surrounding	Left-right; Left-right	Left-right; Half-surrounding	Top-down; Top-down

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
	Half-surrounding				
<i>2nd</i>	天真	童真	幼稚	较真	方针
<i>Stroke number</i>	14	22	18	20	11
<i>Synonymic degree</i>		4.03	4.53	1.7	1
<i>Pronunciation</i>	Tian1 zhen1	Tong2 zhen1	You4 zhi4	Jiao4 zhen1	Fang1 zhen1
<i>Spatial configuration</i>	Single; Top-down	Top-down; Top-down	Left-right; Left-right	Left-right; Top-down	Single; Left-right
<i>2nd</i>	认为	以为	觉得	成为	久违
<i>Stroke number</i>	8	8	20	10	10
<i>Synonymic degree</i>		5.27	6.13	1.03	1
<i>Pronunciation</i>	Ren4 wei2	Yi3 wei2	Jue2 de	Cheng2 wei2	Jiu3 wei2
<i>Spatial configuration</i>	Left-right; Single	Left-right; Single	Top-down; Left-right	Half-surrounding; Single	Single; Half-surrounding
<i>2nd</i>	缺点	弱点	毛病	标点	经典
<i>Stroke number</i>	19	19	14	18	16
<i>Synonymic degree</i>		4.73	5.33	1.07	1
<i>Pronunciation</i>	Que1 dian3	Ruo4 dian3	Mao2 bing4	Biao1 dian3	Jing1 dian3
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Top-down	Single; Half-surrounding	Left-right; Top-down	Left-right; Top-down
<i>2nd</i>	理由	缘由	借口	自由	漫游
<i>Stroke number</i>	16	17	13	11	26
<i>Synonymic degree</i>		5.63	5.23	1.07	1
<i>Pronunciation</i>	Li3 you2	Yuan2 you2	Jie4 kou3	Zi4 you2	Man4 you2
<i>Spatial configuration</i>	Left-right; Single	Left-right; Single	Left-right; Single	Single; Single	Left-right; Left-right
<i>2nd</i>	牢固	坚固	结实	顽固	照顾
<i>Stroke number</i>	15	15	17	18	23
<i>Synonymic degree</i>		6.1	5.93	2.27	1
<i>Pronunciation</i>	Lao2 gu4	Jian1 gu4	Jie1 shi	Wan2 gu4	Zhao4 gu4

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Spatial configuration</i>	Top-down; Surrounding	Top-down; Surrounding	Left-right; Top-down	Left-right; Surrounding	Top-down; Left-right
<i>2nd</i>	讲话	说话	发言	童话	分化
<i>Stroke number</i>	14	17	12	20	8
<i>Synonymic degree</i>		6.43	5.83	1	1.03
<i>Pronunciation</i>	Jiang3 hua4	Shuo1 hua4	Fa1 yan2	Tong2 hua4	Fen1 hua4
<i>Spatial configuration</i>	Left-right; Left-right	Left-right; Left-right	Half-surrounding; Top-down	Top-down; Left-right	Top-down; Left-right
<i>2nd</i>	满意	如意	称心	随意	差异
<i>Stroke number</i>	26	19	14	24	15
<i>Synonymic degree</i>		4.47	6.2	1.03	1
<i>Pronunciation</i>	Man3 yi4	Ru2 yi4	Chen4 xin1	Sui2 yi1	Cha1 yi4
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Top-down	Left-right; Single	Left-right; Top-down	Half-surrounding; Top-down
<i>2nd</i>	起源	发源	来历	能源	田园
<i>Stroke number</i>	23	18	11	23	12
<i>Synonymic degree</i>		5.73	5.23	1.07	1.07
<i>Pronunciation</i>	Qi3 yuan2	Fa1 yuan2	Lai2 li4	Neng2 yuan2	Tian2 yuan2
<i>Spatial configuration</i>	Half-surrounding; Left-right	Half-surrounding; Left-right	Single; Half-surrounding	Left-right; Left-right	Surrounding; Surrounding
<i>2nd</i>	赞扬	表扬	夸奖	飞扬	太阳
<i>Stroke number</i>	22	14	15	9	10
<i>Synonymic degree</i>		6.1	6.27	1.53	1.03
<i>Pronunciation</i>	Zan4 yang2	Biao3 yang2	Kua1 jiang3	Fei1 yang2	Tai4 yang2
<i>Spatial configuration</i>	Top-down; Left-right	Top-down; Left-right	Top-down; Top-down	Single; Left-right	Top-down; Left-right
<i>2nd</i>	经常	时常	频繁	非常	延长
<i>Stroke number</i>	19	18	30	19	10
<i>Synonymic degree</i>		6.17	6	1.8	1.1
<i>Pronunciation</i>	Jing1 chang2	Shi2 chang2	Pin2 fan2	Fei1 chang2	Yan2 chang2

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Top-down	Left-right; Top-down	Left-right; Top-down	Half-surrounding; Single
<i>2nd</i>	重复	反复	再三	回复	祖父
<i>Stroke number</i>	18	13	9	15	13
<i>Synonymic degree</i>		5.63	5.6	1.13	1.03
<i>Pronunciation</i>	Chong2 fu4	Fan3 fu4	Zai4 san1	Hui2 fu4	Zu3 fu4
<i>Spatial configuration</i>	Top-down; Top-down	Half-surrounding; Top-down	Top-down; Single	Surrounding; Top-down	Left-right; Top-down
<i>2nd</i>	好处	益处	优点	住处	接触
<i>Stroke number</i>	11	15	15	12	24
<i>Synonymic degree</i>		6.23	5.93	1	1
<i>Pronunciation</i>	Hao3 chu4	Yi4 chu4	You1 dian3	Zhu4 chu4	Jie1 chu4
<i>Spatial configuration</i>	Left-right; Half-surrounding	Top-down; Half-surrounding	Left-right; Top-down	Left-right; Half-surrounding	Left-right; Left-right
<i>2nd</i>	说明	表明	阐述	聪明	签名
<i>Stroke number</i>	17	16	19	23	19
<i>Synonymic degree</i>		4.8	6.07	1	1.13
<i>Pronunciation</i>	Shuo1 ming2	Biao3 ming2	Chan4 shu4	Cong1 ming	Qian1 ming2
<i>Spatial configuration</i>	Left-right; Left-right	Top-down; Left-right	Half-surrounding; Half-surrounding	Left-right; Left-right	Top-down; Top-down
<i>2nd</i>	连续	持续	不断	手续	含蓄
<i>Stroke number</i>	18	20	15	15	20
<i>Synonymic degree</i>		5.23	5.8	1.03	1
<i>Pronunciation</i>	Lian2 xu4	Chi2 xu4	Bu2 duan4	Shou3 xu4	Han2 xu4
<i>Spatial configuration</i>	Half-surrounding; Left-right	Left-right; Left-right	Single; Left-right	Single; Left-right	Top-down; Top-down
<i>2nd</i>	打动	感动	激励	主动	冷冻
<i>Stroke number</i>	11	19	23	11	14
<i>Synonymic degree</i>		5.17	2.7	1.03	1.03

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Pronunciation</i>	Da3 dong4	Gan3 dōng4	Ji1 lǐ4	Zhu3 dōng4	Leng3 dōng4
<i>Spatial configuration</i>	Left-right; Left-right	Top-down; Left-right	Left-right; Left-right	Top-down; Left-right	Left-right; Left-right
<i>1st</i>	工钱	工资	薪水	工整	恭敬
<i>Stroke number</i>	13	13	20	19	22
<i>Synonymic degree</i>		6.37	6.47	1.07	1
<i>Pronunciation</i>	Gong1 qian2	Gong1 zǐ1	Xin1 shuǐ3	Gong1 zheng3	Gong1 jing4
<i>Spatial configuration</i>	Single; Left-right	Single; Top-down	Top-down; Single	Single; Top-down	Top-down; Left-right
<i>1st</i>	清晨	清早	黎明	清洗	轻视
<i>Stroke number</i>	22	17	23	20	17
<i>Synonymic degree</i>		6.07	5.13	1	1
<i>Pronunciation</i>	Qing1 chen2	Qing1 zǎo3	Li2 ming2	Qing1 xǐ3	Qing1 shì4
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Top-down	Top-down; Left-right	Left-right; Left-right	Left-right; Left-right
<i>1st</i>	难过	难受	伤心	难道	南北
<i>Stroke number</i>	16	18	10	22	14
<i>Synonymic degree</i>		6.03	6.23	1	1
<i>Pronunciation</i>	Nan2 guo4	Nan2 shou4	Shang1 xin1	Nan2 dao4	Nan2 bei3
<i>Spatial configuration</i>	Left-right; Half-surrounding	Left-right; Top-down	Left-right; Single	Left-right; Half-surrounding	Top-down; Left-right
<i>1st</i>	年龄	年纪	岁数	年糕	鲶鱼
<i>Stroke number</i>	19	12	19	22	24
<i>Synonymic degree</i>		6.5	6.33	1.03	1.17
<i>Pronunciation</i>	Nian2 ling2	Nian2 jì4	Sui4 shuǐ	Nian2 gao1	Nian2 yu2
<i>Spatial configuration</i>	Single; Left-right	Single; Left-right	Top-down; Left-right	Single; Left-right	Left-right; Top-down
<i>1st</i>	全体	全部	所有	全职	权威
<i>Stroke number</i>	13	16	14	17	15
<i>Synonymic degree</i>		5.73	5.93	2.17	1.03
<i>Pronunciation</i>	Quan2 tǐ3	Quan2 bù4	Suo3 you3	Quan2 zhí2	Quan2 wēi1

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Spatial configuration</i>	Top-down; Left-right	Top-down; Left-right	Left-right; Top-down	Top-down; Left-right	Left-right; Half-surrounding
<i>1st</i>	认得	认识	知道	认真	任性
<i>Stroke number</i>	15	11	20	14	14
<i>Synonymic degree</i>		5.17	4.73	1.03	1.03
<i>Pronunciation</i>	Ren4 dē2	Ren4 shì	Zhī1 dào4	Ren4 zhēn1	Ren4 xìng4
<i>Spatial configuration</i>	Left-right; Left-right	Left-right; Left-right	Left-right; Half-surrounding	Left-right; Top-down	Left-right; Left-right
<i>1st</i>	庄严	庄重	神圣	庄稼	装修
<i>Stroke number</i>	13	15	14	25	21
<i>Synonymic degree</i>		5.63	5	1	1.03
<i>Pronunciation</i>	Zhuang1 yān2	Zhuang1 zhòng4	Shén2 shèng4	Zhuang1 jiā	Zhuang1 xiū1
<i>Spatial configuration</i>	Half-surrounding; Top-down	Half-surrounding; Top-down	Left-right; Top-down	Half-surrounding; Left-right	Top-down; Left-right
<i>1st</i>	目的	目标	动机	目录	木头
<i>Stroke number</i>	13	14	12	13	9
<i>Synonymic degree</i>		5.73	5.43	1.17	1.03
<i>Pronunciation</i>	Mu4 dì2	Mu4 biāo1	Dòng4 jī1	Mu4 lù4	Mu4 tóu
<i>Spatial configuration</i>	Single; Left-right	Single; Left-right	Left-right; Left-right	Single; Top-down	Single; Single
<i>1st</i>	留神	留心	注意	留学	流传
<i>Stroke number</i>	19	14	21	18	16
<i>Synonymic degree</i>		6.1	5.73	1	1.03
<i>Pronunciation</i>	Liu2 shén2	Liu2 xīn1	Zhu4 yì4	Liu2 xué2	Liu2 chuán2
<i>Spatial configuration</i>	Top-down; Left-right	Top-down; Single	Left-right; Top-down	Top-down; Top-down	Left-right; Left-right
<i>1st</i>	关怀	关切	体贴	关闭	官方
<i>Stroke number</i>	13	10	16	12	12
<i>Synonymic degree</i>		5.97	5.53	1	1.03
<i>Pronunciation</i>	Guan1 huāi2	Guan1 qiē4	Tī3 tiē1	Guan1 bì4	Guan1 fāng1

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Spatial configuration</i>	Top-down; Left-right	Top-down; Left-right	Left-right; Left-right	Top-down; Half-surrounding	Top-down; Top-down
<i>1st</i>	繁荣	繁华	兴旺	繁忙	烦躁
<i>Stroke number</i>	26	23	14	23	23
<i>Synonymic degree</i>		6.23	6.1	1.67	1.03
<i>Pronunciation</i>	Fan2 r <u>o</u> ng2	Fan2 h <u>u</u> a2	Xing1 w <u>a</u> ng4	Fan2 mang2	Fan2 zao4
<i>Spatial configuration</i>	Top-down; Top-down	Top-down; Top-down	Top-down; Left-right	Top-down; Left-right	Left-right; Left-right
<i>1st</i>	担心	担忧	发愁	担任	单位
<i>Stroke number</i>	12	15	18	14	15
<i>Synonymic degree</i>		6.47	5.5	1.03	1
<i>Pronunciation</i>	Dan1 x <u>i</u> n1	Dan1 y <u>o</u> u1	Fa1 ch <u>o</u> u2	Dan1 r <u>e</u> n4	Dan1 w <u>e</u> i4
<i>Spatial configuration</i>	Left-right; Single	Left-right; Left-right	Half-surrounding; Top-down	Left-right; Left-right	Top-down; Left-right
<i>1st</i>	协同	协助	合作	协会	鞋子
<i>Stroke number</i>	12	13	13	12	18
<i>Synonymic degree</i>		3.33	5.27	1.47	1.03
<i>Pronunciation</i>	Xie2 t <u>o</u> ng2	Xie2 zh <u>u</u> 4	He2 z <u>u</u> o4	Xie2 h <u>u</u> i4	Xie2 z <u>i</u>
<i>Spatial configuration</i>	Left-right; Half-surrounding	Left-right; Left-right	Top-down; Left-right	Left-right; Top-down	Left-right; Single
<i>1st</i>	前途	前程	未来	前线	潜水
<i>Stroke number</i>	19	21	12	17	19
<i>Synonymic degree</i>		6.23	5.63	1.13	1
<i>Pronunciation</i>	Qian2 t <u>u</u> 2	Qian2 ch <u>e</u> ng2	Wei4 lai2	Qian2 xian4	Qian2 sh <u>u</u> i3
<i>Spatial configuration</i>	Top-down; Half-surrounding	Top-down; Left-right	Single; Single	Top-down; Left-right	Left-right; Single
<i>1st</i>	坦率	坦诚	直爽	坦克	忐忑
<i>Stroke number</i>	19	16	19	15	14
<i>Synonymic degree</i>		5.3	5.6	1	1

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Pronunciation</i>	Tan3 shuai4	Tan3 cheng2	Zhi2 shuang3	Tan3 ke4	Tan3 te4
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Left-right	Top-down; Single	Left-right; Top-down	Top-down; Top-down
<i>1st</i>	细心	细致	周密	细菌	戏剧
<i>Stroke number</i>	12	18	19	19	16
<i>Synonymic degree</i>		4.8	5.63	1.03	1
<i>Pronunciation</i>	Xi4 xin1	Xin4 zhi4	Zhou1 mi4	Xi4 jun1	Xi4 ju4
<i>Spatial configuration</i>	Left-right; Single	Left-right; Left-right	Half-surrounding; Top-down	Left-right; Top-down	Left-right; Left-right
<i>1st</i>	眼下	眼前	如今	眼神	演员
<i>Stroke number</i>	14	20	10	20	21
<i>Synonymic degree</i>		4.87	5.9	1.1	1
<i>Pronunciation</i>	Yan3 xia4	Yan3 qian2	Ru2 jin1	Yan3 shen2	Yan3 yuan2
<i>Spatial configuration</i>	Left-right; Top-down	Left-right; Top-down	Left-right; Top-down	Left-right; Left-right	Left-right; Top-down
<i>1st</i>	感受	感想	体会	感冒	赶快
<i>Stroke number</i>	21	26	13	22	17
<i>Synonymic degree</i>		5.1	5.83	1	1
<i>Pronunciation</i>	Gan3 shou4	Gan3 xiang3	Ti3 hui4	Gan3 ma4	Gan3 kuai4
<i>Spatial configuration</i>	Top-down; Top-down	Top-down; Top-down	Left-right; Top-down	Top-down; Top-down	Half-surrounding; Left-right
<i>1st</i>	美丽	美观	漂亮	美国	每天
<i>Stroke number</i>	16	15	23	17	11
<i>Synonymic degree</i>		3.9	6.43	1	1
<i>Pronunciation</i>	Mei3 li4	Mei3 guan1	Piao4 liang	Mei3 guo2	Mei3 tian1
<i>Spatial configuration</i>	Top-down; Top-down	Top-down; Left-right	Left-right; Top-down	Top-down; Surrounding	Top-down; Single
<i>1st</i>	区分	区别	辨认	区域	趋势
<i>Stroke number</i>	8	11	20	15	20
<i>Synonymic degree</i>		5.47	5.7	1.17	1.03
<i>Pronunciation</i>	Qu1 fen1	Qu1 bie2	Bian4 ren4	Qu1 yu4	Qu1 shi4

	<i>Common word</i>	<i>Visual- and auditory-priming synonym</i>	<i>No priming synonym</i>	<i>Visual- and auditory-priming non-synonym</i>	<i>Auditory-priming non-synonym</i>
<i>Spatial configuration</i>	Half-surrounding; Top-down	Half-surrounding; Left-right	Left-right; Left-right	Half-surrounding; Left-right	Half-surrounding; Top-down

Note. * ‘1st/2nd’ indicates that the first/second character is common between the prime and target.

Appendix 3-3. *The NTU Institutional Review Board approval letter for Study 2.*

Research Support Office

Reg. No. 200604393R

IRB-2014-06-028

16 July 2014

Associate Professor Chen Shen-Hsing Annabel
School of Humanities and Social Sciences

NTU INSTITUTIONAL REVIEW BOARD APPROVAL
Project Title: Investigating Visual and Auditory Semantic Processing the Chinese Language

I refer to your application for ethics approval with respect to the above project.

The Board has deliberated on your application and noted from your application that your research involves collecting behavioral data from participants using questionnaires.

You have also confirmed that informed consent will be obtained from the participants and you have guaranteed the confidentiality of your participants' biodata obtained from them.

The documents reviewed are:

- a) NTU IRB application form dated **30 June 2014**
- b) Participant information sheet and consent form: version 1 dated **30 June 2014**
- c) Data collection form: version 1 dated **30 June 2014**

The Board is therefore satisfied with the bioethical consideration for the project and approves the ethics application under **Expedited** review. The approval period is from **16 July 2014** to **31 July 2015**. The NTU IRB reference number for this study is **IRB-2014-06-028**. Please use this reference number for all future correspondence.

The following protocol and compliances are to be observed upon NTU IRB approval

1. All research involving procedures greater than minimal risk on minors (individuals who are less than the legal age of 21 years old) requires IRB approved written Parental Consent and assent from the participant to be obtained before any research protocols can be administered. Minimal risk refers to an anticipated level of harm and discomfort that is no greater than that ordinarily encountered in daily life, or during the performance of routine educational, physical, or psychological examination.
2. Only the approved Participants Information Sheet and Consent Form should be used. It must be signed by each subject prior to initiation of any protocol procedures. In addition, each subject should be given a copy of the signed consent form.

Blk N2.1, B4-01, 76 Nanyang Drive, Singapore 637331 Nanyang Avenue, Singapore 639798
Tel : +65 6791 9857, Fax: 6793 2019
www.ntu.edu.sg

Research Support Office

3. Consent forms are important documents therefore they should be stored in the strictest arrangement. Loss of consent form would result in disciplinary action.
4. No deviation from, or changes of, the protocol should be initiated without prior written NTU IRB approval of an appropriate amendment.
5. The Principal Investigator should report promptly to NTU IRB regarding:
 - a. Deviation from, or changes to the protocol.
 - b. Changes increasing the risk to the subjects and/or affecting significantly the conduct of the trial
 - c. All serious adverse events (SAEs) which are both serious and unexpected.
 - d. New information that may affect adversely the safety of the subjects of the conduct of the trial.
 - e. Completion of the study.
6. Continuing Review Request/ Notice of Study completion form should be submitted to NTU IRB for the following:
 - a. Annual review: Status of the study should be reported to the NTU IRB at least annually using the Continuing Review Request/ Notice of Study completion form.
 - b. Study completion or termination: Continuing Review Request/ Notice of Study completion form is to be submitted within 4 to 6 weeks of study completion or termination.

Professor Lee Sing Kong,
Chair, NTU Institutional Review Board
encl.

cc Chair, School of Humanities and Social Sciences
Members, NTU Institutional Review Board

Appendix I. *The Curriculum Vitae of LIU Hengshuang.***EDUCATION****Nanyang Technological University (NTU), Singapore****08/2012-11/2017**

- Ph.D. in Psychology

Thesis: Investigating the Behavioral and Neural Correlates of Auditory Semantic Processing in the Chinese Language

Beijing Normal University (BNU), Beijing, China**09/2009-06/2012**

- M.Phil. (First Class Honors) in National Key Laboratory of Cognitive Neuroscience and Learning

Thesis: An Intervention Study on Improving English Picture Book Reading for Chinese Children Using Compound Input Enhancement

Zhengzhou University (ZZU), Zhengzhou, China**09/2005-06/2009**

- B.A. (First Class Honors) in Psychology

2009 Excellent Thesis (3%), 2006-2008 First Prize Academic Scholarship (3%), 2005 Second Prize Academic Scholarship (10%), 2005-2008 Excellent Triple-A Student (5%)

PUBLICATIONS**Journal Articles**

- Liu, H.S., Lim, A., Miyakoshi, M., Nakai, T., & Chen, S.H.A. (Under Review). Aging patterns of functional connectivity in Japanese auditory semantic processing: an fMRI study.
- Liu, H.S., & Cao, F. (2016). L1 and L2 processing in the bilingual brain: A meta-analysis of neuroimaging studies. *Brain and Language*, 159, 60-73.
- Liu, H.S., & Chen, S.H.A. (2015). Neural Correlates of Chinese and Japanese Semantic Processing: A Meta-analysis. *Language and Cognitive Science*, 1 (1), 77-107.
- Wang, W., & Liu, H.S. (2012). Effectively Improve Foreign Language Instruction in Primary and Secondary Schools with Textual Enhancement. *Journal of the Chinese Society of Education (CSSCI)*, 12, 64-68. (In Chinese)
- Fischer, K.W., Chou, J., Liu, H.S., & Wang, H. (2011). The Future of the Educational Neuroscience: Building Tools for Learning Pathways. *Global Education (CSSCI)*, 290, 44-49. (In Chinese)
- Wang, M., & Liu, H.S. (2011). A Book reviewing: Neuroscience Introduction. *Exploring Education Development (CSSCI)*, 18, 78-79. (In Chinese)

Research Chapters

- Liu, H.S. (2017). Chapter 4 (pp.149-182): How the bilingual education in China could be informed by the research findings of orthographic regularity? In Chou et al., *the Reformation of Second Language Education from the Perspective of Educational Neuroscience* (Eds). Beijing: Educational Science Press. (In Chinese)

Conference Abstract

- Liu, H.S., & Chen, S.H.A. (2017). A meta-analysis of neuroimaging studies in English, Japanese, and Chinese visual semantic processing (**poster presentation**). *2017 Organization for Human Brain Mapping Annual Conference*, Vancouver, Canada (25/June-29/June).
- Liu, H.S., & Chen, S.H.A. (2016). Investigating visual and auditory semantic processing in the Chinese language (**oral presentation**). *The 16th International Conference on the Processing of East Asian Languages*, Guangzhou, China (8/December-10/December).
- Liu, H.S., & Chen, S.H.A. (2016). A meta-analysis of neuroimaging studies in English, Japanese, and Chinese visual semantic processing (**oral presentation**). *Brainconnects 2016*, Taichung, Taiwan (23/September-25/September).
- Liu, H.S., Hale, J.B., & Chen, S.H.A. (2016). Math training leads to more efficient brain networks:

An activation likelihood estimate (ALE) meta-analysis (**poster presentation**). *2016 International Mind, Brain, and Education Society Annual Conference*, Toronto, Canada (15/September-17/September).

- Liu, H.S., Lim, A., Nakai, T., & Chen, S.H.A. (2016). Neural specialization for words and sentences during Chinese listening comprehension: an fMRI study (**poster presentation**). *2016 Organization for Human Brain Mapping Annual Conference*, Geneva, Switzerland (26/June-30/June).
- Liu, H.S., & Chen, S.H.A. (2016). A Meta-analysis of Neuroimaging Studies of English and Chinese Semantic Processing (**poster presentation**). *The 24th Annual Meeting of International Society for Magnetic Resonance in Medicine*, Singapore (07/May-13/May).
- Liu, H.S., Lim, A., Miyakoshi, M., Nakai, T., & Chen, S.H.A. (2015). Aging Patterns of Functional Connectivity in Japanese Auditory Semantic Processing: an fMRI study (**oral & poster presentation**). *Brainconnects 2015*, Nagoya, Japan (31/July-1/August).
- Lim, A., Liu, H.S., Miyakoshi, M., Mayako, M., Nakai, T., & Chen, S.H.A. (2015). Differential brain activations in Chinese and Japanese auditory semantic processing (**poster presentation**). *2015 Organization for Human Brain Mapping Annual Conference*, Honolulu, Hawaii, USA (14/June-18/June).
- Liu, H.S., Lim, A., Miyakoshi, M., Nakai, T., & Chen, S.H.A. (2015). Aging Patterns of Functional Connectivity in Japanese Auditory Semantic Processing: an fMRI study (**poster presentation**). *2015 Organization for Human Brain Mapping Annual Conference*, Honolulu, Hawaii, USA (14/June-18/June).
- Liu, H.S., Lim, A., Miyakoshi, M., Nakai, T., & Chen, S.H.A. (2015). Investigating the Aging Effect on Neural Correlates of Auditory Semantic Processing in the Japanese Language using Functional Magnetic Resonance Imaging (**oral & poster presentations**). *2015 Magnetic Resonance in South East Asia Workshop* (17/January-18/January).
- Liu, H.S., & Chen, S.H.A. (2014). A Meta-analysis of Neuroimaging Studies on Chinese and Japanese Semantic Processing (**poster presentation**). *The 6th Annual Neurobiology of Language Conference*, Amsterdam, the Netherlands (27/August-29/August).

Chapter Translation

- Liu, H.S., & Chou, J., Chapter 1 (pp.7-22), Chapter 3 (pp.42-56), and Chapter 8 (pp.117-138). In Chou et al. (2011), *The Educated Brain Essays in Neuroeducation* (Eds). Beijing: Educational Science Press.
- Chou, J., & Liu, H.S., Chapter 3 (pp.45-65). In Chou et al. (2011), *Educating the Human Brain* (Eds). Beijing: Educational Science Press.
- Liu, H.S., Chapter 2 (pp.29-44), Chapter 10 (pp.179-191), and Index (pp.217-229). In Chou et al. (2013), *The Brain at School Educational Neuroscience in the Classroom* (Eds). Shanghai: East China Normal University Press.
- Liu, H.S., Part 1-2 (pp.73-115). In Chou et al. (In press), *Human Neuro-plasticity and Education* (Eds). Shanghai: East China Normal University Press.
- Liu, H.S., Chapter1-3 (pp.5-72), Chapter8 (pp.165-193), Chapter13 (pp.287-308), Index (pp.309-320). In Chou et al. (In press), *Executive Function in Education: From Theory to Practice* (Eds). Shanghai: Shanghai Education Press.
- Liu, H.S., Chapter2-3 (pp.34-108). In Chou et al. (In press), *Educational Neuroscience* (Eds). Shanghai: Shanghai Education Press.

EDITORIAL JOURNAL ARTICLE

Three rounds of peer-reviewing for one article that was submitted to *Human Brain Mapping*.

RESEARCH EXPERIENCE**Nanyang Technological University (NTU), Singapore**

- Research Associate in the laboratory of Full Professor Annabel Chen, 10/2016-present
Joint project of NTU and Johns Hopkins University "Effective Biliteracy: The impact of script sets on bilingual reading networks for typical and atypical readers"
- Ph.D. candidate in the laboratory of Full Professor Annabel Chen, 11/2013-08/2016
"Neural Correlates of Chinese and Japanese Auditory Semantic Processing Using fMRI"
- Ph.D. candidate in the laboratory of Nanyang Assistant Professor Fan Cao, 08/2012-10/2013
"Neural Correlates of Chinese Character Reading and Pinyin Reading in Chinese Children"

Beijing Normal University (BNU), Beijing, China

- M.Phil. candidate in the laboratory of Prof. WenJing Wang, 09/2010-06/2012
*"An Intervention Study on Improving English Reading Ability of Chinese Children (Pandeng English)",
Funded by Chinese Ministry of Education*
- M.Phil. Project Leader, 01/2010-04/2011
*"How Teaching Styles of the Primary Teachers Graduated from Normal Universities differ from those
from Other Universities", Funded by BNU Student Research Foundation (sponsored the top 10%
proposals)*

Zhengzhou University (ZZU), Zhengzhou, China

- B.A. candidate in the laboratory of Prof. YuZhong Wang, 05/2007-05/2009
*"An Empirical Study of the Two-Dimensional Multi-Layered Mating Theory", Funded by Chinese
National Social Science Foundation*

INTERNSHIP EXPERIENCE**Nanyang Technological University (NTU), Singapore****08/2012-present**

- Examination grader & Checker
*"Introduction to Psychology", "Biological Psychology", "Cognitive Psychology", "Abnormal
Psychology", "Personality and Individual Differences", "Seminar: Psychology of Leadership", "Seminar:
Social Cognition", "Cultural Psychology", "Research Laboratory in Psychology"*

Beijing Normal University (BNU), Beijing, China**03/2011-06/2011**

- M.Phil. Teaching Assistant for Prof. WenJing Wang
"Mind, Brain, and Instructional Design", a Graduate Compulsory Course

A Training Institute for Postgraduate Entrance Examination, Beijing, China**05/2010-07/2012**

- Part-time Psychology Instructor (invited due to the high mark [256, top 20 in Beijing] in 2009
Psychology Major Postgraduate Entrance Examination)
*"Introduction to Psychology", "Experimental Psychology", "Psychological Measurement and
Statistics", "Developmental Psychology", "Educational Psychology"*

Mental Hygiene Clinics, the Ninth People's Hospital, Zhengzhou, China**05/2008-06/2009**

- Intern Psychological Consultant
*Provided mental intervention to patients after "Wenchuan May12 Earthquake";
Was invited to give a lecture on mental health to patients and doctors*

SKILLS

SPSS, Matlab, SPM & BPM (neuroimaging analysis), CONN (functional connectivity), GingerALE (meta-analysis)