# BRAIN ACTIVATION IN THE AUDITORY PROCESSING OF CANTONESE RHYMES IN NATIVE CANTONESE SPEAKERS USING FUNCTIONAL MAGNETIC RESONANCE IMAGING: AN EVENT RELATED STUDY

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# Certificate of Originality

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Lee Wing Kit

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# Abstract

Previous functional studies have demonstrated that major language processing areas at the inferior frontal (Broca's area) and superior temporal gyri (Wernicke's area) were activated by auditory stimuli with the English vowels and Mandarin rhymes. Cantonese is a major southern Chinese dialect. We hypothesized that the Cantonese rhymes would activate the inferior frontal gyrus. We hypothesized that it would also activate the superior temporal gyrus. The activation pattern by Cantonese rhymes would be similar to that from previous studies with English vowels. We also hypothesized the activation pattern from Cantonese rhymes would be similar to that from previous studies with Mandarin rhymes. The purpose of this study was to investigate the feasibility of using functional magnetic resonance imaging (fMRI) with auditory stimuli in Cantonese rhymes in the determination of language processing areas in native Cantonese speakers.

The experiment tested 15 native Cantonese speakers aged from 19 to 25 years. Blood oxygen level dependent (BOLD) fMRI brain images were acquired on each subject using a 1.5 Tesla scanner while they were performing a discrimination task of Cantonese rhymes and filtered rhymes. The filtered rhymes were made by applying a low-pass filter, which attenuated frequencies higher than 200 Hz, onto

the Cantonese rhymes.

A number of brain regions were commonly activated by both Cantonese rhymes and filtered rhymes. On the frontal and parietal cortices, they were bilateral medial frontal (FGM), inferior frontal gyri (IFG), precentral gyri and postcentral gyri. On the temporal cortex, bilateral superior temporal sulci/gyri (STS/STG) were activated by Cantonese rhymes or filtered rhymes. On the occipital cortex, bilateral lingual gyri (LG) and right calcarian sulcus were activated by Cantonese rhymes as well as filtered rhymes. In the comparison of Cantonese rhymes vs. filtered rhymes, although significantly stronger positive activations were only demonstrated at the left middle frontal gyri (MFG) and IFG with Cantonese rhymes, activity in some other brain areas specifically with Cantonese rhymes, but not with filtered rhymes, were noted in separate comparisons of Cantonese rhymes and filtered rhymes with silence. They included bilateral MFG, the left superior parietal gyrus (SPG) and the left middle temporal gyrus (MTG). Stronger and more extensive activations were found in the left brain than the right brain in the comparison of Cantonese rhymes vs. silence. Negative BOLD signals were consistently found bilaterally at angular gyri (AG), and the anterior and posterior cingulate gyri in separate comparisons of Cantonese rhymes and filtered rhymes with silence.

Our result suggested the left IFG and the MFG were responsible in semantic processing of Cantonese rhymes, which was consistent with the previous findings on English vowels and Mandarin rhymes. The activation in the left hemisphere by the Cantonese rhymes in the present study was as extensive as that by English vowels and Mandarin rhymes. With the use of Cantonese rhymes as auditory stimuli, language processing areas in native Cantonese speakers can be identified. Left language lateralization can also be demonstrated with the auditory stimuli of Cantonese rhymes. The present results also showed that the left MFG plays an important role in Cantonese rhymes processing, apart from the Broca's and Wernicke's areas. The present study was the first fMRI study using Cantonese rhymes to localize the language processing areas. It provides neuroscientists evidences of using the auditory Cantonese rhymes to localize the language processing areas in Cantonese speaking community.

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# Chapter One

# Introduction

## 1.1 Overview

Language is the mental faculty for communication. It involves a systematic organization of small basic units with meaningful concepts and the interaction of memory (phonology, orthography or semantics) with sensory input (auditory, visual or tactile processing) and motor output (articulation, writing, signing or drawing) systems (Price, 2000). Linguists often classify language into alphabetic and logographic based on orthographic appearance of morphemes as word strings and characters, while the classification of tone and non-tone languages mainly depends on its ability to make use of pitch contours in recognizing the word meaning of phonemes (Duanmu, 2004). Alphabetic language refers to the language system in which letters, such as those used in English, or symbols equivalent to such letters, to represent the basic sounds of a language (DeFrancis, 1984). Logographic language refers to the language system which uses graphical symbols to represent words (DeFrancis, 1984). Chinese language is a good example which possesses both logographic and tonal characteristics, while English is a typical example of alphabetic and non-tone language. One of the typical differences in the phonological system between Chinese and English is that Chinese can utilize tones to differentiate meaning while English cannot. Cantonese is another example of tone language. It is one of the major dialects for communication in Guangdong, Hong Kong and Macau while Mandarin (Putonghua) is treated as the standard Chinese language and is used as the official language in China. Although both Cantonese and Mandarin are tone languages, their phonological system is completely different, in terms of number of rhymes, consonants and tones (Section 1.3). A Cantonese syllable consists of supra-segmental and segmental components (Bauer and Benedict, 1997). The supra-segmental is a tone that subscribes the prosody of a word for discrimination. The segmental component contains an optional onset and a rhyme (Bauer and Benedict, 1997). A rhyme is the most salient part of a sound. It consists of a nuclei and an optional coda. Cantonese possesses more rhymes than Mandarin which provides the varieties in pronounication (Bauer and Benedict, 1997). Being a tone language, Cantonese utilizes the change in tone to differentiate meaning of words.

In the 19th century, understanding on the brain mechanisms depended on the studies with language disorders, known as aphasia, which were caused by focal brain lesions that resulted, most frequently from stroke and head injury. The early study of aphasia revealed that language processing happens principally on left hemisphere rather than on right hemisphere structures, in all right-handed and most of left-handed individuals (Alexander et al., 1989). Damage at the lateral frontal region (Broca’s area), at the posterior superior temporal lobe (Wernicke’s area), or the white matter tracts that connect Broca's and Wernicke's areas (arcuate fasciculus) (Lichtheim, 1885), was associated with a major and linguistically different profile of language impairment (Kertesz et al., 1982; Alexander et al., 1989; Hart and Gordon, 1990). A printed word was suggested to be processed first in the visual areas of the occipital lobe and then in the angular gyrus, an association area for the translation of visual to auditory word forms (Geschwind, 1965). The transformed input then travels to the adjacent Wernicke's area, thereby accessing the auditory memory of the word. If the word is to be spoken, output from Wernicke's areas is transmitted forward via the arcuate fasciculus to Broca's area in the frontal lobe, where memory for word articulation is stored. This forms the neurological model for language.

In the recent decades, functional neuroimaging has provided a new means for the investigation of various cognitive functions (Price, 2000). The advantages of using functional neuroimaging in the investigation of cognitive functions are: (1) to enable scientists to examine the brain activity in vivo non-invasively; (2) to examine cognitive functions on subjects with normal physiological responses without limitation on patients with brain damage; (3) to reproduce the examinations not confined to particular sensory, motor or cognitive processes (Price, 2000). Among all functional neuroimaging techniques, Wada test was used as a "gold standard" in the identification of hemispheric language dominance in the past. Until the recent decades, fMRI is commonly used in the determination of language lateralization due to its non-invasiveness and high spatial resolution in the acquisition of brain images.

Auditory language inputs have been used in functional magnetic resonance imaging (fMRI) for brain mapping of language processing areas (Binder et al., 1996; Binder et al., 1996; Hertz-Pannier et al., 1997; Benson et al., 1999; Pujol et al., 1999; Adcock et al., 2003; Sabbah et al., 2003; Stippich et al., 2003). Language processing can be divided into three main stages: pre-lexical, lexical and post-lexical processing (Gazzaniga, 2000). Pre-lexical processing corresponds to the neural basis from the processing of inputs to recognize the explicit word forms to the 'lexical-semantic' level where the meaning of words are recognized (Scott and Wise, 2004). Lexical stage corresponds to an integration process to combine linguistic information with contextual and background knowledge for semantic retrieval (Price, 2000). Post-lexical processing corresponds to the construction of appropriate grammatical structure and ascertaining the semantic relations among the words in the sentence for a response (Gazzaniga, 2000). The differences in cognitive processing with visual and auditory language stimuli mainly focus at the pre-lexical processing stage.

A small number of reports showed that the auditory stimulus with English vowels alone was sufficient to identify the lateralization of language (Gootjes et al., 1999; Szymanski et al., 1999; Szymanski et al., 1999; Szymanski et al., 2001). Such a successful application of vowels, if confirmed, presents the potential for simple and easy standardization of auditory language input. It is not clear whether the vowel sound of Chinese, a tone language, would have similar or different effect as English vowels on the brain mapping of language. Therefore, Cantonese rhymes were chosen in the auditory stimulus for brain mapping of the Cantonese community. The purpose of the present study was to evaluate the language processing areas activated by Cantonese rhymes as simple auditory stimuli in healthy right-handed native Cantonese speakers. We expected that the findings in the present study would contribute to the use of fMRI, which is the functional application of the MRI technique in the cerebral region to detect localized changes in blood flow and blood oxygenation in response to neural activity without the use of any contrast media (Kwong et al., 1992), in localizing the language processing areas. We made use of an auditory paradigm with Cantonese rhymes as the stimuli. Auditory paradigm was used because subjects are less dependent on the visual interpretation, which can benefit a larger population, including the poorly educated population like the children and elderly, or those patients with visual disturbance. According to the previous experiments, Mandarin rhymes and English vowels can be used as the auditory stimuli, where the inferior frontal gyrus, superior temporal gyrus, and the middle frontal gyrus were usually activated. We therefore expected that the Cantonese rhymes would activate the inferior frontal gyrus. We also hypothesized that the superior temporal gyrus would be activated. The activation pattern by Cantonese rhymes would be compatible to that from previous studies with English vowels. We also hypothesized the activation pattern from Cantonese rhymes would be similar to that from previous studies with Mandarin rhymes.

## 1.2 Language

Language is the mental faculty for communication. It involves a systematic organization of small basic units with meaningful concepts and the interaction of memory (phonology, orthography or semantics) with sensory input (auditory, visual or tactile processing) and motor output (articulation, writing, signing or drawing) systems (Price, 2000). Basic units, alphabets and strokes, are arranged together to form a word and the morphemes are word strings and characters respectively. In Chinese language and culture, “word” is definable using phonological, morphological, syntactic and orthographic criteria (Packard, 2000). Phonologically, the existence of the potential pauses – the places in a sentence where it is possible to pause – was considered to be a phonological criterion for the definition of “word” (Packard, 2000). Morphologically, “word” is defined as a base together with the expression of the grammatical categories appropriate for its part-of-speech class (Packard, 2000). Syntactically, “word” represents the minimal units of syntax within utterances (Packard, 2000). Linguists often classify languages into alphabetic and logographic based on orthographic appearance of morphemes -- word strings and characters. In the present study, we were studying Cantonese rhymes processing, the segmental unit in Cantonese characters (Section 1.3).

The classification of tone and non-tone languages mainly depends on its phonology whether the language can make use of pitch contours in recognizing the word meaning (Duanmu, 2004). The aural tones are known as lexical tones. Tone is different from intonation in which intonation is used in all languages to express emphasis, emotion or nuances. Chinese is a good example which possesses both logographic and tonal characteristics. It therefore can be classified into a logographic or tone language. Thai is also classified as a tone language but not a logographic language as the morphemes of Thai are word strings instead of squared characters. Opposite to Chinese, English is classified as alphabetic language or non-tone language, where it does not use pitch to distinguish words. The comparisons between alphabetic and logographic languages, and between tone and non-tone languages are shown in Table 1.

| Alphabetic Language (e.g. English) | Logographic Language (e.g. Chinese) |
|---|---|
| Mother<br>Hemp | 媽<br>痲 |
| **Non-tone Language (e.g. English)** | **Tone Language (e.g. Mandarin)** |
| Hemp (neutral)<br>Hemp (question) | 媽 (mā)<br>痲 (má) |

**Table 1. Comparisons of alphabetic vs logographic languages, and tone vs non-tone languages.**

There are many different dialects in Chinese language. They can be roughly classified into seven large groups: Mandarin, Gan, Keija (Hakka), Min, Wu, Xiang and Cantonese (Yue). Mandarin is an official spoken language in China. However, in southern part of China, including Guangdong and Hong Kong, Cantonese is a major dialect for communication. In the local community, Cantonese is spoken in 89% of the population aged five years or above (Summary Results of 2001 Population Census, Census and Statistics Department, HKSAR 2001, http://www.info.gov.hk/censtatd/).

### 1.3 Cantonese

In all formal written communications, Chinese speakers use standard written Chinese no matter what dialects they speak. Standard written Chinese employs Chinese characters, a system based on logograms, where each symbol represents a morpheme. In informal communications, colloquial Cantonese in written form is commonly used by Cantonese speakers. Colloquial Cantonese is written with a mixture of standard Chinese characters and hundreds of extra characters created specifically for Cantonese. Some of the characters are rarely used or used differently in standard Chinese. Its grammatical structures are different from standard written Chinese. An example of colloquial Cantonese and standard written Chinese with the same meaning but in different written form is shown below.

| **Standard Written Chinese** | **Colloquial Cantonese in Written Form** |
|---|---|
| 甚麼事? (What is the matter?) | 咩事? (What is the matter?) |

**Table 2. The comparison between standard written Chinese and colloquial Cantonese in written form.**

Phonologically speaking, the syllable of a Chinese word consists of two components: supra-segmental (tone) and segmental (onset + rhyme) (Bauer and Benedict, 1997). Figure 1 shows the basic structure of a Cantonese syllable. The supra-segmental is a tone that subscribes the prosody of a word, while the segmental component contains an onset and a rhyme (Bauer and Benedict, 1997). There are 20 consonants in Cantonese, those which may occur at the beginning of a syllable (Tang et al., 2002). An onset (consonant) is a sound that is characterized by a closure or stricture sufficient to cause audible turbulence, at one or more points along the vocal tract. It is an optional component within a syllable. It does not sound on its own but only occurs with a rhyme. A rhyme, which is a salient of sound, consists of a nuclei and an optional coda. Cantonese has 6 tones, 20 consonants, and 59 readable rhymes. Thirty-five of the rhymes are meaningless syllable while the other 24 can be recognized as Cantonese words by itself.

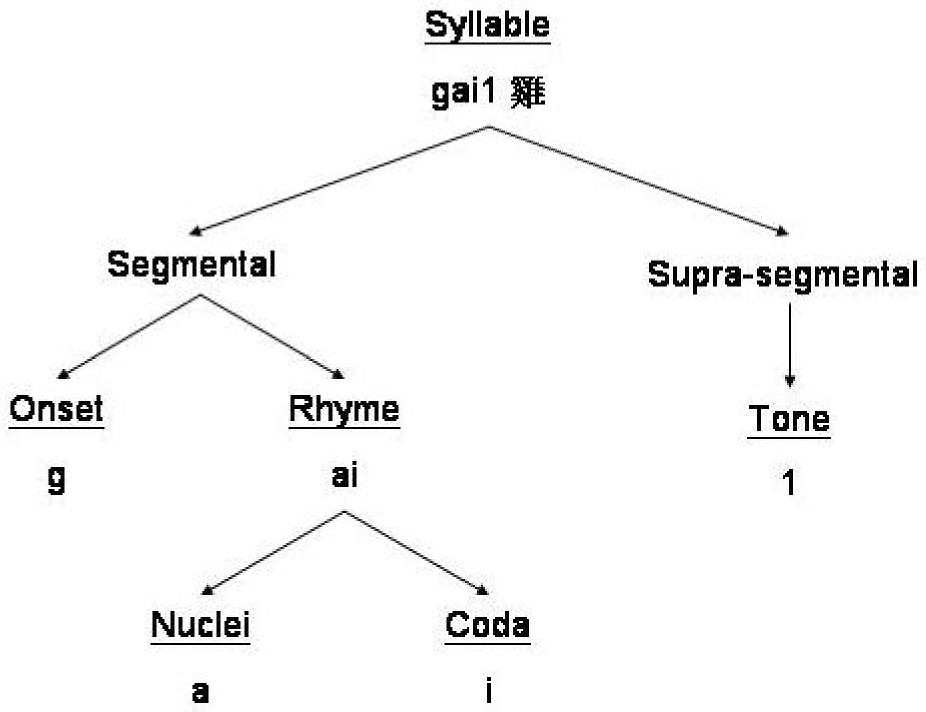


**Figure 1. The components of a Cantonese syllable. The Cantonese syllable ("gai1") contains an onset ("g"), a nuclei ("a"), a coda ("i") and a tone ("1").**

Mandarin sounds quite different from Cantonese, mainly because it has a different phonological system in tone, rhyme, onset and coda. The basic structure of a Mandarin syllable with an example is shown in Figure 2. A syllable in Mandarin is also divided into supra-segmental (tone) and segmental (onset + medial + rhyme) (Chen, 2000). Medial, which is a consonant sound, occurs between the onset and the rhyme in a Mandarin syllable but not in a Cantonese syllable (Chen, 2000). In addition, the tonal system of Cantonese is more complex than that of Mandarin. Cantonese has 6 tones including high level, high rising, mid level, low falling, low rising and low level

(Matthews and Virginia, 1994), while Mandarin has only 4 tones including high level, high rising, low falling rising and high falling. Oral stop consonants, “p”, “t”, or “k”, can be used as coda, for example, "gok3" (角), while oral stops consonants do not appear as a coda in Mandarin. Therefore, Cantonese preserves many different coda that Mandarin has lost or merged (Matthews and Virginia, 1994). For example, the characters, “藝”, “艾”, “憶”, “譯” are all pronounced “yì” in Mandarin, but they are pronounced differently in Cantonese “ngai6”, “ngaai6”, “jik1” and “jik6” respectively. Furthermore, nasals can be independent syllables in Cantonese words, like "ng5" (五), and "ng4" (唔) (Matthews and Virginia, 1994). Table 3 summarizes the major phonological differences between Cantonese and Mandarin (Zhang, 2000; Tang et al., 2002).

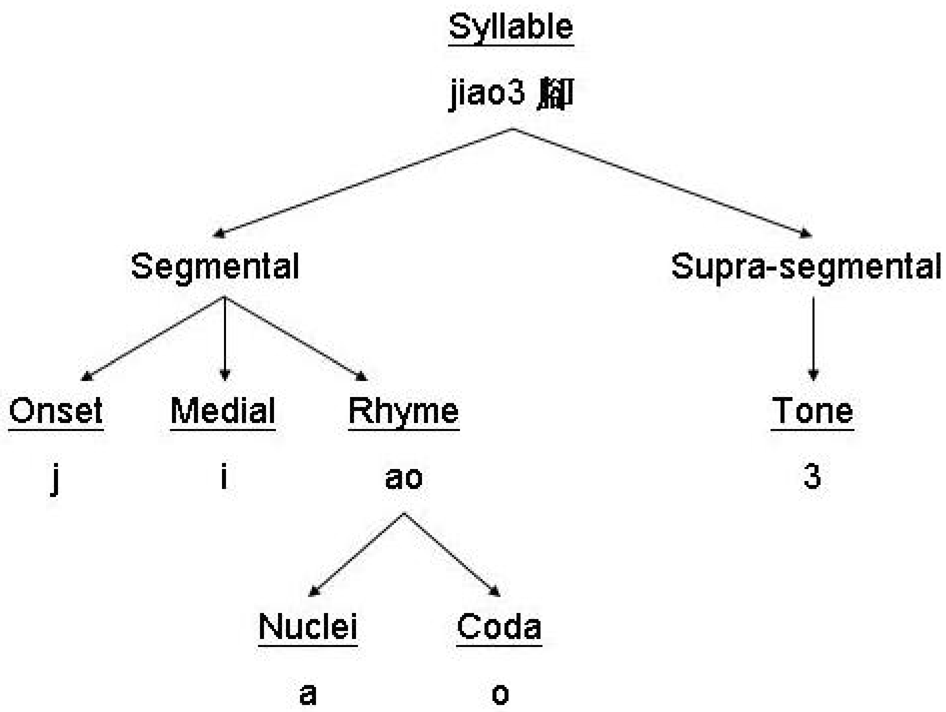


**Figure 2. The components of a Mandarin syllable. The Mandarin syllable ("jiao3") contains an onset ("j"), a medial ("i"), a nuclei ("a"), a coda ("o") and a tone ("3").**

| | Cantonese | Mandarin |
|---|---|---|
| **Number of Rhymes** | 59 | 36 |
| **Number of Consonants** | 20 | 21 |
| **Number of Tones** | 6 | 4 |
| **Oral Stop Consonant as Coda** | Yes | No |
| **Nasals "m" and "n" as independent syllables** | Yes | No |

**Table 3. The major phonological differences between Cantonese and Mandarin.**

English is an alphabetic language, which sounds different from tone languages like Cantonese and Mandarin (Bruce, 1970; Baker, 1995). The basic structure of an English syllable with an example is shown in Figure 3. As Cantonese and Mandarin, an English syllable is also divided into supra-segmental (stress + intonation) and segmental (onset + rhyme) (Brinton, 2000). The segmental component within an English syllable is similar to Cantonese, including an optional onset and a rhyme with an obligatory vowel (Ballard, 2001; Kuiper and Allan, 2004).

The supra-segmental of alphabetic English is completely different from that in Cantonese and Mandarin. Supra-segmental is the prosodic features of a syllable, which include the stress and intonation in alphabetic English (Ballard, 2001; Kuiper and Allan, 2004). To change the tone in tone languages results in a different word meaning (Ballard, 2001; Kuiper and Allan, 2004). However, in alphabetic language, changes in intonation do not amend the meaning of the word with which they are associated, but it can modify the meaning of the utterance as a whole (Ballard, 2001; Kuiper and Allan, 2004). Stress is the syllable with a more prominent sound in relation to the other (Ballard, 2001; Kuiper and Allan, 2004). Factors affecting the prominence of syllables include length, loudness, pitch and quality (Ballard, 2001; Kuiper and Allan, 2004). In general, a stressed syllable tends to be louder, longer, with a higher pitch than unstressed syllable. Stressed and unstressed syllables can only be found in alphabetic languages, including English (Ballard, 2001; Kuiper and Allan, 2004). Cantonese, which is a tone language, utilizes tones to differentiate the meaning of words (Bruce, 1970; Baker, 1995).

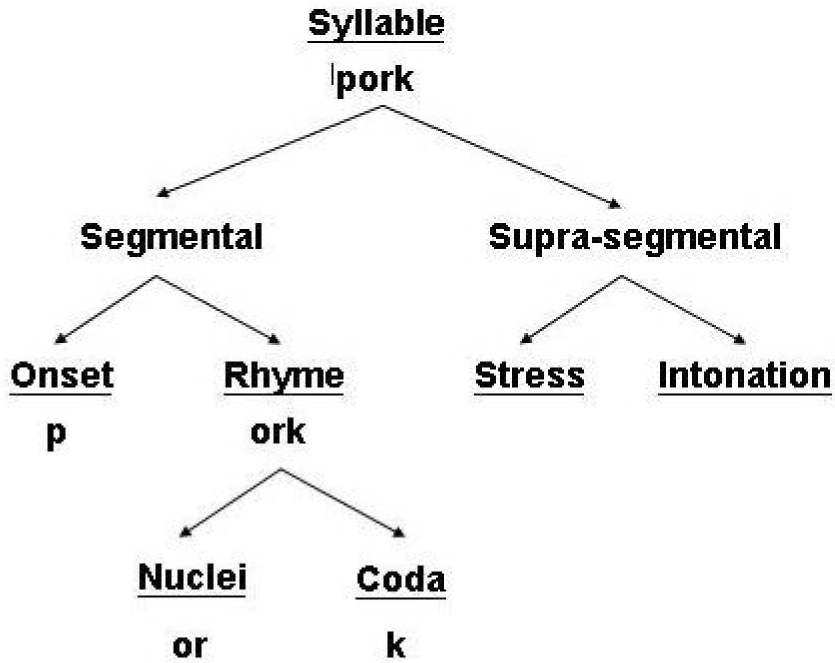


**Figure 3. The components of an English syllable. The English syllable ("ˈpork") contains an onset ("p"), a nuclei ("or"), and a coda ("k"). The position of the stress is indicated by a stroke ("ˈ").**

Being an alphabetic language, English contains a complicated syllable structure since polysyllable is possible within a word. Multiple consonants can be found in the onset or coda within a syllable in alphabetic English, while single consonant is usually identified in the onset or coda in Cantonese (Bruce, 1970; Baker, 1995). For example, in the English word “strong”, both “s”, “t”, “r” are consonants within the onset of the syllable, while in Cantonese word “gai1”, “g” is the only consonant within the onset of the syllable. Besides, unaspirated consonants “b”, “d”, “g”, “j” in Cantonese are aspirated in English, for example, the consonant “g” in the Cantonese word “gam1” (金) is unaspirated (Bruce, 1970; Baker, 1995), while in English word “dog”, consonant “d” is aspirated during pronunciation. Both Cantonese and English possess consonants “p”, “t”, or “k” in coda (Bruce, 1970; Baker, 1995). However, these consonants in Cantonese are not aspirated, for example the consonant “t” in Cantonese “jat1” (日) is unaspirated, while “t” in “sit” in English is aspirated (Bruce, 1970; Baker, 1995). Moreover, similar to Mandarin, no nasal can be identified as independent syllable in English (Bruce, 1970; Baker, 1995). The major differences between English and Cantonese are summarized in Table 4.

| | **Cantonese** | **English** |
|---|---|---|
| **Tones to differentiate meaning** | Yes | No |
| **Multiple consonants in onset or coda** | No | Yes |
| **Aspiration in Onset Consonant “b”, “d”, “g” and “j”** | No | Yes |
| **Aspiration in Coda Consonant “p”, “t” and “k”** | No | Yes |
| **Nasals "m" and "n" as independent syllables** | Yes | No |

**Table 4. The major phonological differences between Cantonese and English.**

### 1.4 Language Processing in Brain

Language components are commonly perceived visually by eyes or aurally by ears before they are processed in the brain. The understanding of the neural basis of language comes from the study of language disorders, known as aphasia, which were caused by focal brain lesions that resulted, most frequently from stroke and head injury (Price, 2000). The early study of aphasia revealed that language processing depends principally on the structures in the left hemisphere rather than in right hemisphere, in all right-handed and most of left-handed individuals (Alexander et al., 1989). Damage to each of the two cortical areas, in the Broca's area at the lateral frontal region and in the Wernicke's area at the posterior superior temporal lobe, was associated with a major and linguistically different profile of language impairment (Kertesz et al., 1982; Alexander et al., 1989; Hart and Gordon, 1990; Khateb et al., 2004).

#### 1.4.1 Language Lateralization

The brain is divided into left and right hemispheres. It was noted that aphasia occurred frequently with damage to the left hemisphere than to the right (Alexander et al., 1989). Paul Broca (Broca, 1961) discovered that all the patients with aphasia in his post-mortem investigations had damage in the left inferior frontal cortex, which was later named as Broca's area. He showed that the two hemispheres were not functionally equivalent. The patients had left hemispheric specialization for language abilities. This functional specialization to a hemisphere is known as hemispheric dominance or lateralization.

Many studies were performed to investigate the hemispheric dominance of language function in healthy subjects and in patients with neurological pathologies (Rasmussen and Milner, 1977; Pujol et al., 1999; Calvert et al., 2000; Knecht et al., 2000; Knecht et al., 2000; Szaflarski et al., 2002; Baciu et al., 2005). An association between handedness and language lateralization was shown. The findings in these studies showed that most people are left dominant for language (Pujol et al., 1999; Knecht et al., 2000; Khedr et al., 2002). Around 90% of right handers (Pujol et al., 1999; Knecht et al., 2000; Khedr et al., 2002) and 70% of left handers (Pujol et al., 1999; Knecht et al., 2000; Khedr et al., 2002) were reported to have left language dominance.

### 1.4.2 Neurological Models of Language

Broca's area is located at the pars triangularis and pars opercularis of the inferior frontal gyrus in the frontal lobe. Broca's area is named after Pierre Paul Broca, who first described it in a post-mortem investigation in 1861 on a patient who had been impaired at articulating language (Broca, 1961). It was associated with the motor images of speech. Wernicke's area is at the posterior part of the superior temporal gyri, posterior to the primary auditory cortex, at the temporo-parietal junction. It is named after Carl Wernicke, a German neurologist and psychiatrist who reported a postmortem study of a patient who had impaired comprehension in 1874 (Wernicke, 1874). It was associated with the auditory images of speech. Wernicke developed a model further to predict that if there was damage to the white matter tracts that connect Broca's and Wernicke's areas (the arcuate fasciculus), patients would have intact speech comprehension and production but a deficit repeating what was heard. This type of disconnection syndrome, referred to as 'conduction aphasia' (Lichtheim, 1885). This model was further enriched by the findings on two alexic syndromes: 'alexia with agraphia' and 'alexia without agraphia' (Dejerine, 1892). The deficit of alexia (reading) and agraphia (writing) was suggested to be associated with damage to the left angular gyrus which was linked to memories of visual word forms. Alexia without agraphia was suggested by a disconnection of the left angular gyrus from the visual cortex. The neurologically based theory of reading was then reformulated by Norman Geschwind (Geschwind, 1965). A printed word is first processed in the visual areas of the occipital lobe and then in the angular gyrus, an association area for the translation of visual to auditory word forms. The transformed input then travels to the adjacent Wernicke's area, thereby accessing the auditory memory of the word. If the word is to be spoken, output from Wernicke's areas is transmitted forward via the arcuate fasciculus to

Broca's area in the frontal lobe, where memory for word articulation is stored. This forms the neurological model for language in 19th century. It is illustrated in the figure below.

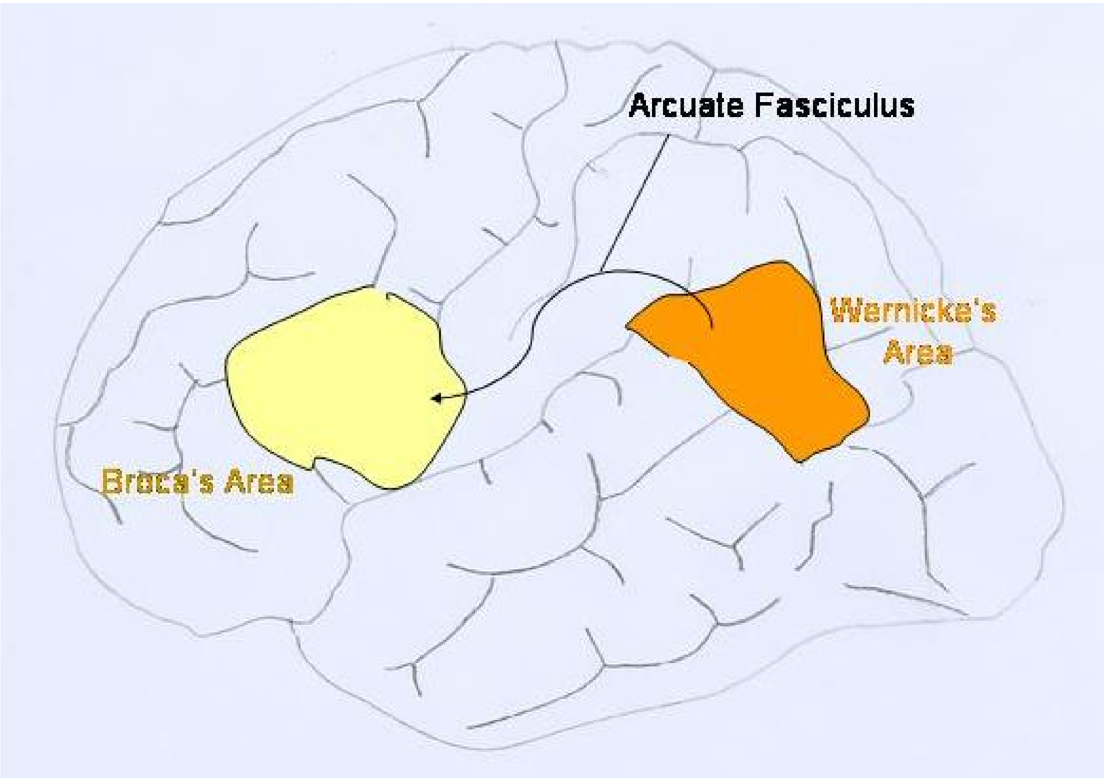


**Figure 4. A schematic diagram illustrating the neurological model for language processing in the 19th century showing the Broca's area, Wernicke's area and the arcuate fasciculus.**

## 1.5 Functional Neuroimaging

In the 19$^{th}$ and 20$^{th}$ century, most of our knowledge about how the brain works and the anatomical location of various neurological functions came from post-mortem investigations on people suffering from brain damage. However, brain damage, whether through stroke or injury, rarely occurred in exactly the right location for researchers' needs in a study. The lack of anatomical precision and vagueness of the behavioral data extremely limited the credibility of the results. In addition, it is impossible to distinguish whether the loss of language function was associated with the lesion or disconnection of undamaged areas. The accurate determination of asymmetrical activity of cerebral hemispheres in vivo was impossible until the development of several functional neuroimaging modalities in the 21$^{st}$ century. These functional neuroimaging techniques can be grouped into two categories according to the underlying mechanisms: procedures for measuring electrical activity of the brain and those for measuring neural metabolism processes (Table 5).

| Changes in electric activity | Changes in neural metabolism |
|---|---|
| Electroencephalography (EEG) | Wada Test |
| Magnetoencephalography (MEG) | Positron Emission Tomography (PET) |
| | Functional Transcranial Doppler Sonography (fTCD) |
| | Functional Magnetic Resonance Imaging (fMRI) |

**Table 5. The functional neuroimaging techniques measuring changes in electrical activity and neural metabolism.**

Among all functional neuroimaging techniques, Wada test has been used as a "gold standard" in the identification of hemispheric language dominance in the past. Until the recent decades, fMRI is commonly used in the determination of language lateralization due to its non-invasiveness and high spatial resolution.

### 1.5.1 Wada Test

Wada test is an intracarotid amobarbital procedure (IAP) which has been used as "gold standard" to study the hemispheric language dominance in clinical settings. It was named after Juhn Wada, who introduced it in 1949 (Wada, 1949). The Wada test independently assesses the capacity of each hemisphere to support language function during selective anesthesia of the contralateral hemisphere. The test is an invasive angiographic procedure conducted with the patient awake. A neuroradiologist performs sequential selective transfemoral catheterization of the internal carotid arteries via femoral artery. Intra-carotid injection of the anesthetic agent, sodium amobarbital, transiently anesthetizes much of the hemisphere on the side of injection, mainly in the territories of the anterior and middle cerebral arteries. During selective hemispheric anesthesia, a neuropsychologist tests language function in the contralateral, non-anesthetized hemisphere. Simultaneously, a neurologist monitors transient neurologic deficits and electroencephalographic (EEG) changes. After the anesthetized hemisphere recovers completely, the procedure is repeated on the other side. Most commonly, anesthetization of the dominant hemisphere causes major language deficits, such as speech arrest, anomia, and paraphasic errors; conversely, anesthetization of the other hemisphere, the non-dominant one, does not. Uncommonly, the language deficits are symmetrically minimal or mild, indicating that both hemispheres support language function, and they are codominant.

The significance of Wada test is to predict the general risk of the brain surgery pre-operatively and to estimate the inconvenience in daily life of patients after surgery. Although it is of proven value, the Wada test has well been documented for its risks and limitations (Woods et al., 1988; Loring et al., 1990; Loring et al., 1993; Desmond et al., 1995; Binder et al., 1996; Jones-Gotman et al., 1997). The required angiographic procedure is invasive, which reported complication rates of up to 3%. The test only measures the relative distribution of language across the two hemispheres while the exact location in language perception cannot be identified due to its limited spatial resolution. In addition, validity of the test depends on demonstration of relatively separate and symmetric arterial supply routes for the two hemispheres. Furthermore, testing distinct functions during the procedure should be performed within the time limit without excessive sedation of the patient. The inadequate samples collected in language tasks due to time limit will affect the validity of the interpretation. Therefore, although the Wada test remains as the gold standard used routinely in determining language dominance, the Wada test may not be the best means for determination of language lateralization and the exact location of the brain during language perception.

### 1.5.2 Functional Magnetic Resonance Imaging (fMRI)

The physical principles of nuclear magnetic resonance (NMR) were discovered independently by Felix Bloch (1946) and Edward Purcell and his colleagues in 1946. In 1973, Paul Lauterbur used NMR signals to create cross-sectional images similar to computed tomography, and the imaging technique was later named as magnetic resonance imaging (MRI) (Ralchie, 2000). MRI produced superb images of human body with high spatial resolution and free of any ionizing radiation. The first successful attempt to monitor local brain blood volume changes with the administration of intravenous contrast agent to enhance MRI signals accelerated the development of functional brain imaging with MRI (Belliveau et al., 1991). Instead of using contrast agents, Ogawa studied the effect of the tissue concentration of deoxygenated hemoglobin on the MRI signals by alternately breathing rats on room air and 100% oxygen (Ogawa et al., 1990; Ogawa et al., 1990). Detailed anatomy of venules and veins were easily visible throughout the rat brain as dark structures due to the loss of MRI signal in the presence of deoxyhemoglobin. This finding was then labeled as blood oxygen level dependent contrast (BOLD). On a 1.5 tesla magnet equipped with echoplanar imaging (EPI) capability, Kwong et al. (Kwong et al., 1992) performed the first MRI experiment successfully to image the functional responses at human visual cortex using BOLD contrast without any administration of contrast agents and the technique is known as BOLD functional MRI (BOLD fMRI), or simply fMRI.

The prevailing BOLD fMRI technique does not measure changes in CBF directly. Rather, it detects increased cerebrovascular oxygen content that accompanies increased CBF during neuronal activation. When neurons are activated, metabolic demand is increased associated with a local hemodynamic change by increasing the blood supply (Ogawa et al., 1990). However, the oxygen consumption of active neurons is much less than the oxygen supply by the increased blood volume (Savoy, 2001). Concentration of deoxyhemoglobin is decreased in venules or veins. With the paramagnetic property of deoxyhemoglobin, a relative increase in MRI signals at the activated region results. Ultimately, BOLD fMRI technique identifies regional brain activation by an increase in T2* weighted signal intensity, through a mechanism mediated by the paramagnetic molecule deoxyhemoglobin (Ogawa et al., 1990; Turner et al., 1991; Kwong et al., 1992; Ogawa et al., 1992). This technique is widely applied in neuroscience and pre-surgical planning for brain mapping.

### 1.5.3 Other Functional Neuroimaging Techniques

Apart from Wada test and functional MRI, electroencephalography (EEG), positron emission tomography (PET), functional transcranial Doppler (fTCD) and magnetoencephalography (MEG) are also the functional neuroimaging techniques which developed in the recent decades for the study of cognitive functions.

EEG measures the electrical potentials directly on scalp surface. It has an advantage of having high temporal resolution of around 1 millisecond (Dale et al., 2000; Momjian et al., 2003). However, its low spatial resolution of around 20 miliimeters and the absence of high-resolution anatomical brain images limit EEG in its application of brain mapping (Darvas et al., 2004). Similar to EEG, fTCD also has a high temporal resolution. It allows a simple assessment of hemispheric lateralization of brain functions by measuring the blood flow velocity in cerebral arteries using Doppler sonography (Knecht et al., 1998; Schmidt et al., 1999; Vingerhoets and Stroobant, 1999). However, the major limitation of fTCD is that it requires the presence of an acoustic temporal bone window for insonation of cerebral arteries (Schmidt et al., 1999). The absence of high-resolution anatomical brain images also limits fTCD in its application of brain mapping (Darvas et al., 2004). Before the development of fMRI technique, PET is commonly used as a tool in brain mapping (Sadato et al., 1998). It has a higher spatial resolution than EEG and fTCD (Tatlidil et al., 2000). However, the drawback of PET scanning is its invasiveness, where radioisotopes are administered to the subjects before the scanning (Tatlidil et al., 2000). As the radioactivity decays rapidly, the monitoring of brain activity is limited within a short time interval. With the concern in non-invasive assessment of brain activity, MEG is developed. MEG measures the induced magnetic flux on the scalp surface. It has the spatial and temporal resolution up to 5-10 millimeters and 1 millisecond respectively (Dale et al., 2000; Momjian et al., 2003). However, the spatial and temporal resolution of MEG is not higher than fMRI (Lev and Grant, 2000). The relatively low availability and high running cost also limit its usage in brain mapping.

fMRI is a non-invasive functional imaging technique when compared to Wada test and PET scanning in the neuroimaging for language processing. Excellent spatial resolution of fMRI provides an advantage over fTCD and EEG in brain mapping (Dale et al., 2000; Momjian et al., 2003). Although the temporal resolution of fMRI is not as good as MEG (Dale et al., 2000), high availablity and relatively low operational cost of fMRI make it dominant in neuroscience research. Figure 5 summarizes the spatial and temporal resolution in different functional neuroimaging modalities. In fact, fMRI research has been devoted to the understanding of neurophysiology during language processing. Using fMRI as a primary tool, along with a variety of brain mapping and analytical techniques, researchers have made important discoveries in functional neuroanatomy as well as the neural pathway in speech perception, recognition and interpretation.

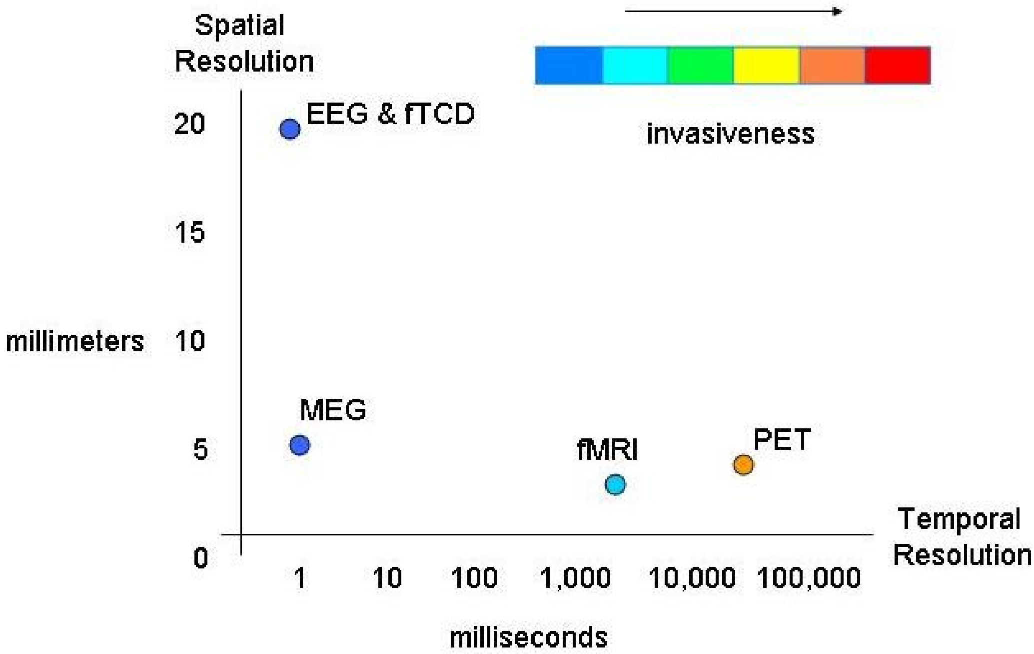


**Figure 5. Comparison of the spatial and temporal resolution among different functional neuroimaging modalities.**

### 1.6 Functional Imaging Studies of Language Processing

Functional neuroimaging, including fMRI, EEG, PET, fTCD and MEG, provides a new means for the investigation of the neural pathway for auditory language processing (Kwong et al., 1992; Ogawa et al., 1992; Sadato et al., 1998; Schmidt et al., 1999; Dale et al., 2000; Price, 2000; Momjian et al., 2003).

#### 1.6.1 Auditory Language Processing

There are three main stages in auditory language processing: pre-lexical, lexical and post-lexical processing (Gazzaniga, 2000) (Figure 6).

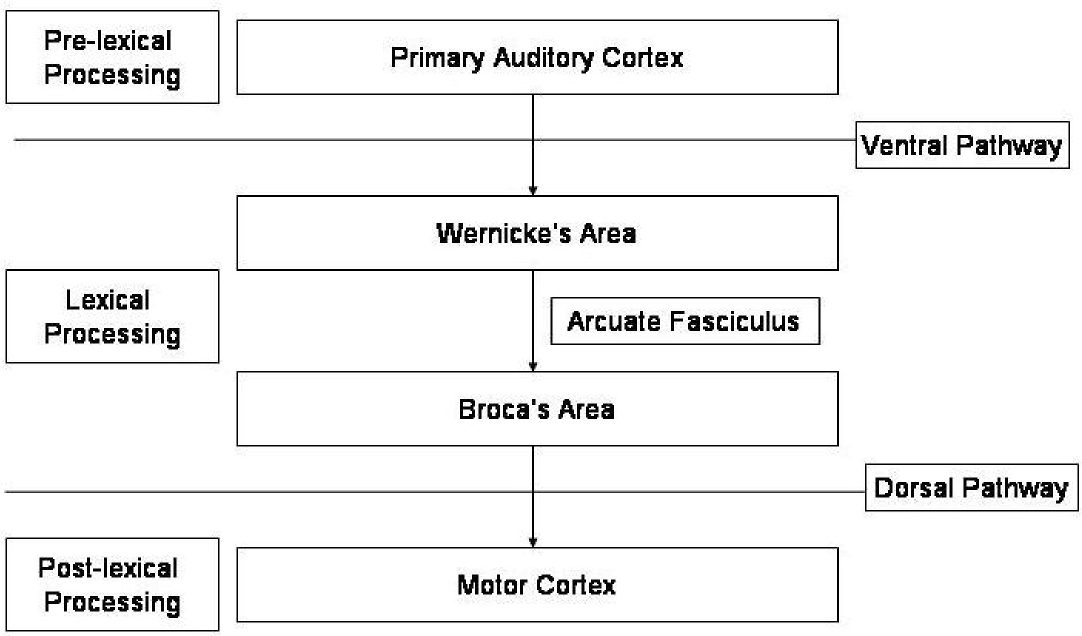


**Figure 6. Neural pathway involved in auditory language processing.**

In pre-lexical auditory language processing, the primary auditory cortex is a sensory area to perceive auditory stimulations. It is located at the superior temporal gyrus (Heschl's gyrus) on both left and right sides of the brain (Figure 7). It is sensitive to auditory content, no matter in phonetic or acoustic in nature (Boatman et al., 2000; Benson et al., 2001). Evidence from patients with lesions over the primary auditory cortex suffering from aphasia has clearly indicated the importance of the primary auditory cortex in both speech perception and production (Buchman et al., 1986; Engelien et al., 1995). These patients are unable to comprehend speech though they can speak, read and write, which is called receptive aphasia (Buchman et al., 1986; Engelien et al., 1995). Previous lesional and imaging studies also indicated the importance of the left superior temporal gyrus in language comprehension (Binder et al., 1996; Boatman et al., 1998; Gandour et al., 2000; Peng et al., 2004).

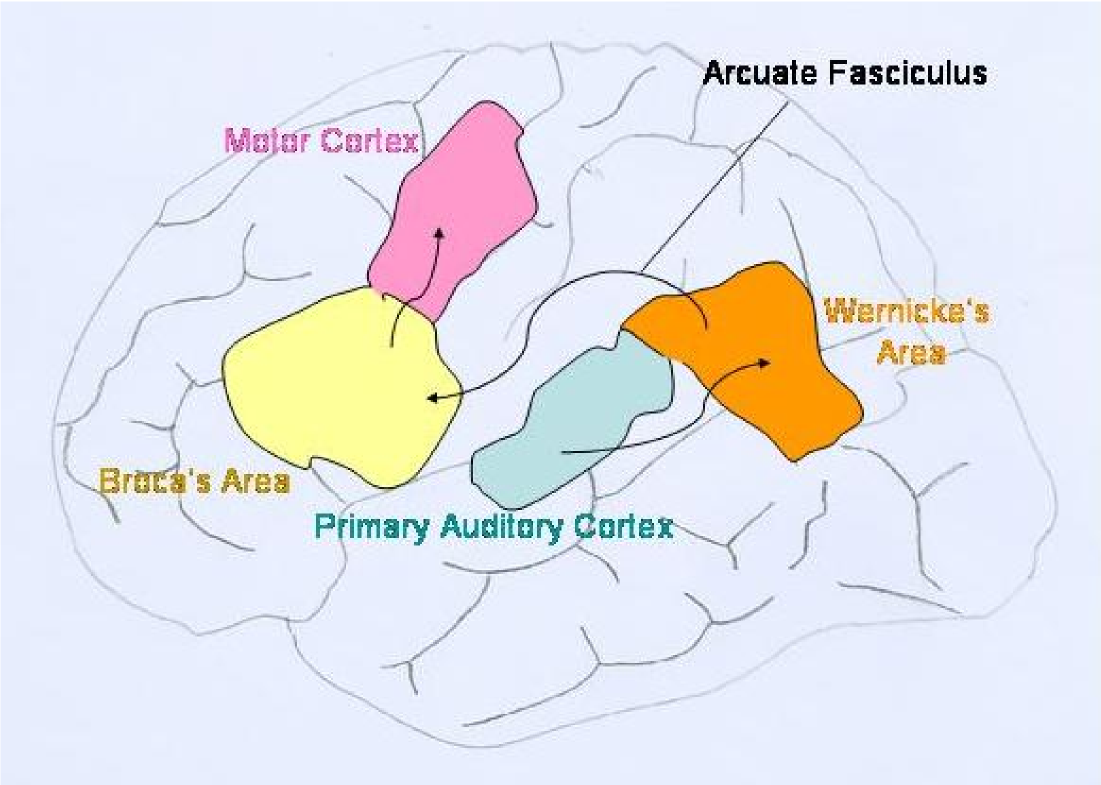


**Figure 7. A schematic diagram illustrating the neural pathway for auditory language processing.**

In lexical language processing, two distinct pathways, ventral and dorsal pathways, participate in speech perception in a task-dependent manner. Both of these pathways are strongly lateralized to the left hemisphere (Gazzaniga, 2000). Auditory stimulations with phonetic contents are perceived by primary auditory cortex and decoded at Wernicke's area via the ventral pathway. The ventral pathway involves cortical areas in the vicinity of the temporal-parietal-occipital junction (Price, 2000). It interfaces sound-based representations of speech at auditory cortex with widely distributed conceptual representations at Wernicke's area (Price, 2000). Wernicke's area is located posterior to the primary auditory cortex at the posterior superior temporal gyrus (pSTG). It is accountable to phonetic processing with the extraction of specifically linguistic features from sound (Benson et al., 2001; Gandour et al., 2002; Hickok and Poeppel, 2004). Previous imaging studies reported that pSTG is involved in the identification and/or discrimination of supra-segmental of complex speech sounds (Benson et al., 2001; Gandour et al., 2002; Hugdahl et al., 2003), as well as the identification of non-speech sounds (Binder et al., 1997; Gandour et al., 2004). Leftward asymmetry of activations at pSTG was identified in the judgment of rhymes (Boatman et al., 1998; Benson et al., 2001). This showed that the left pSTG may be the preferred pathway in phonological processing (Boatman et al., 1998; Benson et al., 2001).

After the decoding process at Wernicke's area, the word meaning of speech is transferred via arcuate fasciculus to Broca's area. Broca's area at the inferior frontal gyrus (IFG) is known as a classical expressive language area (Chee et al., 1999). It acts as a transit between language perception and overt language production (Chee et al., 1999; Benson et al., 2001). Similar to Wernicke's area, left asymmetry of the brain activity at IFG was found during language processing (Price et al., 1996; Binder et al., 1997; Schlosser et al., 1998; Chee et al., 1999; Gandour et al., 2000; Benson et al., 2001; Gandour et al., 2004). The processing of semantic, phonological and short-term storage of auditory information contributes to the stronger activation at the left IFG (Chee et al., 1999; Benson et al., 2001; Burton et al., 2005), where the output is then ready for expression.

In post-lexical language processing, the verbal output is assembled and motor commands are then sent from Broca's area to primary motor cortex for vocalization via dorsal pathway (Gazzaniga, 2000). The motor cortex is responsible for the reconstruction of appropriate grammatical structure and ascertaining the semantic relations among the words in the sentence for an overt speech (Gazzaniga, 2000). Activity in the motor cortex during articulation is always associated with activations to the laryngeal, lingual, facial muscle, lip and tongue. Activation can also be observed in the supplementary motor area (SMA) and the cingulate gyrus. Impairment over the SMA and the cingulate gyrus was associated with difficulties in speech initiation with preserved repetition (Damasio and Geschwind, 1984; Mesulam, 1990).

### 1.6.2 Visual Language Processing

Visual processing of language works in an analogous way as auditory perception.

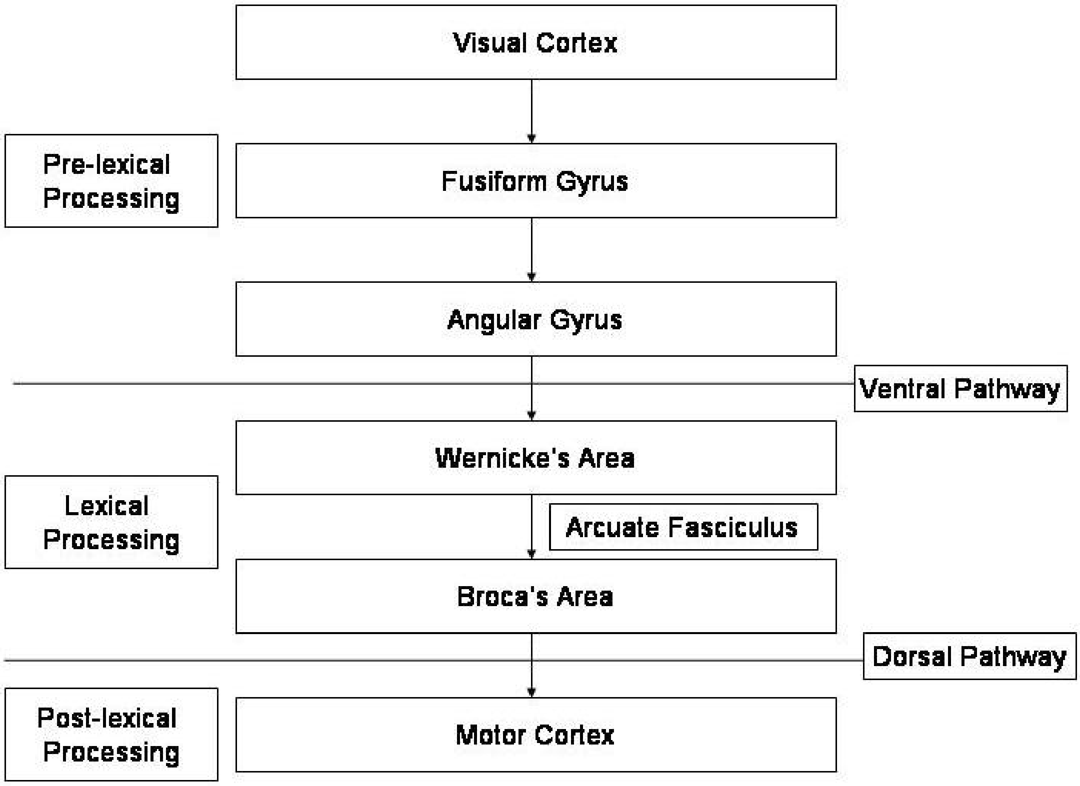


**Figure 8. Neural pathway involved in visual language processing.**

Visual processing engages the visual areas of the occipital lobe instead of the primary auditory areas of the temporal lobe (Figure 8). The printed words are then processed in an association area at angular gyrus for the translation of visual to auditory word forms. The supramarginal gyrus used to be included as part of the association cortex as well in this processing stream. Clinical studies on alexia and agraphia, as well as other studies (Howard et al., 1992; Menard et al., 1996), also supported this postulation. On the contrary, Petersen et al. (Petersen et al., 1988) suggested that the left medial extrastriate cortex is the true site of stored visual word codes since they found that both real words and pseudowords activated the left medial extrastriate cortex, but neither false fonts nor consonant strings activated this area. The similar activations at the left medial extrastriate cortex and posterior ventral or medial occipito-temporal areas were also found in a study of Japanese characters (Fujimaki et al., 1999). The transformed input from the association cortex then travels to the adjacent Wernicke's area, thereby accessing the Broca's area in the left frontal lobe where memory of the word articulation is located, via arcuate fasciculus. Similar to auditory language processing, the motor cortex associated with the supramarginal gyrus and the cingulate gyrus are activated for the speech production (Price, 2000).

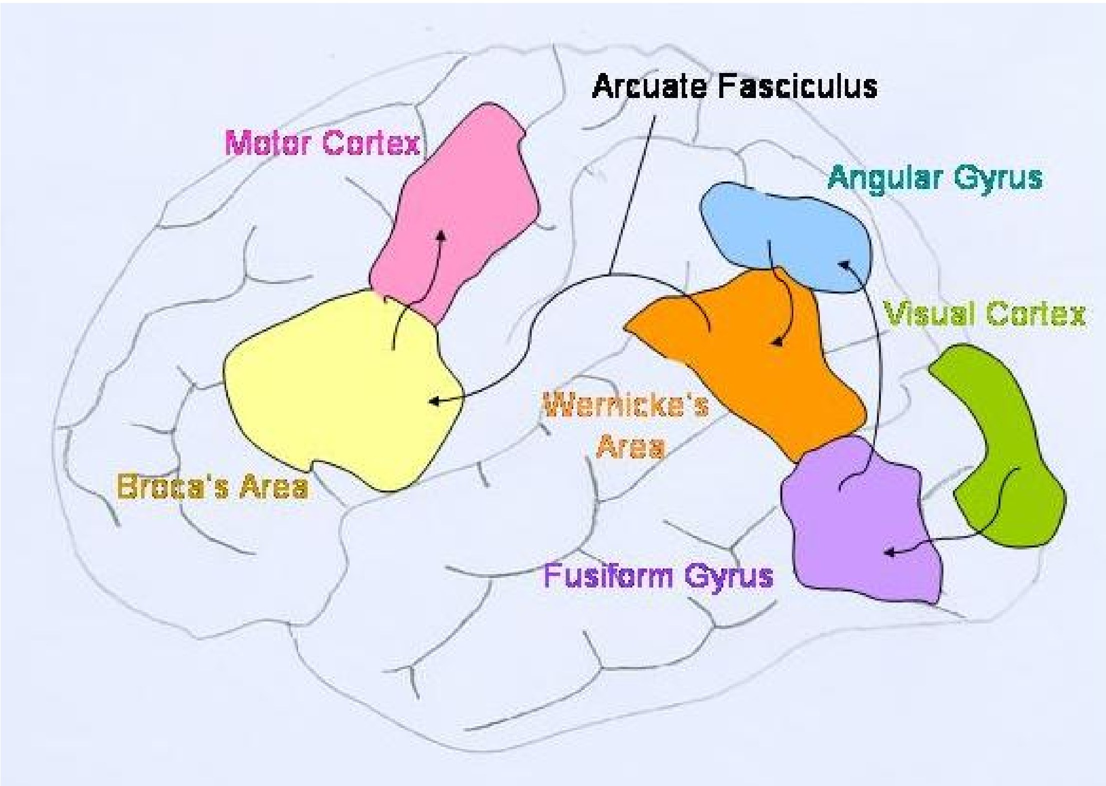


**Figure 9. A schematic diagram illustrating the neural pathway for visual language processing.**

An involvement of basal temporal cortices for visual word form translation in language processing has been reported previously. The middle portion of the fusiform gyrus has been referred to as “basal temporal language area” (Luders et al., 1991; Bookheimer et al., 1998), “multimodal language region” (Buchel et al., 1998), “visual word form area (VWF area)” (Cohen et al., 2000), or as “word form area” (Polk and Farah, 2002) where it is commonly agreed that a perceptually invariant higher-order orthographic regularity is computed from the visual input. Recent meta-analysis showed that the mid-fusiform area is consistently activated in different writing systems (Bolger et al., 2005).

In alphabetic languages (Cohen et al., 2000; Cohen et al., 2002), the visual word form (VWF) system was suggested to specifically devote to the processing of letter strings. On the basis of imaging and neuropsychological data, Cohen et al. (Cohen et al., 2002) suggested that VWF area computes a representation of abstract letter identities from visual input, a representation invariant for irrelevant parameters such as size, location, font, or case. Cohen et al. suggested that the VWF appeared strictly unimodal. In contrast to the studies by Cohen and her team, Price et al. (Price et al., 2003) argued that the claimed VWF area does not respond solely to visual presentation of stimuli, but also to the auditory presentation of stimuli (Price et al., 2003). They also showed that this area responds in picture and object naming tasks (Moore and Price, 1999). Therefore, they proposed that the fusiform area may be a multimodal area for different types of stimuli and link with multiple cognitive processes. However, in Chinese language studies with auditory stimuli, activations at the fusiform gyrus by auditory stimuli with language components were reported occasionally (Hsieh et al., 2001). It is possible that there are not many Chinese language studies with auditory stimuli. Although the reason is still unknown, it is clear that there are some factors which may produce the differences in findings. There may be a cultural difference in the auditory performance of language processing. The differences in imaging tools used and the tasks designed can be other factors. In the literature showing VWF responding to auditory stimuli, most of the studies cited by Price et al. (Price et al., 2003) used PET for imaging the functional areas in brain.

### 1.7 Hemispheric Lateralization in Rhyme Processing with fMRI

Rhyme is a salient component within a syllable and it has the potential to demonstrate how sound is processed in the brain. Rhyme processing is a pre-requisite for further decoding of a speech (Salmelin et al., 1999; Obleser et al., 2001). In order to comprehend a routine involved in functional interpretation of languages, studies on rhyme processing in the brain should be performed at the highest priority (Salmelin et al., 1999; Obleser et al., 2001). Numerous functional studies have demonstrated the left and right hemispheres were not symmetrically involved in rhyme processing in different languages (Gootjes et al., 1999; Rinne et al., 1999; Tervaniemi et al., 2000; Makela et al., 2003; Rudner et al., 2005). Left-hemispheric language predominance was always identified in right handers for the processing of rhymes in both tone and non-tone languages.

In the studies of non-tone languages, left lateralization in the processing of vowels was always identified. Several studies on the perception of Finnish vowels, was found to activate the left hemisphere of the brain in native Finnish speakers (Gootjes et al., 1999; Tervaniemi et al., 2000; Makela et al., 2003). Study on native Scandinavians with the use of Finnish and Norwegian vowels also demonstrated left language dominance (Hugdahl et al., 2003). Similar findings were also demonstrated in English (Benson et al., 2001; Poldrack et al., 2001) and German (Obleser et al., 2001; Jancke et al., 2002).

In the studies of tone languages, left hemispheric lateralization of rhyme processing was frequently found (Gandour et al., 2000; Siok et al., 2003; Lin et al., 2005). Lin et al. (2005) indicated leftward asymmetry of brain activity at STG in the judgment of Mandarin rhymes in native Chinese speakers. Lin et al. (2005) explained the neural pathway involving the left STG is more preferable to the right in the processing of rhymes. Gandour et al. (2000) reported that native Thai speakers also showed significant activations at the left IFG when processing Thai rhymes. This implied that the left hemisphere plays an active role in processing of segmental components. The brain processing areas in the processing of Cantonese rhymes were therefore proposed to be lateralized to the left hemisphere as well.

## 1.8 Aims of the Present Study and the Hypothesis to be Tested

We proposed to use fMRI as the imaging modality, which provides high resolution anatomical brain images with brain activities, in localizing the language processing areas. Auditory paradigm with Cantonese rhymes was used as a stimulus to localize the language processing areas. Auditory instead of visual paradigm was used since it was less dependent in visual interpretation, which is applicable to both poorly educated population and patients with poor vision. In the present study, Cantonese rhymes were chosen as auditory stimuli to be presented to the native Cantonese speakers. Rhyme is one of the basic units of a syllable (Bauer and Benedict, 1997). We proposed to use the most fundamental unit (rhymes) in localizing the language processing area (Baciu et al., 2001; Owen et al., 2004; Cousin et al., 2006). Rhyme also forms the most salient part of a word. Rhyme processing is a pre-requisite for further decoding of speech (Salmelin et al., 1999; Obleser et al., 2001). Understanding the rhyme processing may provide useful information for further studies in higher level language cognition, for example word processing or sentence processing. In the local community, over 80% of the population speaks Cantonese (Summary Results of 2001 Population Census, Census and Statistics Department, HKSAR 2001, http://www.info.gov.hk/censtatd/). Findings from the previous studies on English vowels and Mandarin rhymes may not benefit the Cantonese-speaking community. Cantonese is a dialect of Chinese with different speech prosody from Mandarin although both the Cantonese and Mandarin are branches in the family of Chinese language (Ching et al., 1994; Matthews and Virginia, 1994; Cheung et al., 2001). Cantonese has six lexical tones (Tang et al., 2002) while Mandarin has four. In addition, Cantonese possesses more coda than Mandarin. It is not clear whether Cantonese rhymes would have a compatible activation pattern as English vowels and Mandarin rhymes in language processing.

We made the following hypothesis. We hypothesized that the Cantonese rhymes would activate the inferior frontal gyrus (Broca's area). The Cantonese rhymes would also activate the superior temporal gyrus (Wernicke's area). We hypothesized that the activation pattern by Cantonese rhymes would be similar to that from previous studies with English vowels. We also hypothesized that the activation pattern from Cantonese rhymes would be similar to that from previous studies with Mandarin rhymes. We aimed to use fMRI to determine the brain areas for the processing of Cantonese rhymes in healthy right-handed native Cantonese speakers. To our knowledge, this will be the first fMRI study using auditory stimuli with Cantonese rhymes. By examining the effect of Cantonese rhymes on language regions, our findings would provide evidences of using Cantonese rhymes to localize the language processing area in local Cantonese speaking community.

# Chapter Two

# Material and Methods

## 2.1 Subjects

A total of 15 native Cantonese speakers aged from 19 to 25 years were recruited. All subjects were in years of formal education with tertiary level or above. The handedness of the subjects were measured by the Edinburgh Handedness Inventory (Oldfield, 1971) (Appendix 1) and they exhibited normal hearing sensitivity. The exclusion criteria were: 1) known or suspected central nervous system disease; 2) known or suspected ocular injuries; 3) known or suspected pregnancy; 4) contraindications to MRI study (cardiac pacemakers, therapeutic or accidental presence of magnetizable metals or prosthesis in the body, past head or spinal trauma requiring neurosurgery); 5) claustrophobia. MRI scanning was then performed on each subject in the Department of Radiology and Organ Imaging at the United Christian Hospital. All procedures were approved by the Ethics Committees at The Hong Kong Polytechnic University and the United Christian Hospital. Informed written consent was obtained from the subjects prior to the study.

## 2.2 MR Acquisition

MRI brain scanning was performed on a 1.5 Tesla scanner (Siemens Sonata, Germany) at the Department of Radiology and Organ Imaging in the United Christian Hospital. Foam rubber earplugs were used to muffle the MRI scanning noise. The head was immobilized in a standard head coil with foam rubber pads. Four imaging datasets were acquired: 1) standard high-resolution sagittal images acquired with volumetric T1 weighted 3D-FLASH sequence (TR=11ms, TE=4.76ms, flip angle=20º, FOV=256mm, matrix=256×208, slice thickness=1mm, gap=0.2mm) as anatomical reference for functional images; 2) T2*-weighted sequence for the identification of possible brain lesions; 3) two sets of BOLD fMRI images acquired with gradient-echo echo planar imaging (EPI) sequence (TR=2000ms, TE=60ms, flip angle=90º, FOV=200 mm, matrix=64x64, thickness=5mm, gap=1.5mm) while the subject performs the auditory language task.

### 2.3 Auditory Task of Cantonese Rhymes

Subjects performed an auditory task to determine the processing locations for Cantonese rhymes in the brain using stimuli with Cantonese rhymes. Each subject received practice on the tasks 30 minutes prior to scanning. The event-related paradigm consisted of 120 trials. Each trial lasted for 4 seconds and could be one of the following conditions: 1) a Cantonese rhyme; 2) a filtered rhyme; 3) silence. Subjects were required to make discrimination judgments on Cantonese rhymes from the filtered rhymes. In the present study, Cantonese rhymes in tone one were chosen as auditory stimuli to be presented to the native Cantonese speakers. Rhyme is one of the basic units of a syllable (Bauer and Benedict, 1997) and it is the most salient part of a word. The present study would like to use the most fundamental unit (rhymes) in localizing the language processing area (Baciu et al., 2001; Owen et al., 2004; Cousin et al., 2006). There were only 9 vowels in Cantonese (Tang et al., 2002). However, the 9 Cantonese vowels were inadequate to make up a paradigm with significant events. To avoid any effect from familiarity with the repetition of the stimuli, Cantonese rhymes were chosen instead of vowels in the present study. Cantonese has 59 readable rhymes. Thirty-five of them do not have meanings while the remaining twenty-four can be recognized as Cantonese words by themselves. Although it can be recognized as Cantonese words, the readable rhymes are abstract in meaning and mainly found in verbal content. The selection criterion of the rhymes in the present study was that the rhymes should be easily identified by the subjects. In order to increase the ease of discrimination, the 24 recognizable Cantonese rhymes with tone one were chosen as one kind of stimuli with semantic and segmental phonetic information in the present study. Cantonese rhymes chosen in the present study were shown in Table 6.

| | Cantonese rhymes | Equivalent Cantonese words |
|---|---|---|
| 1 | ap | 噏 |
| 2 | at | 兀 |
| 3 | am | 庵 |
| 4 | an | 奀 |
| 5 | ang | 鶯 |
| 6 | au | 歐 |
| 7 | o | 柯 |
| 8 | on | 安 |
| 9 | ak | 厄 |
| 10 | ai | 唉 |
| 11 | ok | 呵 |
| 12 | ou | 噢 |
| 13 | aa | 丫 |
| 14 | aak | 握 |
| 15 | aam | 啱 |
| 16 | aang | 罌 |
| 17 | aai | 哎 |
| 18 | aau | 拗 |
| 19 | ong | 骯 |
| 20 | oi | 哀 |
| 21 | aap | 鴨 |
| 22 | aat | 壓 |
| 23 | aan | 晏 |
| 24 | e | 誒 |

**Table 6. Twenty-four recognizable Cantonese rhymes with tone one chosen as auditory stimuli in the present study.**

Twenty-four filtered rhymes were constructed with the same method as in the study by Hsieh et al. (2001). A low-pass filter was applied onto 24 Cantonese rhymes. The low-pass filter allows the passage of low frequencies only while attenuate frequencies higher than the cut-off frequency (200 Hz). The characteristic of the filtered rhymes is the elimination of the high spectral information while preserving the acoustic features of the Cantonese rhymes in terms of duration and amplitude. None of the filtered rhymes were recognized as Cantonese rhymes or words. The filtered rhymes contained similar duration and amplitude as the corresponding Cantonese rhymes. However, any semantic or phonologic components within Cantonese rhymes were excluded by the low-pass filter in the filtered rhymes (Hsieh et al., 2001; Gandour et al., 2003). All three conditions were edited to have equal energy level. The probability of the appearance of Conditions 1, 2 and 3 was evenly distributed. The three conditions were presented in a randomized order. The auditory materials were delivered binaurally through a headphone attached to a semi-rigid tube which was connected to an MR-compatible sound transducer. Background scanner noise was constant throughout all baseline and activation periods.

Individual comparisons of the conditions Cantonese rhymes, filtered rhymes with silence were performed to investigate activated brain areas. The comparison of Cantonese rhymes versus silence was the identification of the activated areas involved in phonological, semantic, and acoustic processing. In the comparison of filtered rhymes versus silence, only the activated areas in acoustic processing were expected. Direct comparison of the activations by Cantonese rhymes and filtered rhymes were hypothesized to be able to demonstrate the brain areas involved in phonological and semantic processing.

## 2.4 MRI Data Analysis

All fMRI data was subjected to the Analysis of Functional NeuroImage (AFNI) software (Cox, 1996) (National Institute of Mental Health, http://afni.nimh.nih.gov) on a Pentium computer running the Linux operating system with the pre-processing strategy similar to that in a study by Beauchamp et al. (Beauchamp et al., 2003). The first 5 volumes in each functional dataset, collected before equilibrium magnetization was reached, were discarded. For each subject, the functional data was then motion-corrected and co-registered to the 10$^{th}$ image of the first functional dataset using three-dimensional volume registration. A spatial filter with a root-mean-square width of 4mm was applied to each functional dataset. Low signal intensity voxels located outside the brain were excluded from the functional images by a clipping function. A multiple regression analysis was performed to find brain areas showing changes of MR signal related to processing of two conditions (Cantonese rhymes and filtered rhymes) with reference to silence. The impulse response function to each condition was estimated with 2-sec resolution using deconvolution. A separate regressor was used to model the response in each 2-sec period in a 20-sec window following each stimulus presentation. The response magnitude to each stimulus type was calculated by averaging the beta-weights of the regressors from the $2^{nd}$ through $10^{th}$ second of the response so as to capture the positive blood-oxygenation level dependent response (Cohen, 1997).

The results from analyses performed within individual subjects were reported in order to assess whether the results were consistent across subjects. Single subject analyses were performed on unsmoothed data. In order to protect against type I error, individual voxel probability threshold of $p<0.01$ was held to correct the overall significance level to $\alpha<0.05$. Based upon a Monte Carlo simulation with 1000 iteration runs via AlphaSim program in AFNI (Cox, 1996) on the brain volume, it was estimated that a $378cm^3$ contiguous volume (7 voxels, each measuring 3mm x 3mm x 6mm) would provide the significance level $\alpha=0.03$, which met the overall threshold of $p<0.05$. Individual subject p-value maps were interpolated to 1mm using a cubic interpolation algorithm and overlaid on each subject's anatomical scan and transformed to the standardized space of Talairach and Tounoux (Talairach and Tournoux, 1988).

Group activation maps were also reported. The primary goal of this analysis was to obtain normalized coordinates giving a general indication of brain areas in which auditory stimuli of language may be present. The brain volume in standardized space with the response magnitude to each stimulus type for each subject was spatially smoothed with a Gaussian kernel (4 mm FWHM) to reduce the false negative due to individual variability of brain shape. These brain volumes were then grouped for Analysis of Variance (ANOVA). Analysis of group subject data used the same thresholds for statistical significance as in single subject analysis. Statistical p-maps were created for each of the contrasts of interest.

An anatomical brain volumes was randomly chosen from the subject group and then reconstructed using FreeSurfer (Fischl et al., 1999) (MGH/MIT/HMS Athinoula A. Martinos Center for Biomedial Imaging, Boston, http://surfer.nmr.mgh.harvard.edu). The inflated cortical surface of the hemispheres was used as the underlay for the visualization of the statistical parametric maps using AFNI Surface Mapper (SUMA) (National Institute of Mental Health, http://afni.nimh.nih.gov). The procedures of inflation of cortical surface were well documented by Fischl et al. (Fischl et al., 1999).

# Chapter Three

# Results

### 3.1 Demographic Profile of Subjects

A total of 15 native Cantonese speakers (7 males and 8 females) aged from 19 to 25 years (mean age, 21.13 years; SD, 1.92 years) were included. 11 volunteers were excluded either because of the motion artifacts, or because of the absence of brain activations at the primary auditory cortex indicating that those subjects were not concentrating on the auditory stimuli. The number of subjects included in the present study was appropriate by taking into account of the signal percent change of 0.5% with BOLD fMRI technique, 80% power, type I error of 5% and less than 5mm FWHM smoothing (Desmond and Glover, 2002). Demographic profile of the subjects is summarized in Table 7. The laterality quotient was measured by the Edinburgh Handedness Inventory (Appendix 1) (Oldfield, 1971), which ranges from -100 for strong left-handedness to +100 for strong right handedness. It was measured by the preferences in the use of hands in the activities, including writing, drawing, throwing, using scissors, using toothbrush, using chopsticks, using spoon, using broom, striking match and opening lid. All the subjects in the present study were right-handed with the laterality quotient (LQ) calculated in Table 7 (mean laterality quotient, 82; SD, 15.68). A number of brain areas showing activations were observed in all comparisons (Tables

8-10).

| | Subjects | Gender | Age | Laterality Quotient (LQ) |
|---|---|---|---|---|
| 1 | ckc | M | 23 | 90 |
| 2 | lot | F | 21 | 100 |
| 3 | mhk | M | 24 | 60 |
| 4 | ch | M | 20 | 100 |
| 5 | cly | F | 20 | 80 |
| 6 | wwk | F | 21 | 90 |
| 7 | yts | M | 21 | 80 |
| 8 | cls | F | 20 | 60 |
| 9 | llk | F | 25 | 90 |
| 10 | wly | F | 20 | 80 |
| 11 | ltm | F | 19 | 90 |
| 12 | yyw | F | 24 | 60 |
| 13 | ccm | M | 20 | 70 |
| 14 | ckh | M | 20 | 100 |
| 15 | yyh | M | 19 | 90 |

**Table 7. Demographic profile of all the subjects included in the present study.**

| Cantonese rhymes vs. silence | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Subjects** | **Activation** | | | | | | |
| | | **IFG** | **MFG** | **STG** | **MTG** | **SPG** | **IG** | **AG** |
| 1 | ckc | + | + | + | + | + | Nil | Nil |
| 2 | lot | + | + | + | + | Nil | Nil | - |
| 3 | mhk | + | + | + | + | + | Nil | - |
| 4 | ch | + | + | + | + | Nil | Nil | - |
| 5 | cly | + | + | + | + | + | + | - |
| 6 | wwk | + | + | + | + | Nil | + | - |
| 7 | yts | + | + | + | + | + | - | - |
| 8 | cls | + | + | + | + | + | Nil | - |
| 9 | llk | + | + | + | + | Nil | Nil | Nil |
| 10 | wly | + | + | + | + | + | Nil | Nil |
| 11 | ltm | + | + | + | + | + | Nil | Nil |
| 12 | yyw | + | + | + | + | Nil | Nil | - |
| 13 | ccm | + | + | + | + | + | Nil | - |
| 14 | ckh | + | + | + | + | + | Nil | Nil |
| 15 | yyh | + | + | + | + | + | Nil | Nil |

**Table 8. Summary of the activated areas from the individual subjects in the comparison of Cantonese rhymes versus silence. Key: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; STG, superior temporal gyrus; MTG, middle temporal gyrus; SPG, superior parietal gyrus; IG, insula gyrus; AG, angular gyrus. '+' represents the presence of positive BOLD signal; '-' represents the presence of negative BOLD signal; 'Nil' represents the absence of BOLD signal.**

| Filtered rhymes vs. silence | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Subjects** | **Activation** | | | | | | |
| | | **IFG** | **MFG** | **STG** | **MTG** | **SPG** | **IG** | **AG** |
| 1 | ckc | + | Nil | + | + | Nil | Nil | Nil |
| 2 | lot | + | Nil | + | + | Nil | Nil | - |
| 3 | mhk | Nil | Nil | + | + | - | Nil | - |
| 4 | ch | + | + | + | + | + | Nil | Nil |
| 5 | cly | + | + | + | + | Nil | Nil | Nil |
| 6 | wwk | + | Nil | + | Nil | + | + | - |
| 7 | yts | Nil | Nil | + | + | Nil | Nil | - |
| 8 | cls | + | Nil | + | Nil | Nil | Nil | - |
| 9 | llk | + | + | + | + | Nil | Nil | Nil |
| 10 | wly | + | Nil | + | + | Nil | - | - |
| 11 | ltm | + | + | + | + | - | Nil | - |
| 12 | yyw | + | Nil | + | + | Nil | Nil | - |
| 13 | ccm | + | Nil | + | Nil | Nil | Nil | - |
| 14 | ckh | + | Nil | + | + | + | Nil | Nil |
| 15 | yyh | Nil | Nil | + | + | Nil | Nil | - |

**Table 9. Summary of the activated areas from the individual subjects in the comparison of filtered rhymes versus silence. Key: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; STG, superior temporal gyrus; MTG, middle temporal gyrus; SPG, superior parietal gyrus; IG, insula gyrus; AG, angular gyrus. '+' represents the presence of positive BOLD signal; '-' represents the presence of negative BOLD signal; 'Nil' represents the absence of BOLD signal.**

| Cantonese rhymes vs. Filtered rhymes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Subjects** | **Activation** | | | | | | |
| | | **IFG** | **MFG** | **STG** | **MTG** | **SPG** | **IG** | **AG** |
| 1 | ckc | + | + | Nil | Nil | Nil | Nil | Nil |
| 2 | lot | Nil | Nil | Nil | Nil | Nil | Nil | Nil |
| 3 | mhk | + | + | Nil | Nil | Nil | Nil | Nil |
| 4 | ch | Nil | Nil | Nil | Nil | Nil | Nil | Nil |
| 5 | cly | + | + | + | Nil | Nil | Nil | Nil |
| 6 | wwk | + | + | Nil | Nil | Nil | Nil | Nil |
| 7 | yts | + | + | Nil | Nil | Nil | Nil | Nil |
| 8 | cls | + | + | Nil | Nil | Nil | Nil | Nil |
| 9 | llk | Nil | + | Nil | Nil | Nil | Nil | Nil |
| 10 | wly | + | + | + | Nil | Nil | Nil | Nil |
| 11 | ltm | Nil | + | Nil | Nil | Nil | Nil | Nil |
| 12 | yyw | Nil | Nil | Nil | Nil | Nil | Nil | Nil |
| 13 | ccm | + | + | + | Nil | Nil | Nil | Nil |
| 14 | ckh | + | + | Nil | Nil | Nil | Nil | Nil |
| 15 | yyh | + | + | Nil | Nil | Nil | Nil | Nil |

**Table 10. Summary of the activated areas from the individual subjects in the comparison of Cantonese rhymes versus filtered rhymes. Key: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; STG, superior temporal gyrus; MTG, middle temporal gyrus; SPG, superior parietal gyrus; IG, insula gyrus; AG, angular gyrus. '+' represents the presence of positive BOLD signal; '-' represents the presence of negative BOLD signal; 'Nil' represents the absence of BOLD signal.**

### 3.2 Cantonese Rhymes versus Silence

On the frontal and parietal cortices, positive activations were observed at bilateral medial frontal, middle and inferior frontal gyri, precentral gyri and postcentral gyri consistently in fifteen subjects (Table 8). The averaged functional map from all the subjects was shown in Figure 10. The left superior parietal gyrus was also activated. On the temporal cortex, positive activations were shown bilaterally at superior temporal gyrus/sulcus and middle temporal gyrus. On the occipital cortex, positive activations were also demonstrated at bilateral lingual gyri and calcarian sulci. The left occipital pole was also activated.

Negative BOLD signals were observed bilaterally at the tempo-parietal junction and limbic areas. They included the bilateral angular gyri, anterior and posterior cingulate gyri. No positive and negative BOLD signals were found at bilateral fusiform gyri.

In general, the activated areas with positive or negative BOLD signals were more extensive on the left hemispheric surface than on the right hemispheric surface. The strength of positive activations in the left brain was also stronger than those in the right brain. Brain regions showing positive and negative BOLD signals in the comparison of Cantonese rhymes vs. silence are summarized in Table 11.

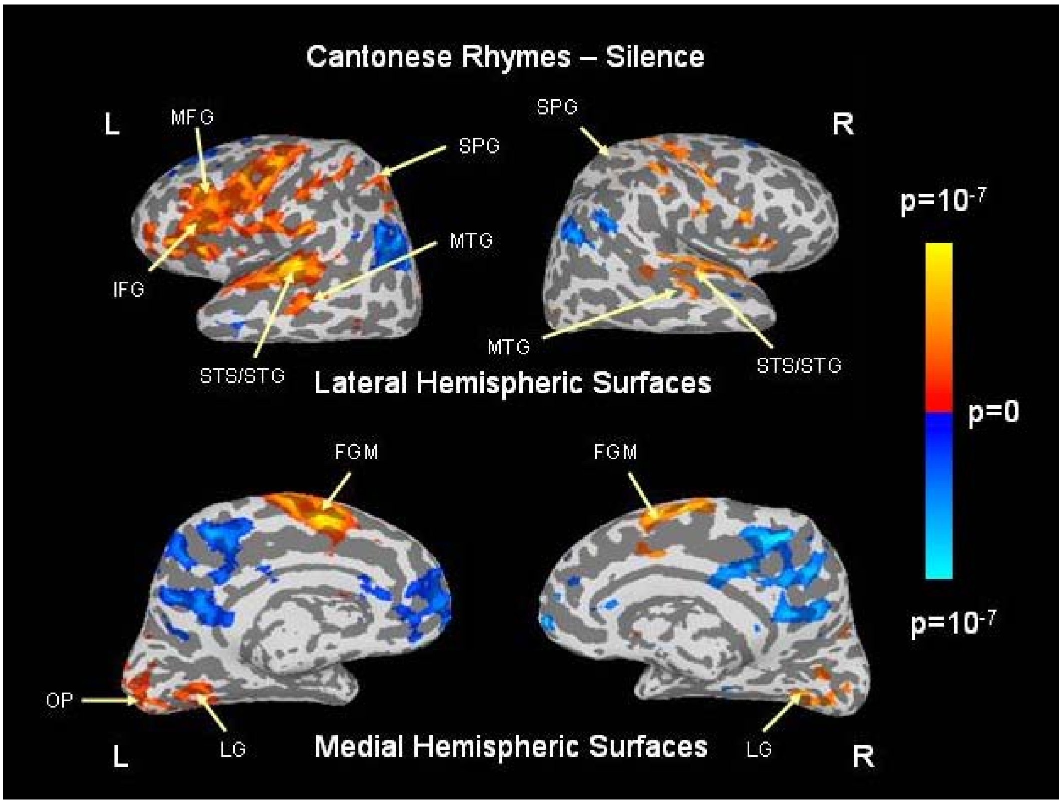


**Figure 10. Activation maps showing the positive and negative BOLD signals on the lateral and medial hemispheric surfaces in the comparison of Cantonese rhymes vs. silence. Key: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; FGM, medial frontal gyrus; STG, superior temporal gyrus; STS, superior temporal sulcus; MTG, middle temporal gyrus; SPG, superior parietal gyrus; OP, occipital pole; LG, lingual gyrus.**

| Brain Regions in Left Hemisphere | Brain Regions in Right Hemisphere |
|---|---|
| **Positive BOLD signals** | |
| *Frontal lobe*<br>Inferior frontal gyrus<br>Middle frontal gyrus<br>Medial frontal gyrus<br>Precentral gyrus | *Frontal lobe*<br>Inferior frontal gyrus<br>Medial frontal gyrus<br>Precentral gyrus |
| *Temporal lobe*<br>Superior temporal gyrus<br>superior temporal sulcus<br>Middle temporal gyrus | *Temporal lobe*<br>Superior temporal gyrus<br>superior temporal sulcus<br>Middle temporal gyrus |
| *Parietal lobe*<br>Postcentral gyrus<br>Superior parietal gyrus | *Parietal lobe*<br>Postcentral gyrus |
| *Occipital lobe*<br>Lingual gyrus<br>Calcarian sulcus<br>Occipital pole | *Occipital lobe*<br>Lingual gyrus<br>Calcarian sulcus |
| **Negative BOLD signals** | |
| *Parietal lobe*<br>Angular gyrus | *Parietal lobe*<br>Angular gyrus |
| *Limbic region*<br>Anterior cingulate gyrus<br>Posterior cingulate gyrus | *Limbic region*<br>Anterior cingulate gyrus<br>Posterior cingulate gyrus |

**Table 11. Summary of anatomical areas showing positive or negative BOLD signals in the comparison of Cantonese rhymes vs. silence.**

### 3.3 Filtered Rhymes versus Silence

On the frontal and parietal cortices, positive activations were observed at bilateral medial frontal, inferior frontal gyri, precentral gyri and postcentral gyri in twelve subjects (Table 9). The averaged functional map from all the subjects was shown in Figure 11.

Different from the findings in the comparison of Cantonese rhymes vs. silence, the bilateral middle frontal gyri and the left parietal gyrus were not activated. On the temporal cortex, positive activations were shown bilaterally at superior temporal gyrus/sulcus. Instead of having bilateral activations at middle temporal gyri, only the right middle temporal gyrus was activated. On the occipital cortex, positive activations were also demonstrated at bilateral lingual gyri. The left occipital pole and right calcarian sulcus were also activated.

Similar to the findings in the comparison of Cantonese rhymes vs. silence, negative BOLD signals were observed bilaterally at the tempo-parietal junction and limbic areas. They included the bilateral angular gyri, anterior and posterior cingulate gyri. No positive and negative BOLD signals were found at bilateral fusiform gyri.

In general, the extent of the activated areas with positive or negative BOLD signals was similar on both left and right hemispheric surfaces. Brain regions showing positive and negative BOLD signals in the comparison of filtered rhymes vs. silence are summarized in Table 12.

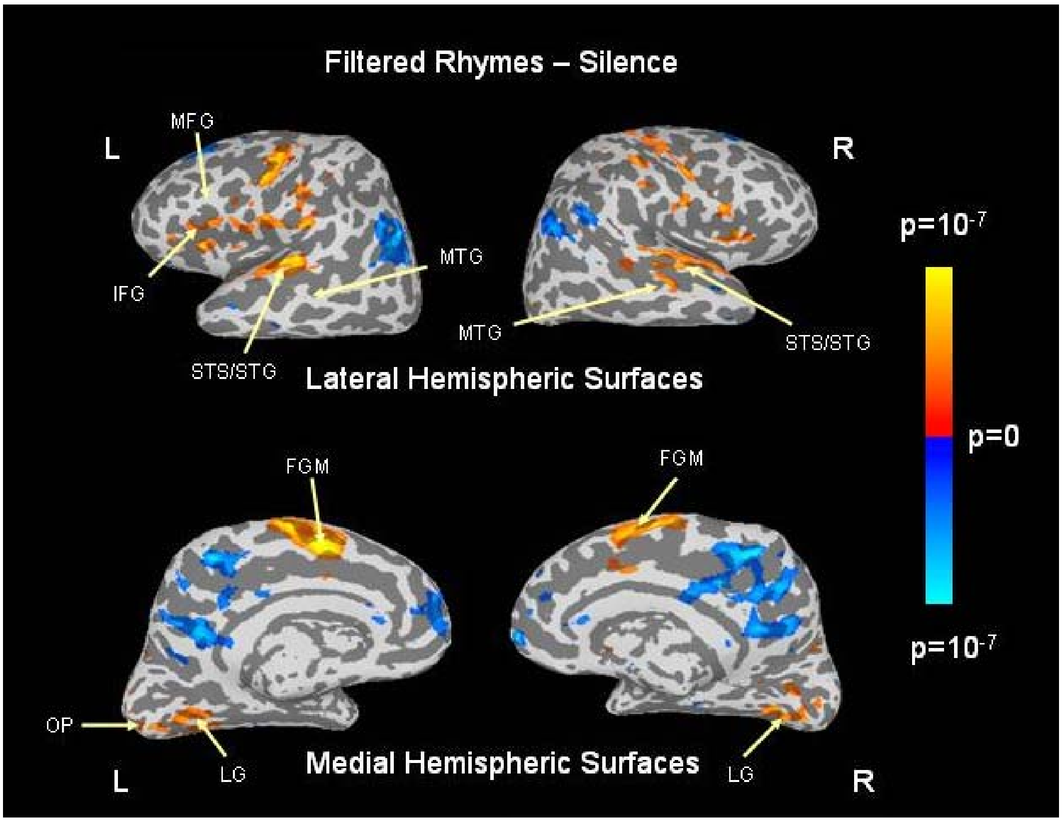


**Figure 11. Activation maps showing the positive and negative BOLD signals on the lateral and medial hemispheric surfaces in the comparison of filtered rhymes vs. silence. Key: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; FGM, medial frontal gyrus; STG, superior temporal gyrus; STS, superior temporal sulcus; MTG, middle temporal gyrus; OP, occipital pole; LG, lingual gyrus.**

| **Brain Regions in Left Hemisphere** | **Brain Regions in Right Hemisphere** |
|---|---|
| **Positive BOLD signals** | |
| *Frontal lobe*<br>Inferior frontal gyrus<br>Medial frontal gyrus<br>Precentral gyrus | *Frontal lobe*<br>Inferior frontal gyrus<br>Medial frontal gyrus<br>Precentral gyrus |
| *Temporal lobe*<br>Superior temporal gyrus<br>Superior temporal sulcus | *Temporal lobe*<br>Superior temporal gyrus<br>Superior temporal sulcus<br>Middle temporal gyrus |
| *Parietal lobe*<br>Postcentral gyrus | *Parietal lobe*<br>Postcentral gyrus |
| *Occipital lobe*<br>Lingual gyrus<br>Occipital pole | *Occipital lobe*<br>Lingual gyrus<br>Calcarian sulcus |
| **Negative BOLD signals** | |
| *Parietal lobe*<br>Angular gyrus | *Parietal lobe*<br>Angular gyrus |
| *Limbic region*<br>Anterior cingulate gyrus<br>Posterior cingulate gyrus | *Limbic region*<br>Anterior cingulate gyrus<br>Posterior cingulate gyrus |

**Table 12. Summary of anatomical areas showing positive or negative BOLD signals in the comparison of filtered rhymes vs. silence.**

### 3.4 Cantonese Rhymes versus Filtered Rhymes

Positive activations were only demonstrated at the left middle and inferior frontal gyri on the frontal cortices in ten and twelve subjects respectively (Table 10). No positive or negative BOLD signals were shown on the right frontal, bilateral parietal, temporal and occipital cortices. Brain regions showing positive BOLD signals in the comparison of Cantonese rhymes vs. filtered rhymes are summarized in Table 13. The averaged functional map from all the subjects was shown in Figure 12.

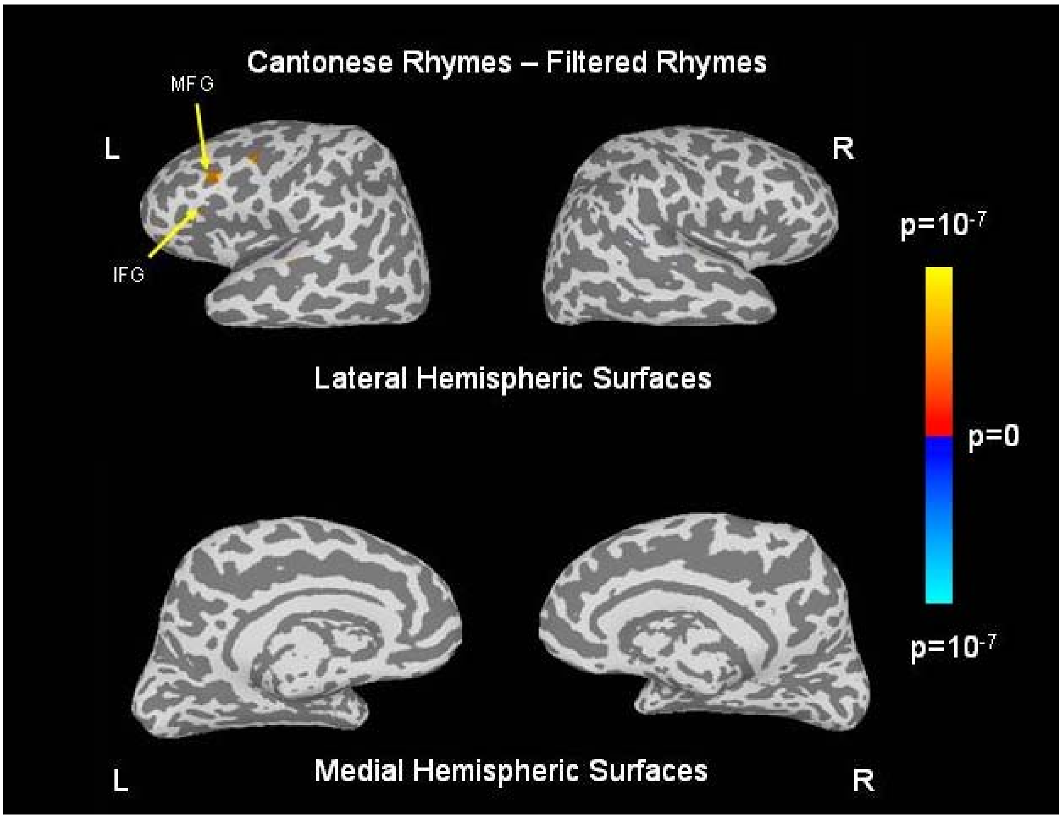


**Figure 12. Activation maps showing the positive and negative BOLD signals on the lateral and medial hemispheric surfaces in the comparison of Cantonese rhymes vs. filtered rhymes. Key: IFS, inferior frontal gyrus; MFS, middle frontal gyrus.**

| **Brain Regions in Left Hemisphere** | **Brain Regions in Right Hemisphere** |
|---|---|
| **Positive BOLD signals** | |
| *Frontal lobe*<br>Inferior frontal gyrus<br>Middle frontal gyrus | Nil |

**Table 13. Summary of anatomical areas showing positive or negative BOLD signals in the comparison of Cantonese rhymes vs. filtered rhymes.**

# Chapter Four

# Discussion

Language areas activated by auditory stimuli with Cantonese rhymes and filtered rhymes were studied in healthy right-handed native Cantonese speakers. A number of brain regions were commonly activated by both Cantonese rhymes and filtered rhymes. On the frontal and parietal cortices, they were bilateral medial frontal (FGM), inferior frontal gyri (IFG), precentral gyri and postcentral gyri. On the temporal cortex, bilateral superior temporal sulci/gyri (STS/STG) were activated by Cantonese rhymes or filtered rhymes. On the occipital cortex, bilateral lingual gyri (LG) and right calcarian sulcus were activated by Cantonese rhymes as well as filtered rhymes. In the comparison of Cantonese rhymes vs. filtered rhymes, although significantly stronger positive activations were only demonstrated at the left middle frontal gyri (MFG) and IFG with Cantonese rhymes, activity in some other brain areas specifically with Cantonese rhymes, but not with filtered rhymes, were noted in separate comparisons of Cantonese rhymes and filtered rhymes with silence. They included bilateral MFG, the left superior parietal gyrus (SPG) and the left middle temporal gyrus (MTG). Stronger and more extensive activations were found in the left brain than the right brain in the comparison of Cantonese rhymes vs. silence. Negative BOLD signals were consistently found bilaterally at angular gyri (AG), and the anterior and posterior cingulate gyri in separate comparisons of Cantonese rhymes and filtered rhymes with silence.

In the present study, Cantonese rhymes are considered as speech sounds with semantic contents since each rhyme in the auditory stimulus can be recognized as a Cantonese word. The filtered rhymes are considered as speech sounds as well since they are also recognized as human sound track, however, they do not have semantic contents as none of the filtered rhymes are recognized as a Cantonese rhyme or word. Our functional results suggest that bilateral MFG, left MTG and left SPG in addition to the brain areas related to processing of auditory stimuli are recruited for language processing. Left hemispheric lateralization is also suggested in language processing.

**4.1 Processing of Filtered Rhymes**

All the activations observed in the comparison of filtered rhymes vs. silence overlapped with those observed in the comparison of Cantonese rhymes. This suggests that the activated brain areas including precentral gyri, postcentral gyri, IFG, FGM and STS/STG are sensitive to acoustic features of the speech signals irrespective to the presence of language contents.

It is not surprising in our study that the STS/STG was activated in both auditory input of filtered rhymes, as the primary auditory cortex is located at mid portion of STG

(Vouloumanos et al., 2001). Beauchamp et al. (Beauchamp et al., 2004) suggested that STS/STG is a multisensory integration area. With the auditory stimuli of speech or complex non-speech sounds, the activations at STS/STG are more bilateral (Binder et al., 1997; Benson et al., 2001; Vouloumanos et al., 2001; Gandour et al., 2004) with right side having stronger activations (Beauchamp et al., 2003). In the present study, more extensive activations were found at the right STS/STG than the left STS/STG. The activations were extended to the right MTG., where no activation was found at the left MTG. Our findings with non-speech are consistent with the previous literature, where the right STG is suggested to be responsible for resolving temporal event of a complex auditory signal (Beauchamp et al., 2003).

On the frontal cortex, bilateral activations at IFG were demonstrated in perceiving filtered rhymes. It indicates that acoustic processing is able to activate the IFG (Zatorre et al., 1992). Recruitment of the IFG in non-speech perception is no longer an unexpected finding (Chee et al., 1999; Benson et al., 2001; Hsieh et al., 2001). Several studies have reported the IFG activation for non-linguistic conditions, including rapid acoustic modulations (Muller et al., 2001), and short-term memory (Paulesu et al., 1993; Klingberg et al., 1996). In fact, activation at the IFG in filtered rhymes cognition was lesser in extent when compared with that from Cantonese rhymes-silence in the present study. These results were similar to Benson et al. (2001) that smaller activity was identified in non-speech relative to speech processing.

Similar to IFG, activation at the bilateral FGM was also recognized in the processing of filtered rhymes. Binder at al. (1997) suggested that the FGM is involved in memory encoding functions (Binder et al., 1997). Additional processes engaged in filtered rhymes processing, for example, decision and executive control processes, may contribute activation at the FGM (Poldrack et al., 2001).

Activation of the precentral and postcentral were seen bilaterally in comparison of filtered-pitches with silence. The precentral and the postcentral gyrus are the location of the primary motor (Ugur et al., 2005) and the somatosensory cortex respectively (Takeda et al., 2000; Satoh et al., 2002). Nagao et al. (1999) revealed that the precentral gyrus is responsible for coordination of speech articulation (Nagao et al., 1999). Apraxia of speech would be developed associated with infarct in the precentral gyrus. Satoh et al. (2002) pointed out that infarction over the postcentral gyrus would develop disturbance of the elementary somatosensory functions (Satoh et al., 2002), which supporting the role of the postcentral gyrus in the perception of auditory information.

### 4.2 Processing of Cantonese Rhymes

A number of brain areas were shown to be activated in the processing of Cantonese rhymes as well as filtered rhymes. They include the STS/STG, IFG, FMG, precentral and postcentral gyrus. Cantonese rhymes elicited additional activations at the bilateral MFG, left MTG and left SPG than filtered rhymes. In general, activations in the comparison of Cantonese rhymes vs. silence were more extensive on the left hemisphere than that on the right hemisphere. The strength of activation of positive activations in the left brain was also stronger than that on the right brain. As Cantonese rhymes contain semantic contents, extended regions activated by the Cantonese rhymes are likely due to the linguistic nature of the auditory stimulations.

A prominent activation at the left frontal lobe was identified in processing of Cantonese rhymes. Activation at the left IFG extended anteriorly and superiorly to involve the MFG and spread posteriorly towards the precentral and the postcentral gyrus. The extensive activation is due to the involvement of semantic network while discrimating rhymes (Pugh et al., 1996; Chee et al., 1999; Burton et al., 2003; Gandour et al., 2004; Seghier et al., 2004; Edwards et al., 2005). This is supported by previous studies that the left lateralization was observed at frontal cortex when meaningful words were presented (Price et al., 1996; Schlosser et al., 1998; Benson et al., 2001; Gandour et al., 2004; Edwards et al., 2005). Since the Cantonese rhymes are recognized as words with semantic contents, the extensive activation over the left frontal cortex was probably due to the semantic involvement in cognitive task in the present study.

Activation on the temporal cortex involved the bilateral STG/STS in Cantonese rhyme processing as well in filtered rhymes. It extended inferiorly to include the left MTG in Cantonese rhymes perception. Binder et al. (2000) found that areas at the periphery of the Heschl's gyrus, particularly the dorsolateral STG, responded actively to pure sine wave tones, while areas around the STS and the MTG were more active with the speech stimuli (Binder et al., 2000). Our results are consistent with previous studies that activation to semantic contents within the STG is although bilateral, the activation is more extensive in the left hemisphere (Binder, 1997; Binder et al., 2000; Benson et al., 2001).

The left and the right MTG have different roles in auditory perception. The left MTG is responsible for the perception of linguistic nature of the auditory stimuli while the right MTG is responsible for the acoustic nature of the auditory stimuli. In the present study, activations were found at the right MTG in perceiving filtered rhymes indicating that the right MTG is accountable for resolving temporal event of complex auditory stimuli (Beauchamp et al., 2004). On the other hand, in the perception of Cantonese rhymes, activations at bilateral MTG were demonstrated. It is supported by previous studies that the left MTG is responsible for the perception of the semantic content of speech (Muller et al., 1997; Binder et al., 2000; Balsamo et al., 2002).

In our present study, significant activation was found at the left SPG in the comparison of Cantonese rhymes vs. silence. The left SPG was activated by the semantic tasks in Chee et al. (1999) study. Activation at the left SPG was again identified in rhyme detection in Gandour et al. (2003) study. However, the role of the left SPG is not limited to semantic processing. Wolbers et al. (2003) showed that activation at the SPG could be evoked by mental imagery (Wolbers et al., 2003). Since the Cantonese rhymes presented to the subjects in the present study possessed semantic contents, imagination of the corresponding logographic characters with equivalent sound by the subjects might be elicited. Involvement of the left SPG during Cantonese rhyme processing may require further confirmation.

### 4.3 Comparison of Cantonese Rhymes vs. Filtered Rhymes

In the present study, significant differences of brain activity were found at the left IFG and MFG in the comparison of Cantonese rhymes vs. filtered rhymes though they were weak. In the previous literature, comparisons of brain activity in speech and non-speech perception frequently showed small significant differences (Gandour et al., 2000; Hsieh et al., 2001; Vouloumanos et al., 2001).

In the present study, two factors may possibly contribute to the less extensive differences in the comparison of Cantonese rhymes vs. filtered rhymes. The discrimination judgment task on Cantonese rhymes was rather passive which is different from those attentive tasks in previous studies. For example, in Hsieh et al. (2001) study, subjects were required to make discrimination judgment on consonants, vowels and tones that occurred in the first and the last syllables of each trial (Hsieh et al., 2001). However, the phonological components presented to the subjects were embedded within a syllable instead of a direct delivery of the rhymes in our study, additional brain activation may probably involved in recognition of the phonological component (e.g. vowels) from a syllable before the discrimination judgment is made. Besides, intervening syllables within each trial in Hsieh et al. (2001) paradigm may elicit the effect of working memory during discrimination judgment task. Since some unrelated intervening syllables were introduced between the first and the last syllables, subjects probably need to pay extra attention to memorize the phonological component from the first syllable before the delivery of the last syllable during the cognitive task. However, the paradigm designed in the present study was rather passive and avoided any possible involvement of working memory. Based on the fact that active participation in cognitive processing was possible to induce a more extensive activation (Rinne et al., 1999; McDermott et al., 2003; Peng et al., 2004), a less significant activation in the comparison of Cantonese rhymes vs, filtered rhymes can only be identified from the passive task in the present study.

The background noise from the scanner may probably contribute a masking effect on the pitch presented to the subject (Bandettini et al., 1997). It minimizes the intrinsic differences of the sound between the Cantonese rhymes and filtered rhymes. The differences of the strength of activations in the comparison of Cantonese rhymes and filtered rhymes therefore become smaller.

In the present study, left lateralization of the significant differences was shown at the IFG and MFG in the comparison of Cantonese rhymes and filtered rhymes. It is due to the left hemispheric lateralization of brain activity in the processing of Cantonese rhymes. In the studies of non-tone languages, left hemispheric dominance in speech processing was always identified (Alho et al., 1998; Gootjes et al., 1999; Obleser et al., 2001; Hugdahl et al., 2003) (Section 1.7). Benson et al. (2001) suggested that the neural pathway within the left hemisphere was the preferred route in the processing of speech. In the studies of tone languages, left-hemispheric dominance in rhyme processing was always identified with healthy right-handed subjects (Gandour et al., 2000; Lin et al., 2005) (Section 1.7). This implies that the left hemisphere plays an active role in processing of segmental components.

### 4.4 Negative BOLD Signals

Areas more active during silence relative to any of the discrimination judgment tasks were identified with negative BOLD signals. The negative BOLD were found at the angular gyrus and the anterior and posterior cingulate gyrus in the comparisons of Cantonese rhymes and filtered rhymes vs. silence. Negative activations at the angular gyrus, anterior and posterior cingulate gyrus were also demonstrated in previous studies (Chee et al., 1999; Gandour et al., 2000; Hsieh et al., 2001; Birn et al., 2006; Damoiseaux et al., 2006; Fransson, 2006). There were four reasons to explain the presence of the negative BOLD signal from the previous literature.

Firstly, Shmuel et al. (2002) explained that the negative BOLD response was purely a hemodynamic response (Shmuel et al., 2002). When a subject received a stimulus, neurons at certain brain region of that subject may be activated. Such neuronal activation causes an increase in metabolic demand, associated with an increase in blood supply to the neurons in the activated brain region. According to Shumuel et al., (2002), the increase in blood supply in active brain regions comes from the relatively inactive brain regions. This is called “blood steal” effect (Shmuel et al., 2002). Therefore, active brain regions showed positive BOLD signal while negative BOLD signal may be identified in the relatively inactive brain regions. Second explanation from Smith et al. (2004) suggested that the negative BOLD signals are the result of active neuronal suppression (Smith et al., 2004). Functional activity is reduced below the baseline in certain brain regions surrounding the relatively active regions in response to particular stimuli. Areas with decreased activation are supplied with less blood which in turn contributed a negative BOLD response during the stimulus period (Smith et al., 2004). Thirdly, Rother et al. (2002) suggested that the negative BOLD signal may come from the increase level of neuronal activity by stimulation in certain brain regions, but for some reason, that certain brain region cannot receive a corresponding increase in blood supply (Rother et al., 2002). In this case, a negative BOLD signal was showed in that brain region. Finally, Raichle et al. (2001) suggested that the negative BOLD signal may come from the "default mode network", where a set of brain regions are hypothesized to be more active at rest and reflects the activity of the brain when not performing any cognitive tasks (Raichle et al., 2001). This speculation was supported by both Damoiseaux et al. (2006) and Fransson (2006) that brain regions within that default mode network are correlated at rest (Damoiseaux et al., 2006; Fransson, 2006). Therefore, while a subject is performing a cognitive task, blood supply flows from the underlying default mode network towards the active brain regions, which in turn contributes a negative BOLD signal in the default mode network. In the present study, the negative BOLD signal observed at the angular gyrus, and the anterior and posterior cingulate gyri in Cantonese rhyme processing, which is consistent with the presence of default mode network proposed by Raichle et al. (2001).

## 4.5 Comparison of the Present Findings on Cantonese Rhymes with Those Reported in Previous Studies on Mandarin Rhymes

Mandarin is a tone language which depends on the pitch contour to recognize the word meaning (Matthews and Virginia, 1994). The neural substrate underlying English and Mandarin processing may not be the same, since English is an alphabetic language while Mandarin is a tone language. Although both Mandarin and Cantonese are tone languages, there are several phonological differences between them (Section 1.3). Cantonese possesses 59 rhymes, 20 consonants and 6 tones while Mandarin has 36 rhymes, 21 consonants and 4 tones. Cantonese preserves more coda that Mandarin has lost or merged (Matthews and Virginia, 1994). These phonological differences may contribute to the differences in brain activity.

Gandour et al. (2003) indicated that Mandarin rhymes was able to activate the temporal lobe (Gandour et al., 2003). It is consistent with the present finding that bilateral activation was identified in the STG/STS and the MTG, with the peak activation over the left hemisphere in Cantonese rhymes processing. In Hsieh et al. (2001) study, activation at the bilateral STG was limited in extent in perception of Mandarin rhymes (Hsieh et al., 2001). Hsieh et al. (2001) explained that the limited activation over the bilateral STG was due to the paradigm design, where most of the activation at the STG was subtracted out in the comparison between the Mandarin rhymes and the low-pass-filtered pitch processing (Hsieh et al., 2001). The involvement of the bilateral STG/STS and the MTG was attributed to the perception both linguistic and acoustic content in the Cantonese rhymes.

In the present study, Cantonese rhymes activated the SPG within the parietal lobe. It can also be recognized in Mandarin rhymes processing in the study of Gandour et al. (2003). However, no such activation was found at SPG in Hsieh et al. (2001) study. Wolbers et al. (2003) suggested that activation at the SPG may be elicited by mental imagery (Wolbers et al., 2003). Activation at the SPG in Cantonese rhymes processing in the present study may be attributed to the imagination of the logographic characters of the corresponding rhymes by the subjects.

Insula was an area activated by Mandarin rhymes in Hsieh et al. (2001) study but not in Gandour et al. (2003) study (Hsieh et al., 2001; Gandour et al., 2003). Neither activation was shown at the insula in Cantonese rhymes processing in the present study nor English vowels processing in Benson et al. (2001) study (Benson et al., 2001). Anatomically, the insular cortex is connecting to the pre- and post-central gyrus, IFG, adjacent to the auditory cortex, and several limbic structures including the anterior cingulate gyrus (Hsieh et al., 2001). The insula is well positioned to play a critical role in verbal communication (Hsieh et al., 2001; Gandour et al., 2003). Previous neuroimaging studies also suggested that the insula is responsible for covert or overt responses (Hsieh et al., 2001; Gandour et al., 2003). Therefore, any articulatory rehearsal processes during the perception of the sound may elicit activation over the insula. Since the discrimination judgment task on Cantonese rhymes did not involve any covert or overt responses, no significant activation at the insula was found in the present study. However, in Hsieh et al. (2001) study, subjects may try to perform the articulatory rehearsal in their mind during the extraction of the segmental information. Since the rhyme was embedded within a syllable in the paradigm of Hsieh et al. (2001) study, the subject should identify the rhyme within the syllable before any discrimination judgment can be made. Subjects may attempt to pronounce the syllable covertly during the identification of the Mandarin rhyme, which in turn contributed the activation in insula in Hsieh et al. (2001) study. Therefore, it suggested that the activation of the insula depended on the paradigm design and the perception strategy of the subjects.

Negative BOLD signal was identified at both the anterior and the posterior cingulate cortex in the present study. However, only the posterior cingulate cortex showed negative BOLD signal in Hsieh et al. (2001) study (Hsieh et al., 2001; Gandour et al., 2003). No negative BOLD signal was reported in Gandour et al. (2003) study (Hsieh et al., 2001; Gandour et al., 2003).

Both Cantonese and Mandarin are tone languages. The IFG, MFG, and the STG were commonly activated in the processing of both Cantonese and Mandarin rhymes, which means that these areas may play an important role in tone languages processing. Additional areas responsible for Cantonese rhymes processing may include SPG while insula may be additionally involved in Mandarin rhymes perception, depends on the reading strategies of the subjects as mentioned above.

| | Cantonese Rhymes | Mandarin Rhymes | |
|---|---|---|---|
| | | Hsieh et al. (2001) | Gandour et al. (2003) |
| IFG | +++ | +++ | +++ |
| MFG | +++ | +++ | +++ |
| STG | +++ | + | +++ |
| SPG | + | Nil | + |
| Insula | Nil | + | Nil |
| Anterior Cingulate Gyrus | - | Nil | Nil |
| Posterior Cingulate Gyrus | - | - | Nil |

**Table 14. Summary on the comparison of the activated areas with Cantonese rhymes in the present study and with Mandarin rhymes in the previous studies. Key: number of '+', degree of positive activation interpreted visually from the statistical map and results from the previous study; '-', negative BOLD signal; 'Nil', no activation; 'N/A', not shown in the study.**

### 4.6 Comparison of the Present Findings on Cantonese Rhymes with Those Reported in Previous Studies on English Vowels

The localization of areas related to language processing is important for understanding the neural substrate in processing of languages for further decoding of speech (Binder, 1997). English is an alphabetic language that is commonly utilized as auditory stimuli for the localization of cortical functions in previous studies (Poeppel et al., 1997; Szymanski et al., 1999; Benson et al., 2001). There were several studies on perception of different compartments in English, including the processing of vowels (Poeppel et al., 1997; Szymanski et al., 1999; Benson et al., 2001), words (Klein et al., 1995; Binder, 1997; Chee et al., 1999; Burton et al., 2001; Valaki et al., 2004) and sentences (Muller et al., 1997; Schlosser et al., 1998; Michael et al., 2001). Benson et al. (2001) utilized fMRI to investigate the perception of English vowels while both Szymanski et al. (1999) and Poeppel et al. (1997) used MEG (Poeppel et al., 1997; Szymanski et al., 1999; Benson et al., 2001). However, both Szymanski et al. (1999) and Poeppel et al. (1997) concentrated their investigation on the temporal lobe instead of the whole brain in their studies (Poeppel et al., 1997; Szymanski et al., 1999). Szymanski et al. (1999) showed a significant dominance in the left temporal lobe in processing English vowels, which is consistent to the present findings with Cantonese rhymes (Szymanski et al., 1999). A bilateral activation over the temporal region was seen in Poeppel et al. (1997) study (Poeppel et al., 1997; Szymanski et al., 1999). In Benson et al. (2001), left hemispheric dominance was demonstrated in the processing of English vowels (Poeppel et al., 1997; Szymanski et al., 1999; Benson et al., 2001).

On the frontal cortex, activation at the left IFG was shown from previous study with English vowels (Benson et al., 2001). The activation spread towards the left MFG due to the semantic involvement in English vowel processing. It is not surprising a similar activation was found in Cantonese rhymes processing in the present study. Benson et al. (2001) revealed a significant activation at the left FGM as well with English vowels. In the present study, significant activations were found over the left frontal lobe as in the previous studies, at the IFG, MFG, and FGM, which was attributed to semantic involvement in Cantonese rhymes processing.

On the temporal cortex, bilateral STG and MTG were activated by the English vowels (Benson et al., 2001). In the present study, extensive activation was also identified in the temporal lobe, involving the bilateral STS, STG, and MTG, with the peak activation in the left hemisphere. The bilateral STS, STG, and the MTG were suggested to be responsible for perception of both the linguistic and acoustic nature of speech (Beauchamp et al., 2004). The MEG study by Poeppel et al. (1997) also demonstrated a bilateral activation over the temporal region (Poeppel et al., 1997). Benson et al. (2001) also showed that bilateral temporal cortex was extensively activated in the processing of English vowels (Benson et al., 2001). The activated areas extended to the posterior portion of Heschl's gyrus, MTG, and the anterior angular gyrus (Benson et al., 2001).

On the parietal cortex, SPG was activated in processing Cantonese rhymes in the present study, where no such activation was found in processing English vowels (Benson et al., 2001). In Mandarin rhymes processing, activation of the SPG was not always found. To date, only Gandour and his team (2003) showed activation in the SPG while no such activation was found in Hsieh et al. (2001) study with Mandarin rhymes. This implies that both the Mandarin rhymes and Cantonese rhymes are not consistently activated the SPG, while no activation was revealed in English vowels. The SPG is responsible for mental imagery (Wolbers et al., 2003) (Section 4.2). Since Mandarin and Cantonese were tone languages with logographic configuration in visual form, interpretation of the Mandarin and Cantonese rhymes may elicit possible imagination of the corresponding logographic character with equivalent sound, which in turn contributed activation at the SPG. On the other hand, English vowels, with alphabetic appearance in visual form, may not be able to initiate the imagination system in Benson et al. (2001) study. Therefore, no activation was showed in English vowels processing.

Angular gyrus was activated by the English vowels in Benson et al. (2001) study.

No significant activation was revealed in Hsieh et al. (2001) and Gandour et al. (2003) studies with Mandarin rhymes. In the present study, a negative activation was showed in the angular gyrus in Cantonese rhymes perception. It suggested that alphabetic English was possible to activate the angular gyrus. Activation of the angular may attribute to the reading strategy of the subjects during the task. During the perception of English vowels in Benson et al. (2001) study, subjects may attempt to spell the word silently before the English vowels can be identified from the syllable. Since angular gyrus plays an important role in spelling, such reading strategy of the subjects in Benson et al. (2001) study may contribute significant activation of the angular gyrus. On the other hand, both Cantonese and Mandarin are logographic languages with the pinyin seldom spelt during the perception. It may explain why the angular gyrus may not be activated in both Hsieh et al. (2001) and Gandour et al. (2003) studies with Mandarin rhymes. However, negative activations were identified in bilateral angular gyrus. The appearance of negative activation may due to the blood drainage from less active areas to activated regions (blood steal effect) (Shmuel et al., 2002). In the present study, angular gyrus may play an insignificant role during the perception of Cantonese rhymes. Therefore, blood supply to the angular gyrus may be drained with a negative BOLD signal identified.

Negative BOLD signal at the anterior and posterior cingulate gyrus were showed in the present study. However, in Benson et al. (2001) study, positive BOLD signal was identified. Activation in the cingulate gyrus may be affected by the attentive level of the subjects during the cognitive task. Increased attentive level of the subjects in the task may increase the activation in the cingulate gyrus. The discrimination task in the present study was rather passive when compared with that from Benson et al. (2001) study. Therefore, it was not surprising that the anterior and posterior cingulate gyrus were not activated by the Cantonese rhymes. Possible reasons for the present of the negative BOLD signal were suggested in Section 4.4.

A summary on the comparison of the activated areas with Cantonese rhymes in the present study and with English vowels from the previous studies is shown in Table 15.

| | Cantonese Rhymes | English Vowels | |
|---|---|---|---|
| | | Benson et al. (2001) | Szymanski et al. (1999) |
| IFG | +++ | +++ | N/A |
| MFG | +++ | +++ | N/A |
| FGM | ++ | + | N/A |
| STG | +++ | +++ | ++ |
| MTG | +++ | +++ | ++ |
| Angular Gyrus | - | + | N/A |
| SPG | + | Nil | N/A |
| Anterior Cingulate Gyrus | - | + | N/A |
| Posterior Cingulate Gyrus | - | + | N/A |

**Table 15. Summary on the comparison of the activated areas with Cantonese rhymes in the present study and with English vowels from previous studies. Key: number of '+', degree of positive activation interpreted visually from the statistical maps and results from the previous study; '-' negative BOLD signal; 'Nil', no activation; 'N/A', not shown in the study.**

### 4.7 Neural Pathway in Cantonese Rhymes Processing

Processing of Cantonese rhymes involved a number of brain regions (Section 4.1-4.3). On the frontal cortex, they were IFG and the MFG. On the temporal cortex, activation was identified in the STG and the MTG. A neural pathway in Cantonese rhymes processing can be derived based on the results in the present study.

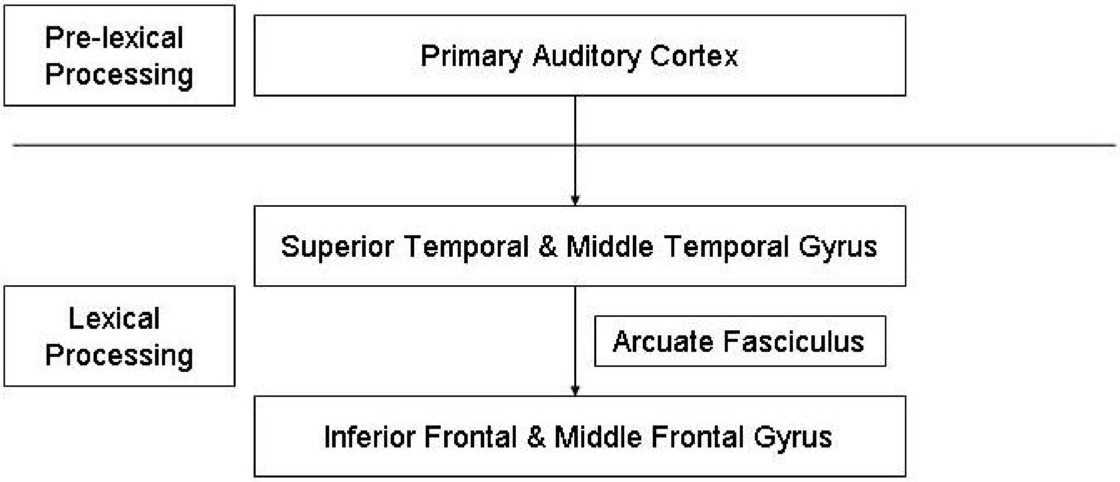


**Figure 13. Neural pathway involved in auditory Cantonese rhymes processing.**

Neural pathway in auditory language processing included pre-lexical and lexical processing (Section 1.6). In the pre-lexical processing of Cantonese rhymes, the primary auditory cortex was involved, which is a sensory area to perceive auditory stimulations (Boatman et al., 2000; Benson et al., 2001). After the perception of the Cantonese rhymes at the primary auditory cortex, in lexical processing, the perceived phonetic contents were further decoded at the Wernicke's area. In the present study, an extensive activation was seen at the Wernicke's area associated with the involvement of the MTG. It indicated that the MTG plays an important role in Cantonese rhymes processing as well as the Wernicke's area. The present findings revealed that the left MTG is responsible for the perception of phonological component of the Cantonese rhymes while the right MTG is responsible for the acoustic perception of the Cantonese rhymes. After the decoding process at Wernicke's area and the MTG, the Cantonese rhymes are transferred via arcuate fasciculus to Broca's area for further decoding. Due to the involvement of the semantic network, a prominent activation at the Broca's area was identified. The activation extended anteriorly and superiorly to involve the MFG in the present study, which indicated that apart from the Broca's area, the MFG plays a significant role in semantic processing of Cantonese rhymes as well.

### 4.8 Improvement

To cross check the findings from behavioural response with those in fMRI, a button box can be used. Data from those subjects who did not pay attention to the task can be rejected, which can reduce the contamination of the findings (Klein et al., 1995; Vouloumanos et al., 2001; Gandour et al., 2003; Peng et al., 2004; Seghier et al., 2004). During the discrimination judgment task in the present study, subjects were required to decide whether the presented sound a Cantonese rhyme or a filtered rhyme. Overt response from the subjects during the discrimination task may contribute to motion artifact (Lurito et al., 2000). Therefore, the response of the subjects was not monitored in the present study.

# Chapter Five

# Conclusion

The present study demonstrated the activation at the inferior frontal gyrus and the middle frontal gyrus was deviated towards the left hemisphere in the comparison of Cantonese rhyme versus filtered rhyme processing. Regions activated by the filtered rhymes included the STS/STG, IFG, FGM, precentral gyri and postcentral gyri. It suggested these regions are sensitive to acoustic features of the speech signals irrespective to the presence of language contents. Bilateral STG were activated in the processing of filtered rhymes since the primary auditory cortex is located at the middle portion of STG. Apart from semantic processing, bilateral IFG are also sensitive to acoustic features of the speech signals. Bilateral FGM were responsible for memory encoding while the precentral and postcentral gyrus were the sensory cortex which explained the activation in filtered rhyme perception.

All the activations observed in the comparison of filtered rhymes versus silence overlapped with those observed in the comparison of Cantonese rhymes. The activation in Cantonese rhymes was more extensive with additional activated regions in the bilateral MFG, the left MTG and the left SPG. Since the Cantonese rhymes in the present study contain semantic contents, extended regions activated by the Cantonese rhymes are likely due to the linguistic nature of the auditory stimulations. Activation in the IFG was left lateralized due to the semantic involvement of the cognitive task. Activation at the bilateral STG/STS was extended inferiorly to include the left MTG in Cantonese rhyme perception. The left MTG is responsible for the perception of linguistic nature of the auditory stimuli while the right MTG is responsible for the acoustic nature of the auditory stimuli. The left SPG may be activated by the imagination of the corresponding logographic characters with equivalent sounds.

Significant differences of brain activity were identified at the left IFG and the left MFG in the comparison of Cantonese rhymes and filtered rhymes. It revealed that both the left IFG and the left MFG plays an important role in semantic and phonological processing with Cantonese rhymes. However, activation pattern was quite weak. One of the reasons may be the discrimination judgment task was rather passive in the present study. On the contrary, active participation in cognitive processing was proved to elicit a more extensive activation. Another reason may be due to the masking effect of the scanner noise during the perception of the pitch sounds. The scanner noise may shield the intrinsic differences of the sound between the Cantonese rhymes and filtered rhymes. Perception of Cantonese rhymes may not be able to stand out to demonstrate a significant activation in the comparison of Cantonese rhymes versus filtered rhymes. To cross check the findings from behavioural response with those in fMRI, a button box can be used. Data from those subjects who did not pay attention to the task can be rejected, which can reduce the contamination of the findings. As mentioned in Section 1.5, MEG is another non-invasive imaging modality to localize the language processing areas. Therefore, MEG can be utilized as the imaging modality with the same paradigm in future studies to ensure both the left IFG and the left MFG plays a critical role in semantic and phonological processing with Cantonese rhymes.

The possible reasons for the presence of the negative BOLD signal in this study were the blood steal effect, active neuronal suppression, lacking of the blood supply even under activation, or the involvement of default mode network. In the present study, negative BOLD signal was shown in the angular gyrus and the anterior and posterior cingulate gyrus.

English vowels and Mandarin rhymes were utilized as auditory stimuli for localization of cortical functions in previous studies. To compare the findings across the previous studies on English vowels, left IFG, left MFG, left MFG, left STG and the left MTG were the most consistently activated, which coincided with those in the present study with Cantonese rhymes. The activation was almost exclusively in the left hemisphere as the present study. Angular gyrus was activated by English vowels, which was not demonstrated in English words or sentences processing. Only a negative BOLD signal was identified in the present study. Activation at the SPG in Cantonese rhymes processing may due to the imagination of the corresponding logographic characters with the equivalent sound by the subjects when the Cantonese rhymes were presented. Due to the attentional demand of the paradigm, English vowels processing activated the left anterior cingulate cortex, which was identified as a negative BOLD signal in Cantonese rhymes processing in the present study.

The neural substrate underlying English and Mandarin processing may not be the same, since English is an alphabetic language while Mandarin is a tone language. The most consistent activation across previous studies with Mandarin rhymes was shown at the left IFG and the left MFG due to the semantic involvement. However, activation at the temporal lobe was limited by the passive listening task in the previous Mandarin rhymes studies. Nevertheless, the STG was shown to play an important role in other studies with Mandarin and Thai words. SPG was identified in Cantonese rhymes processing since the paradigm may elicit the mental imagery of the subject. Insula was an area possibly activated by the Mandarin rhymes but not by the Cantonese rhymes. The insula plays a critical role in overt and covert vocal production. Since the discrimination judgment task on Cantonese rhymes was rather passive, no significant activation at the insula was identified in the present study. Attentional process was possibly elicited activation at the anterior cingulate gyrus in the previous Mandarin rhymes studies. However, only a negative BOLD signal was identified in Cantonese rhymes processing, owing to the passive feature of the discrimination judgment task in the present study. Both studies on Mandarin rhymes and Thai words showed a negative BOLD signal in the posterior cingulate gyrus, which was consistent with the present result.

A neural pathway in Cantonese rhymes processing can be derived from the present study, with the framework based on the neurological model of language (Section 1.4.2). In the pre-lexical processing of Cantonese rhymes, the primary auditory cortex was involved, which is a sensory area to perceive auditory stimulations. In the lexical processing, the perceived phonetic contents were decoded at the Wernicke's area associated with the MTG. They were responsible for the perception of phonological component of the Cantonese rhymes. After the decoding process at Wernicke's area, the Cantonese rhymes are transferred via arcuate fasciculus to Broca's area. Semantic decoding was carried out in Broca's area associated with the MFG. It suggested that both the MTG and the MFG play an important role in lexical processing of Cantonese rhymes, apart from the well-known language processing area, Broca's and Wernicke's area.

The present study was the first fMRI study using Cantonese rhymes, the salient basic unit of a syllable, as auditory stimuli to localize the language processing areas. It provided a significant basis of using fMRI to localize the language processing areas non-invasively, which especially benefits the local Cantonese speaking community.

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# Appendix 1

## Information Sheet for Participants

Project Title: *Language lateralization in native Cantonese speakers using visual and auditory stimulation: a functional MRI study*

I. Personal Particulars:

Name: _______________________________ Gender: __________ Age: ___________

DOB: ____________ Education level: _______________ Born Place: ____________

Weight: ____________ HKID: ____________________

II. Background Information:

Do you know Korean? YES / NO

Do you have any known or suspected central nervous system disease? YES / NO

Do you have any known or suspected psychiatric symptoms? YES / NO

Do you have any known or suspected auditory symptoms? YES / NO

III. Handedness Assessment:

Please indicate your preferences in the use of hands in the following activities by putting + in the appropriate column. Where the preferences is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If in any case you are really indifferent put + in both columns.

| Items | | LEFT | RIGHT |
|---|---|---|---|
| 1 | Writing | | |
| 2 | Drawing | | |
| 3 | Throwing | | |
| 4 | Scissors | | |
| 5 | Toothbrush | | |
| 6 | Chopsticks | | |
| 7 | Spoon | | |
| 8 | Broom (Upper Hand) | | |
| 9 | Striking Match | | |
| 10 | Opening Lid | | |

Laterality Quotient (LQ) = ________

# Appendix 2

# Consent Form for Participants

**Protocol Title:** Language lateralization in native Cantonese speakers using visual and auditory stimulation: a functional MRI study

**Student Investigator:** Mr. Lee Wing-kit, B.Sc.

**Chief Supervisor:** Dr. Chan Suk-tak, Ph.D

**Co-investigator(s)/Study Staff:** Dr. Tang Sze-wing, Ph.D; Kenneth K. Kwong, Ph.D.

**Description of Subject Population:** Right-handed native Cantonese speakers

**PURPOSE**

We would like permission to enroll you as a participant in this research study. The purpose of this study is to demonstrate the language lateralization by using visual Chinese and auditory Cantonese paradigm.

**STUDY CONTACTS**

The investigator in charge of this study is Mr. Lee Wing-kit who can be reached at 2766 4005.

**PROCEDURES**

This study will require your participation in one magnetic resonance imaging (MRI) session, lasting approximately forty-five minutes.

The MR scanning will be performed by the staff radiographers of the Hospital Authority at the Department of Radiology and Organ Imaging in United Christian Hospital.

You will lie with a comfortable posture on the table and be slid into a large horizontal cylinder which is inside a magnet. Foam rubber earplugs will be used to stifle the banging sounds from the MRI scanner. Your head will be immobilized in a head coil with Velcro strip and foam rubber pads. During the scanning, you will be asked to keep stable and perform a simple language task. A practicing session will be given to you before you go into the scanner. If required (for example, you are very uncomfortable, or feel that you cannot continue), you will be able to speak with the investigators outside the scanning room while in the scanner, through a microphone just above your head. There is also an emergency signaling device (a ball to squeeze) to immediately alert us to any problem.

All the procedures do not require the administration of contrast agent or any other drugs.

**COSTS**

This is a purely research study with no direct costs to you.

**RISKS AND DISCOMFORTS**

MRI uses powerful magnets to make images. Therefore, if you have metal implants, such as surgical clips or pacemakers, you should not have the MRI scanning. However, there is no known health risks associated with this exposure. You may feel uncomfortable in the narrow cylinder (claustrophobia). The MRI makes loud banging noises as it takes images. Earplugs can be provided to reduce the noises. The MRI can be stopped at any time at your request.

**REFERRAL FOR INCIDENTAL FINDINGS**

In the event of an additional abnormality being identified on the MR images, measures will be taken to refer you to an appropriate clinician for further investigation.

**BENEFITS**

You will not receive direct benefits from the present study.

**CONFIDENTIALITY**

Any information and data produced by this study will not be given to anyone other than the research team of the present project in a form that could identify you without your written consent. It is possible that your medical and research record, including sensitive information and/or identifying information, may be inspected by the Research Committees in the Hong Kong Polytechnic University, Queen Elizabeth Hospital and United Christian Hospital. If your record is inspected, your privacy and the confidentiality of your information will be protected with reasonable efforts.

**REFUSAL OR WITHDRAWAL OF PARTICIPATION**

You do not have to participate in this study. If you decide to participate, you can change your mind and withdraw from the study at any time without affecting your present or future care in the United Christian Hospital and in the Queen Elizabeth Hospital.

This study was approved by the Human Subjects Ethics Sub-Committee of the Department of Optometry and Radiography, The Hong Kong Polytechnic University.

However, if you think there are any procedures that seem to violate your welfare, you may explain in writing to Dr. Andrew Lam, Chair of the Departmental Research Committee, Department of Optometry and Radiography, The Hong Kong Polytechnic University.

**SIGNATURE**

I confirm that the purpose of the research, the study procedures and the possible risks and discomforts as well as potential benefits that I may experience have been explained to me. Procedures of withdrawing my participation in the study have also been discussed. All my questions have been answered. I have read this consent form. My signature below indicates my willingness to participate in this study.

_____________________________________________ ___________

Subject Date

_____________________________________________ ___________

Witness/Advocate/Minor/Legal Guardian (if required) Date

_____________________________________________ ___________

Additional Signature (if required) (identify relationship to subject) Date

I have explained the purpose of the research, the study procedures, identifying those that are investigational, the possible risks and discomforts as well as potential benefits and have answered any questions regarding the study to the best of my ability.

_____________________________________________ ___________

Study Representative Date

研究同意書

**擬訂主題**：廣東人於視覺及聽覺刺激下語言功能性磁力共振腦影像分析

**學生研究員**： 李永杰先生

**主督學** ： 陳淑德博士

**副研究員/其他研究員**：鄧思穎博士、鄺健民博士

**研究目標**：於廣東土生土長並慣用右手的成年人

目的
我們須得到你的允許參與是項研究，本研究目的是透過功能性磁力共振腦影像分析論証腦部於視覺及聽覺刺激下的語言使向性。

研究聯絡人
你可致電 2766 4005聯絡學生研究員李永杰先生。

研究程序
本研究須得到你於一次磁力共振腦掃描的參與和協助，需時約45分鐘。

磁力共振掃描將在基督教聯合醫院放射診斷部門進行，會由醫院管理局屬下放射診斷部門的放射技師負責。你會躺在床上，然後被帶進掃描器內，我們會供應耳塞作爲保護聽覺之用途，我們會利用魔術膠貼和軟墊固定你的頭在掃描器內。在掃描過程中，你必須保持穩定，接受一個簡單的視覺及聽覺功能測試。如有任何需要 (例如:身體感到不適，或覺得不能繼續掃描過程)，你可透過掃描器內的對話器或緊急訊號裝置，通知掃描室外的研究人員。

全部程序不需注射顯影劑或藥物。

費用
由於這個是科學研究，所以你毋須付上任何費用。

研究風險和不安的感覺
磁力共振掃描是利用強大的磁場來製造醫學影像，如果你體內有任何金屬移植組織，例如一些手術用的夾子或心臟起膊器，你便不能接受磁力共振掃描。 至今還沒有數據顯示磁力共振掃描與健康風險有關係，當你接受磁力共振掃描被送到

狹窄的掃描器內，你或會感到不適 (幽閉恐佈)，當掃描器在製造影像過程中，會產生噪音，我們會供應耳塞作爲保護聽覺用途，你亦可隨時要求停止掃描。

偶爾性發現的轉介

假若在磁力共振影像中發現異常的情況，你將被轉介到適當的醫生作詳細檢查。

利益

在這項研究中，你不會得到任何直接的利益。

資料保密

任何資料包括個人資料是不會未經你的書面同意，以可辨認你身分的形式，交予本研究無關的人士，你的病歷或研究記錄包括一些敏感性的資料和身分資料，有可能會被香港理工大學，基督教聯合醫院和伊利沙伯醫院的研究委員會查閱，如你的記錄須被查閱，你的私隱和個人資料會盡量以合理方法保護。

拒絕和退出參與是項研究

你不一定需要參與是項研究，如你決定參與，你可隨時改變決定和退出是項研究，這樣不會影響你現在或將來在香港理工大學眼科視光學診所，伊利沙伯醫院和基督教聯合醫院所接受的護理。

本研究是得到香港理工大學眼科視光學及放射學系道德倫理委員會批准，如你覺得任何程序侵犯你的個人權益，你可以書面與香港理工大學眼科視光學及放射學系研究委員會主席林國璋博士釋述。

簽署

本人確定是項研究的目的、程序、可能性風險、不安的感覺、以及潛在的利益，已向本人清楚解釋，退出參與是項研究的程序亦已討論，所有問題已被回答，我已詳細閱讀這同意書，本人下方的簽署表示本人願意參與這項研究。

________________________________________

參與者　　　　　　　　　　　　　　　　　　日期

________________________________________

見證人 / 律師 / 未成年人 / 合法監護人(如需要)　　　　日期

本人已解釋是項研究的目的、程序、可能性風險、不安的感覺、以及潛在的權益

和回答所有問題。

研究代表　　　　　　　　　　　　　　　　　　日期