ERP Studies of Tone Lateralization

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To my parents, who gave me birth.

To my supervisor, who ignited my academic life.

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Abstract

In this dissertation, I discuss the effects of the linguistic role and the physical property on the hemispheric specialization (lateralization) of the lexical tones. In the previous studies of lateralization, there are two contradictory hypotheses. One emphasizes the linguistic role and predicts a left lateralization of tone perception, while the other emphasizes the physical property and predicts a right lateralization of tone perception. Both hypotheses have their supporting evidence.

In my Event-Related Potential studies, these two factors are analyzed collectively. Two dichotic listening experiments, one word phonological priming experiment, and one sentence semantic violation experiment are conducted. The results indicate that the linguistic role (e.g. semantics) causes the tone processing toward the left side, whereas the physical property causes the tone processing toward the right side.

No previous tone lateralization studies have analyzed the underlying factors. Following the philosophy that language is built upon multiple cognitive functions, I further examine the effects of semantic memory and pitch processing on the lateralization of tones in various language tasks. My findings help bridge the previous theoretical discrepancies and unify the conflicting ex-

perimental results regarding tone lateralization.

摘要

本论文的研究主题是：语言因素以及声音的物理性质对于声调感知的脑功能侧化的影响。在以往脑功能侧化的研究中，有两种相互对立的假说。其中一种强调语言因素的作用，并预计声调的感知是左侧化的；而另一种假说则强调声音物理性质的影响，并预计声调的感知是右侧化的。这两种假说都有其各自的实验依据。

在本论文的脑电波事件相关电位实验中，这两种因素的影响都得到了检验。整个实验包括两个双耳分听实验，一个语音启动效应实验，以及一个句子中的语义违反实验。实验结果表明：语言因素（语义）导致声调处理趋向左侧化；而声音的物理性质导致声调处理趋向右侧化。

这种分析声调处理脑功能侧化的影响因素的观点是新颖的。它来自于一种将语言看作是由多个认知功能构建成的哲学观。在这种哲学观的引导下，本论文作者在多个语言任务实验中，讨论了语义及声音的音调处理对声调侧化的作用。这种观点有助于弥补以往两种理论的分歧，并统一了以往相互矛盾的声调侧化实验结果。

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Chapter 1

Introduction

Summary

This work is about tone lateralization, i.e., which hemisphere of the human brain activates more when processing the lexical tone. Both the structure and the function of the brain are not symmetric in the two hemispheres. I will first introduce the brain structure and the lateralization structurally and functionally, both of which relate with tone perception. In exploring tone lateralization, I use ERP (Event-Related Potential) experiments that consider the aspects of the linguistic role and the physical property of tone, since tone has the linguistic function to distinguish lexical meanings using the physical property of pitch changes over several hundreds of milliseconds.

1.1 Thesis structure and hypothesis

The thesis consists of six chapters. Chapter 1 introduces the basic brain structures, and Chapter 2 reviews the former studies of tone lateralization.

In Chapter 3 and 4, I describe the ERP experiments to explore tone lateralization, show the data analysis procedures, and discuss the experimental results.

In Chapter 5, the effect of noise on tone lateralization in dichotic listening is discussed, because other researchers in their tone dichotic listening experiments have introduced the noisy condition, in which the effect of noise needs to be analyzed.

In the final chapter, I give a general discussion on the current work by showing the relationship between my study and other neuroimaging studies on speech processing. In the end, I point out some future work.

My hypothesis in this dissertation is that as a whole, there is no absolute lateralization of tone perception, both the physical property and the semantics affect tone lateralization. This view comes from previous studies on the lateralization of tones, speech and music, and semantic processing, as well as related brain structures. I will begin with a review of the anatomical structures of the brain.

1.2 Brain structural and functional lateralization

Let us first look at the basic structures of our brains and how they process the speech sounds.

The basic structures of our brains go as follows. The human central nervous system consists of the *cerebral hemispheres*, cerebellum, brain stem, and spinal cord (see Figure 1.1).

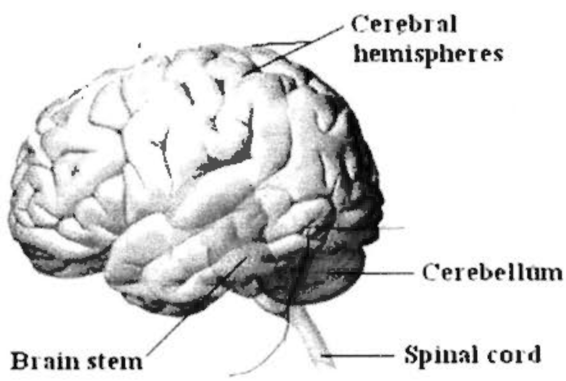


Figure 1.1: Major divisions of the central nervous system

The cerebral hemispheres form the largest region of the human brain. They are responsible for the cognitive functions such as perception, motor function, memory, and emotion. The cerebral hemispheres include the *cerebral cortex*, the underlying *white matter*, and other three deep-lying structures: the basal ganglia, the amygdala, and the hippocampus [34].

The cerebral cortex is the thin outer layer of the cerebral hemispheres, which is also called the *gray matter* (see Figure 1.2).

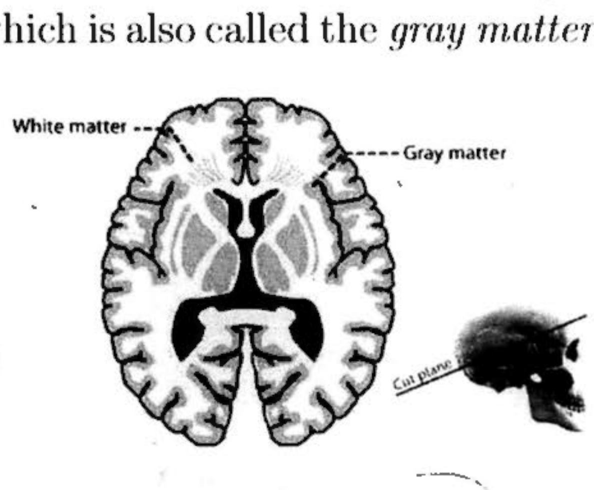


Figure 1.2: White matter and gray matter

White matter is the myelinated axons from neurons in certain layers of the gray matter projecting to other regions of the cerebral cortex. Since language functions are most related with the cerebral cortex and the underlying white matters, I will discuss the structures of these two parts in the rest of the dissertation.

The cerebral cortex is anatomically divided into four lobes: *frontal*, *parietal*, *temporal*, and *occipital* lobes. The cerebral cortex has a highly convoluted shape, formed by grooves (*sulci*) that separate elevated regions (*gyri*). One of the most prominent sulci—the lateral sulcus or *sylvian fissure*—separates the temporal lobe from the frontal and parietal lobes. Another prominent sulcus—the central sulcus—separates the frontal and parietal lobes [34] (see Figure 1.3).

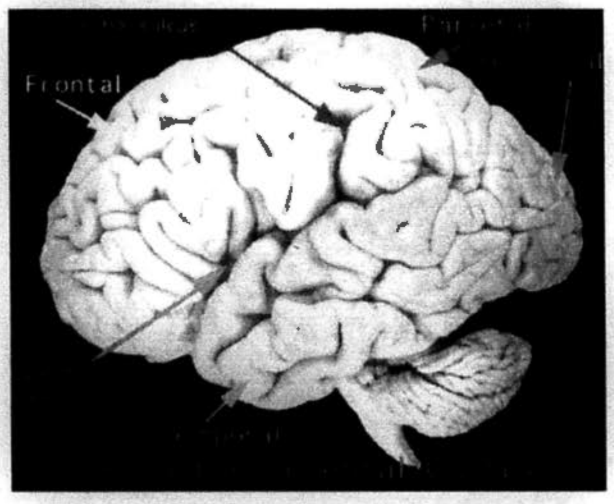


Figure 1.3: Four lobes of the cerebral cortex

The primary auditory cortex (PAC) is located in the medial two-thirds of Heschl's gyrus [51], which is a convolution of the temporal lobe that runs obliquely outward and forward from the posterior part of the lateral sulcus. General auditory processing includes PAC bilaterally. Frontal and temporal lobes, as well as underlying white matter connections, are the most important for speech processing, especially the Broca's area [11] and the Wernicke's area [65]. The Broca's area is in the *left* inferior frontal gyrus (IFG) and the Wernicke's area is an area in the posterior *left* superior temporal gyrus (STG) (See Figure 1.4).

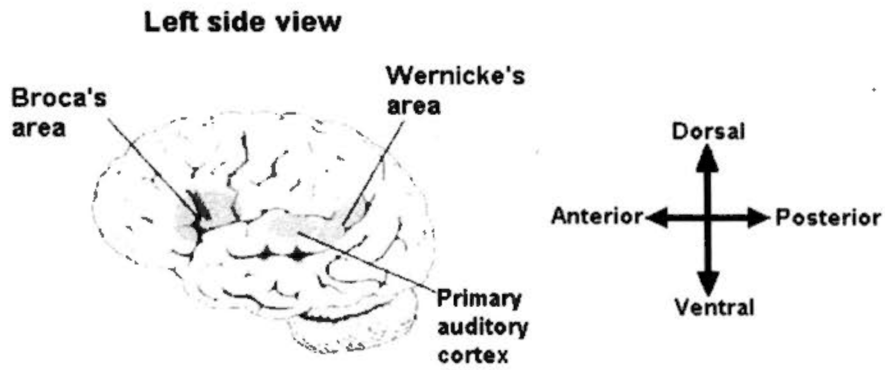


Figure 1.4: Broca's area and Wernicke's area

Patients with the left inferior frontal gyri damaged have speech production deficits. One severe case in which the patient can only utter one syllable 'tan', was firstly reported in 1861 by Broca [11]. It is the starting point of the cognitive neuroscience studies. Patients with the Wernicke's area damaged are associated with speech comprehension problems as well as the symptom of producing fluent but meaningless speech [65]. It was first proposed by Wernicke [65] and later reported by Geschwind [22] that the impairment of the underlying white matter that connects these two regions along the lateral sulcus (also called the sylvian fissure) is related with a syndrome of speech disorder with good comprehension. This syndrome is called the conduction aphasia [22, 1]. In early aphasia and brain lesion studies, Broca's area, Wernicke's area, and the sylvian fissure between them were thought to be the unique regions for speech processing.

However, this view neglected the fact that many other brain regions also take part in language processing. Recent neuroimaging studies have found that the superior marginal gyrus, angular gyrus, middle frontal gyrus, middle temporal gyrus, and inferior temporal gyrus, including the Broca's area and Wernicke's area and their right homologue regions, are also involved in language processing. The activation of these regions is bilateral, although in many right handed people these regions in their left hemispheres are activated more than those in the right homologous regions. In addition, the right hemisphere is especially important for prosody and pragmatics. Therefore, language is a whole brain function, instead of a function only involving a single or two regions.

There are bundles of neural fibers connecting different regions within the same hemisphere as well as between the similar homologue regions in the two hemispheres. The fiber bundles connecting two hemispheres are called the corpus callosum, which is involved in the communication between the two hemispheres.

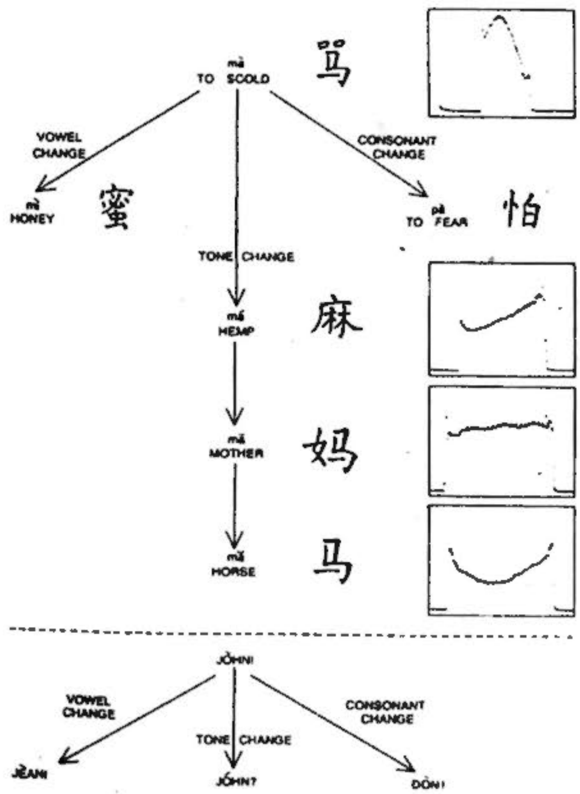
The cytoarchitecture (cellular composition) is asymmetric between the two hemispheres in many regions of the cerebral cortex. The PAC in the left hemisphere has greater cells that are heavily myelinated [71]. The Broca's area has greater gray matter volumes than the homologue in the right hemisphere [8]. The fiber projections between the Broca's area and the Wernicke's area have ventral and dorsal streams, and the ventral stream is more left lateralized than the dorsal ones [47]. These structural asymmetries could be the biological bases for the functional lateralization of sounds with different physical properties or semantic processing, such as the lexical tone and the stop-consonants, or syllables with or without meanings.

1.3 Tone and languages

Tone is a linguistic term. It is primarily the use of pitch variations to distinguish lexical meanings [61]. And pitch is a perceptual concept which depends on the hearer's perception of the fundamental frequency f0. Here, F0 is an acoustical term which refers to the number of pulses per second that a speech signal contains [69]. Each pulse is correspondent to a single vibration of the vocal folds inside the larynx. When vocal folds are pulled tightly close to each other, by controlling the cartilages of the larynx, air cannot pass through the glottis (opening of the vocal folds) easily. If the air is pressed by the lungs, it will push open the vocal folds for a short period of time. Then with the dropping of the air pressure, vocal folds will close again [60]. This is one cycle of the vocal folds vibration. The tighter the vocal folds are pulled, the higher the vibration frequency is. This is how speakers change the f0 of their speech sounds. The typical number of cycles is around 100 per second for male speakers. Women and children have higher frequencies of vocal folds vibration. So they have higher f0 (e.g. 400Hz) than men. In sum, the number of vocal folds vibration is equal to f0. Our perception of f0 is called pitch, which can be used linguistically as tones, to distinguish word meanings.

A language is called a 'tone language' if the pitch of the word can change the meaning of the word [69]. Tone languages are found all around the world [61]. Based on a very rough estimation, about 70 percent of the world's languages are tone languages [69]. The areas in which tone languages are extensively distributed include Africa, East and South-East Asia and the Pacific, and the Americas [69]. And the tone languages include "(1) the vast majority of African languages, (2) almost all of the languages of the Sino-Tibetan family together with many neighboring languages of Southeast Asia, and (3) certain clusters of American Indian languages" (p93, [61]).

An example of the tones in Mandarin is shown in Figure 1.5. The right column shows the f0 of four monosyllabic Mandarin words, with the same syllable 'ma'. When the f0 decreases, syllable 'ma' means scold. When this syllable is produced with the increasing f0, it means 'hemp'. A high level pattern of the f0 with syllable 'ma' means mother. And this syllable means horse with a low dipping pattern of the f0.



Taken from p. 58 of W.S-Y. Wang, ed., (1982) *Human Communication*. New York: W. H. Freeman Company.

Figure 1.5: Four tones of Mandarin, Figure from [59]

Tone is superimposed mainly over the vowel of a syllable in Mandarin. The length of the tone is usually around several hundreds of milliseconds. The pitch changes of the tone can also be defined physically as the fundamental frequency of the glottal tone, or F0 [62].

Regarding tone lateralization, according to the "task-dependent" view, tone perception should be left lateralized, because it bears language function and the left hemisphere is the language dominant side [57]. However, the "cue-dependent" view predicts that tone perception should be right lateralized, since the right hemisphere has an advantage in processing pitch changes [71], which are the physical properties of tones. There is supporting evidence for both of these views. For example, two behavioral studies [57] [63], using the dichotic listening paradigm have shown a right ear advantage (REA, left hemisphere advantage) on tone perception, whereas a recent ERP study [42], using the MMN (Mismatch-Negativity) paradigm, has shown a right hemisphere advantage on tone perception around 200 ms after the stimulus onset under the pre-attentive condition. The previous research on tone lateralization will be discussed in detail in Chapter 2.

□ **End of chapter.**

Chapter 2

Background

Summary

Although tone is an important feature in languages, the studies of the tone and the neural mechanisms of tone processing are relatively rare, compared with those of the consonants and vowels. The lateralization of tones is especially controversial and has not been studied thoroughly.

In this chapter, I will summarize previous behavioral and neuroimaging studies about tone lateralization. The necessary background knowledge about these experiments will be given, including dichotic listening (simultaneous presentation of two different sounds, one to each ear), fMRI (functional magnetic resonance imaging), and ERP (event-related potential), as well as other relevant neuroimaging techniques.

Not all of the behavioral and neuroimaging studies' results about tone lateralization are consistent with each other. I will discuss the possible reasons underlying these conflicting results and the merits of each experimental paradigm. In the end, I will state the motivation of conducting my ERP studies on tone lateralization.

2.1 Behavioral studies

2.1.1 Dichotic listening

Dichotic listening (DL) is a behavioral experiment paradigm to study hemispheric lateralization in auditory modality. This paradigm was first invented by Broadbent [10] to investigate the memory capacity when subjects hear two pieces of information from two separated channels. During the experiments, subjects hear a series of digits in their two ears simultaneously. For example, subjects hear three digits "734" in their left ears, and at the same time, another three digits "215" in their right ears. Then, they are asked to report what they have heard in both ears.

DL was first introduced to test the lateralization in speech perception by Kimura [35]. Her paradigm is the same as in Broadbent's experiment. In calculating lateralization, she compares the correct answers in subject's two ears. If the right ears get more correct digits than the left ears, then, there is a right ear advantage. The results have shown that for subjects having left hemisphere dominance for language, a right ear advantage (REA) is observed, and the right hemisphere language dominant subjects show a left ear advantage (LEA) in the dichotic trials.

Before the DL experiment, the hemisphere dominance was determined by WADA test [58]. In this test, subjects are injected with sodium amytal in their left or right internal carotid artery to sedate one hemisphere. If the subject cannot speak during the several minutes before the effect of the medication dissipates, the hemisphere which was injected with the sodium amytal is assumed to be the language dominant hemisphere. After the language dominant hemisphere is decided, the DL is tested. And the results of the DL test always show that the ear contralateral to the language dominant hemisphere has an advantage in recalling the digits, which indicates that DL is a robust measurement of hemispheric advantage.

Based on this fact, Kimura has proposed a model that when the sounds from two ears are different, the sound from the ear contralateral to one hemisphere will suppress that from the ipsilateral ear. In her word, "each ear has connections with the auditory receiving area in each hemisphere, but the pathways connecting the ears to their opposite hemispheres are apparently more effective than the ipsilateral pathways" (p164, [37]). So the left hemisphere perceives the right ear's sound better than the left ear's and the right hemisphere perceives the left ear's sound better than the right ear's. Because of the left hemispheric advantage in perceiving a series of spoken digits, the right ear shows an advantage in the DL test.

Although the ear advantages of the digits in the DL are always consistent with the language dominant hemisphere tested by the WADA test, they are not always consistent with the handedness. Among subjects with the left hemisphere advantage for language, around 10% are left handers (10 out of 103 subjects, see p168 in [35]). They have a REA, as same as the other 90% right handers in this group. Around 25% right hemisphere language dominant subjects are right handers (3 out of 12 subjects, see p168 in [35]. But they show a LEA, which is consistent with the other left handers in this group. Usually in the behavioral studies, right-handed subjects are chosen. But there is a small chance to include right hemisphere language dominant subjects (3 out of 96 in [35]).

In sum, Kimura has proposed that the ear advantages of DL rely on two things. The first is that the contralateral auditory pathway will suppress the ipsilateral pathway, when the information from the two ears contradicts each other. The second is that the left hemisphere has an advantage in processing speech materials. Besides, based on the fact of the LEA in perceiving melodies [36], there is evidence supporting a right hemisphere advantage on perceiving the non-speech melodic materials. (See Figure 2.1)

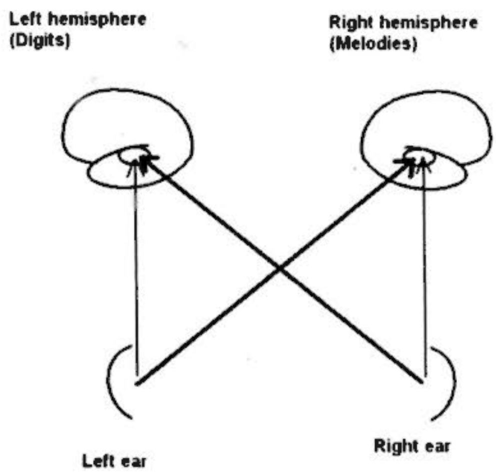


Figure 2.1: The mechanism of DL, reproduced from [37]

These hemispheric specializations of perceiving different kinds of speech and non-speech materials are consistent with other brain lesion and brain imaging results. And Kimura's model is well accepted as the mechanism underlying the DL when it is applied to test the hemispheric advantages.

2.1.2 DL on CVC syllables and non-linguistic pitches

Studdert-Kennedy and Shankweiler are the first scholars to use the consonant-vowel-consonant (CVC) syllables in the DL experiment [56]. They aim to find the ear advantages of language materials in a better controlled condition. The materials they investigated are six stop-consonants /b, d, g, p, t, k/ and six vowels /i, ə, æ, ɑ, ɔ, u/. All the CVC syllables are natural speech recorded from a phonetician. After conducting the DL on 12 subjects, they find "a significant right-ear advantage for initial stop consonants; and a significant, though reduced, right-ear advantage for final stop consonants; a nonsignificant right-ear advantage for six medial vowels; and significant and independent right-ear advantage for the articulatory features of voicing and place in initial stop consonants" (p592, [56]).

The authors interpret the result as the left hemisphere advantage for specific language materials such as stop-consonants. Their discussion follows the "task-dependent" view that the language functions are lateralized to the left hemisphere. They conclude that "while the general auditory system common to both hemispheres is equipped to extract the auditory parameters of a speech signal, the dominant hemisphere may be specialized for the extraction of linguistic features from those parameters" (p579, [56]). However, the significant REA does not exist in the medial vowel in their experiment, and they cannot explain why the medial vowels have no REA. Therefore, their experimental results do not fully support this hypothesis.

Curiously, their experimental results can be explained by the "cue-dependent" view. Zatorre et al. (p38, [71]) proposes that "the auditory cortices in the two hemispheres are relatively specialized, such that temporal resolution is better in left auditory cortical areas and spectral resolution is better in right auditory cortical areas". Poeppel (p245, [49]) suggests that the lateralization correlates with the time window of the acoustic features: "left auditory areas preferentially extract information from short (~20–40 ms) temporal integration windows. The right hemisphere homologues preferentially extract information from long (~150–250 ms) integration windows".

If we investigate the acoustic features of Studdert-Kennedy and Shankweiler's materials, we can find that the lateralization patterns which are indicated by the ear advantages correlate with the acoustic features in temporal and spectral spans [70, 71], especially in the time course [49]. If we look into the dichotic trials composed of two stop-consonants, which show a significant REA, the contrasts of the acoustic features of the two stop-consonants are the formant transitions happening in the first 20–40 milliseconds of the consonants. So it should be preferentially processed by the left hemisphere. The other results of the DL are also consistent with this hypothesis. For the dichotic trials contrasting with vowels, there is no contrasts of fast formant transition in the vowel dichotic trials. The results also show no significant REA, It is consistent with Poeppel's hypothesis that for the sounds having no acoustic features happening within 20–40 milliseconds, there is no REA or left hemisphere advantage in the processing. Although they expected to explain the experimental results according to the "task-dependent" hypothesis, their results, in fact, favor the "cue-dependent" hypothesis more. One thing to notice is that their experiment is a phonological discrimination task, which does not include obvious semantic operations.

The other kind of DL is to use the non-linguistic pitches as the materials. In Kimura's experiment, DL with melodies shows a LEA, which indicates a right hemisphere advantage in melody processing [36]. A better controlled experiment using non-linguistic pitches has been done by Sidtis [54, 55]. The experimental procedure follows the "A-B-X" paradigm, which is different from the DL using linguistic materials, because the subjects may not be able to name the notes they hear. In Sidtis' experiment, subjects hear two pairs of dichotic trials as 'A' and 'B', and one diotic (simultaneous presentation of two identical sounds, one to each ear) probe as the 'X'. They are asked to discriminate whether the last note has been presented in the previous two dichotic trials. The stimuli are 550 ms pitches with the fundamental frequency plus two harmonics. The experimental results confirm a LEA in pitch processing, which supports the "cue-dependent" hypotheses as well.

Both Zatorre et al.'s and Poeppel's hypotheses of lateralization belong to the "cue-dependent" hypotheses. These views emphasize the correlation of the lateralization and the acoustic properties of the materials. One difference between the two is that Zatorre et al.'s hypothesis includes both the temporal and spectral domains, while Poeppel's hypothesis only focuses on the temporal domain. In the speech and non-speech materials, the distinctive acoustic feature is the fast formant transitions in speech and the slow varying pitch changes in non-speech. The fast formant transition in the stop-consonants is a broadband feature which lasts about 20–40 milliseconds. The pitch changes in the non-speech always happen longer than 200 milliseconds and occur in a narrow spectral range. The experimental results of the lateralization of these two types of materials support both groups of the "cue-dependent" hypotheses.

Instead of the acoustic features, the "task-dependent" hypothesis emphasizes the function of the materials, namely whether they have language functions or not. From the DL on consonants or non-linguistic pitches, the "task-dependent" hypothesis can also explain the experimental results, but it cannot explain the non-significant REA for vowels, although vowels are one part of the language. Up to this point, the "cue-dependent" hypothesis is more acceptable to explain the experimental results with more consistency. However, other than the acoustic features, there are other factors influencing the lateralization and supporting the "task-dependent" hypothesis. For example, the real-word has a greater extent of REA than the pseudo-word, which indicates that a linguistic role, such as semantics, can enhance the left hemisphere advantage in perception [56].

2.1.3 DL on lexical tones

In the case where pitch changes are used to contrast lexical meaning, the factors of the acoustic feature and the linguistic role intertwine, and the "cue-dependent" and the "task-dependent" hypotheses predict an opposite result regarding tone lateralization. The acoustic feature of tones is the pitch change, which is the same as that in the non-linguistic pitches. According to the "cue-dependent" hypothesis, tones should be right lateralized. However, the pitch changes in lexical tone indicate different word meaning. When the sound is within the language system, the "task-dependent" hypothesis predicts a left lateralization of tones.

Van Lancker and Fromkin are the first scholars to test the lateralization of tones using the DL [57]. According to their experimental results, "tone-words and consonant-words are better heard at the right ear, while the hums show no ear effect". (Hum is the speech pitch changes without lexical meaning.) They also compare the performance of the non-tone language speakers and the tone-language speakers. "Preliminary results on English-speaking subjects suggest that the consonant-words give the usual right ear effect, while the tone-words and the hums do not". Based on these facts, they claim that "pitch discrimination is lateralized to the left hemisphere when the pitch differences are linguistically processed" (p101,[57]).

In their experiments, Thai language is used and both Thai and English speakers are involved. Another similar study was done in 2001 by Wang et al. using Mandarin and involving Mandarin and English speakers [63]. The results of these two experiments are consistent. However, not all of such studies have the same results. Baudoin-Chial has also conducted a DL on Mandarin recruiting Mandarin and French speakers [3]. She has not found a significant REA in Mandarin speakers in tone perception. Wang et al. have criticized that Baudoin-Chial did not use any method to increase the error rate, so that the high accuracy rate and the ceiling effect have prevented her from finding a significant REA.

Wang et al. [63] use the white noise at a -10dB S/N ratio to increase the error rate of the Mandarin speakers to match that of the English speakers. In Van Lancker and Fromkin's experiment [57], they also use a method to increase the error rate of the tone language speakers. In half of the trials, they conjunct two trials together so that the memory load of the native Thai speakers doubles and the reaction time for the trials is decreased by half, compared with that of the English speakers. However, both Van Lancker and Fromkin's and Wang et al.'s work has not considered the effect of noise on lateralization. I have conducted an experiment on the effect of noise on tone lateralization [53]. The results will be discussed in Chapter 6. The inconsistent results among different behavioral DL studies on lexical tones have also been shown in neuroimaging studies. I will introduce the basics of methods of neuroimaging studies and the experiments on tones and speech.

2.2 Neuroimaging techniques

2.2.1 EEG (electroencephalography)

In Chapter 1, I have mentioned that the cerebral cortex is composed of the gray matter and the white matter. The gray matter contains six layers of cells. In these layers, there is a certain kind of cell called the Pyramidal cell. These cells align parallel to each other and perpendicular to the surface of the cortex. The summation of the electrical field changes of these cells is regarded as the source of EEG signal [66].

The EEG data are collected by the electrodes put outside of the scalp. The merit of the EEG is that the temporal resolution is high, on the millisecond basis. The recorded EEG data are rather noisy and hard to analyze based on a single trial. The widely used analyzing method is the event-related potential (ERP), which is calculated by averaging a set of time locked EEG data collected under the same type of stimuli. The ERPs in different conditions may be different. This potential difference reflects different cognitive functions involved. However, it is hard to locate the sources of the electrical field potential changes. This is a drawback of the EEG method.

2.2.2 fMRI (functional magnetic resonance imaging)

The magnetic resonance imaging (MRI) is a technique used to create strong magnetic fields to capture the image of the biological tissue. There are two types of magnetic fields in the MRI machine, the static field and the pulse sequence. The static magnetic field created by a MRI scanner is typically within the range of 1.5 to 4.0 Tesla. A series of changing magnetic gradients and oscillating electromagnetic fields created by a MRI scanner at the same time are called the pulse sequence. The energy from this field is absorbed by the atomic nuclei, and will later be emitted by the nuclei. The amount of the emitted energy depends on the number and type of the present nuclei. Different tissues contain different proportions of various types of molecules, which have different kinds of atomic nuclei. By adjusting the pulse sequence, the MRI scanner can detect different types of tissues. For example, the MRI of the brain can detect the difference between the gray and white matters. When the MRI is used to detect the blood oxygenation changes of the brain over time, the brain activity can be localized to certain brain regions. This method is called functional magnetic resonance imaging or fMRI. Although the temporal resolution is on the minute basis, the spatial resolution of fMRI is rather good.

2.2.3 Other neuroimaging methods

PET (positron emission tomography) is an invasive neuroimaging method that can measure the blood flow changes in the brain. This method requires an injection of the radioactive material into the artery. When the radioactive material travels with the blood and the time does not exceed half of the decay period, the blood flow changes and the glucose metabolism can be detected by measuring the radioactive substances. In this way, the localization of the cognitive function can be measured.

DTI (diffusion tensor imaging) is used to detect the white matter beneath the gray matter. It is a kind of MRI which can trace the maximum diffusion direction of the water molecule. This direction indicates the way of the neural fiber bundle, because the water molecule diffusion direction is restricted in the neural fibers.

MEG (magnetoencephalography) is a method to measure directly the magnetic field changes of the neural activities. It has both the good temporal resolution as in EEG and the precise spatial resolution as in fMRI. The measurement should be done in a magnetic-shielded room to prevent the influence of the earth magnetic filed. And it can only measure the activity of the surface of the cortex.

PET experiment detects the blood flow changes and fMRI detects the blood oxygenation, which have similar origin of sources. The magnetic field changes that MEG measures have the same neural sources as that of the electrical field changes measured by EEG. DTI is used to detect the white matter anatomy of the brain, which may predict the functional connectivities ("the mechanism for the coordination of activity between different neural assemblies in order to achieve a complex cognitive task or perceptual process", p827, [17]). The experimental results using these neuroimaging techniques will be mentioned together with the results of ERP and fMRI experiments in exploring speech and language.

TMS is a technique to create a local magnetic field and to induce a temporal suspension or interruption of the cognitive functions, so that the brain regions relating with certain cognitive functions can be detected. This method is also frequently utilized to explore the brain functions relating to speech and language.

In exploring tone lateralization, I use EEG experiment, because its high temporal resolution is suitable for the measurement of the neural activities during speech perception. Although it is hard to locate the neural sources precisely, the electrical potential changes measured in the left and right sides outside of the scalp infer the hemispheric advantages.

2.3 Neuroimaging studies on speech perception and tone lateralization

2.3.1 Neuroimaging studies on speech perception

The nerve fibers from the ascending auditory system enter the PAC (primary auditory cortex). In the Brodmann area (BA) system, PAC includes BA41 and BA42. The surrounding regions in the superior temporal gyrus (STG) and sulcus (STS) in BA22 are called the belt region or secondary auditory cortex. Posterior to the auditory cortex, the core region in the Wernicke's area within the lateral sulcus is called the planum temporale.

To detect the brain activation, one important principle of the neuroimaging study is the rule of summation. For example, in the fMRI measurement, if one region has a significantly stronger blood oxygen level-dependent (BOLD) signal in one condition than the other, it is regarded to be involved in the first condition more than the other. Usually, the second condition to be compared is the control condition, while the first condition is the experimental condition and includes one more cognitive function than that of the control. After the subtraction of the signals of the experimental versus the control conditions, regions showing a significant positive difference are regarded as processing the additional cognitive function.

By subtracting different conditions, the brain localization of certain cognitive functions, such as auditory, phonemic or semantic processing, is determined. By contrasting the sound perceiving condition with the silent condition, the regions for general auditory processing are located, which involve the PAC, belt region, and planum temporale. The auditory analysis of the complex sounds, such as the phonetic processing, is located in the lateral surface of STG and the STS, more ventrally to the regions of general auditory processing. These are detected by contrasting the speech perceiving condition with the non-speech sound perceiving condition. The semantic processing involves a vast region ventrally distributed to the STS, such as the middle temporal gyrus (MTG). These are determined by contrasting word listening condition to the non-word and other complex sound perceiving conditions. From the above results, a model of the dorsal-to-ventral hierarchical speech processing in the temporal lobe emerges [7]. These results also support Hickok and Poeppel's hypothesis that the ventral part of the temporal cortex processes semantics, while the dorsal part of the temporal cortex processes phonetics [25, 26].

With regard to lateralization, the semantic processing is the most left lateralized. The phonetic processing is more left lateralized than the general auditory processing. In [7], the author summarized the lateralization patterns as "the degree of lateralization appears to be strongest for lexical-semantic areas, less for phonological and verbal workingmemory areas, and still less for sensory cortex activations (e.g., auditory cortex in STG)" (p237).

These ventral and dorsal regions are connected to the anterior (BA45/47) and posterior (BA44) parts of the inferior frontal gyrus (IFG) respectively, which is shown by tracking the white matter using DTI [2]. There is also evidence showing that the IFG is involved in the perceptual tasks, especially the left IFG or Broca's area [24]. The functional neuroimaging study examining the semantic and phonetic processing in the frontal area shows that the anterior IFG (BA45/47) involves more in the semantic tasks, while the posterior IFG (BA44) involves more in the phonetic processing [44]. These facts show the connections between the brain structures and functions. The regions that are connected together are involved in similar functions.

ERP experiments are also used to explore the phonetic and semantic processing. According to Friederici's model of the auditory sentence processing [18], the phonetic processing is done in the first 100ms and is reflected in the N1 component of the ERP waves. The semantic processing is related with the N400 component which is around 300ms to 500ms after the stimulus onset. This model proposes that the cognitive processing of different aspects of the language functions is linearly conducted. However, the processing may not necessarily be serial. Early ERP components as early as in 120ms and 180ms may also reflect the semantic processing [48]. In my ERP experiment on tone lateralization, both the early and late time windows including P2 (200ms after the stimulus onset) and N400 components are explored.

2.3.2 Neuroimaging studies on tone lateralization

Most results of the former neuroimaging investigations on tone lateralization follow the "task-dependent" hypothesis, especially those of the PET and fMRI studies. The comparison of the tone processing in tone and non-tone language speakers shows that the left hemisphere has a more extensive activation in tone language speakers [20, 27, 38]. The greater activations exist in a broad brain network including the frontal, parietal and temporal lobes. Even in tone-language, such as Thai and Mandarin, speakers, the Thai tone processing is more left lateralized in native Thai speakers, compared to that of the Mandarin speakers [21], and the region that shows the difference exists in the Broca's area.

These results at least show that the long-term language training alters the functional activity of the brain when exposed to the same kind of stimuli. However, it is unknown in what aspect the tone is processed differently in different language speakers. Since the non-linguistic pitch processing is lateralized to the right hemisphere in non-tone language speakers [70], it is reasonable to hypothesize that the additional activation in the left hemisphere in tone-language speakers is caused by semantics. Here we assume that the pitch processing is in similar brain regions for both the tone and non-tone language speakers. To the knowledge of the author, there is no evidence in any behavioral or neuroimaging studies showing that the prosody processing is different for tone and non-tone language speakers.

According to the "cue-dependent" hypothesis, the prosody processing should be right lateralized in any language speakers, because the physical property of prosody is the slow variation of the pitch. Tone also contains the pitch variations. If the semantic role is removed, the tone pattern may be processed more rightward.

There is one ERP experiment [42] that investigates tone lateralization, in which the subjects' attention is removed. The results reflect a right lateralization of the tone processing, and the lateralization pattern is reversed from that of the consonant processing. Berlin et al.'s fMRI experiment [4] also shows a left lateralization of the fast formant transition of the stop-consonants.

Moreover, when the part of the stop-consonant is prolonged with a decrease in the rate of the formant transition, this left lateralization also decreases. Jamison et al. [31] have found that the fast (21ms as the mean duration) and slow (667ms as the mean duration) sound changes are left and right lateralized respectively in the temporal lobe. These results are good supporting evidence of the "cue-dependent" hypothesis that the fast and slow changing acoustic cues are processed in the left and right hemispheres respectively [71]. It also indicates that the speech perception is left lateralized, because the speech contains fast changing acoustic cues, while the music perception is right lateralized, because the music is mainly composed of the slow varying pitch changes.

One possible reason for the opposite results between Gandour et al.'s fMRI experiment and Luo et al.'s ERP experiment on tone lateralization is that the time resolution of the BOLD signal is at the level of second, which is the source of the fMRI signal. However, the ERP experiment investigates the electrical potential changes which reflect directly the neural activities, and the time resolution is at the level of millisecond. In Luo et al.'s experiment, they investigate the component around 200ms after the stimulus onset, and claim that the right lateralization of tone processing is just at the early time window. It is obvious that the fMRI experiment has no advantage at the temporal domain and cannot be used to explore the brain activity within a second.

The other possibility to explain the conflicting results is that the experimental paradigm used in Luo et al.'s experiment is the mismatch negativity (MMN), which is a pre-attentive task. In the auditory MMN experiment, subjects' attention is usually drawn to the visual modality. For example, subjects are asked to read books or watch movies silently. When they are doing so, the semantic processing may not arouse automatically, and the lateralization pattern of tone is dominated by its acoustic property. However, in Gandour et al.'s experiment, subjects are asked to do the discrimination task on tones. In this active task, although it only requires phonological processing, the semantic processing may also be activated to help the discrimination.

2.3.3 Motivations of my ERP experiments

As analyzed above, both the linguistic role and the acoustic property may affect lateralization. However, there were no previous systematical studies to examine both of these factors on tone lateralization. By looking at the definition, tone is the pitch variations to distinguish lexical meaning. It is natural to consider the effects of both the acoustic property of pitch and the linguistic role such as semantics on tone lateralization. When the tone patterns do not contrast with the lexical meaning, the abstract tone patterns are still part of the phonological system in the language, which are called tonemes. It is also meaningful to explore the lateralization of tonemes, even if they do not bear lexical semantics. In the exploration of tone lateralization, the toneme is also considered as part of it. In order to have a better understanding of the factors that affect tone lateralization, I take account of these two factors, both of which impact on tone lateralization, though they are in favor of two competing hypotheses.

In Luo et al.'s study [42], the lateralization of tone has been compared with that of the consonant, which reflects the effect of acoustic property on tone lateralization. However, no one has carefully explored the role of semantics on tone lateralization. Although Van Lancker and Fromkin's DL experiment use hums as the pitch changes without semantics, this condition is not well controlled to explore speech without semantics, because the acoustic properties of hums are not comparable to words. Speech materials such as CVC syllables or words usually have formant transitions, while hums do not. In my ERP experiments, I use real words and pseudo-words. The acoustic properties of pseudo-words are comparable to real words, but these pseudo-words do not contain semantics.

In my ERP experiments, I will investigate both the semantic and acoustic aspects of tone processing. The fine temporal resolution of the ERP paradigm allows me to explore the hemispheric lateralization within a second.

□ **End of chapter.**

Chapter 3

ERP experiments on tone lateralization

Summary

In this chapter, I will introduce my ERP experiments on tone lateralization, including the experimental design, sample materials, and methods. In the previous studies of tone lateralization, there is only one ERP study on tone lateralization. In Luo et al.'s work [42], they use the MMN paradigm to do the experiment. Since it is a passive listening task and no language tasks are involved, their results of the tone lateralization only reflect a pitch processing irrelevant of the linguistic function of tone.

My ERP studies include four experiments, all of which are language tasks. The first two are DL experiments, the third one is word priming, and the last one is semantic violation in sentences. Details about the experiments are introduced below.

3.1 A brief introduction to ERP study

A schematic representation of the ERP experiment procedure is shown in Figure 3.1. During the experiment, an experimental control computer presents the stimulus (auditory in my experiments) to the subjects. They are asked to finish some language tasks and their responses will be recorded by the experimental control computer. In the same time, the brain waves of the subjects are collected by a recording computer. And the signal is amplified and digitized by the amplifier before recording. The continuously recorded brain waves of all channels are EEG signals, which are tagged with time stamps synchronizing with the stimulus presentation. This procedure allows the following ERP analysis.

After the experiment, EEG data goes through 7 major steps (see Chapter 4 for details), especially the segmentation of EEG signals and the averaging of multiple EEG segments with the same type. The averaging procedure enhanced the signal to noise ratio and the ERP wave is obtained. Each component of the ERP wave has its own time window and topographic distribution. There are two naming systems of the ERP components. Take 'P1' for example, 'P' represents for positive and '1' represents for the first, so that 'P1' indicates the first positive going component. The other type of naming system uses the time window of the peaks to name the components. For example, 'N400' means a negative going component which peak is around 400 ms after the stimulus onset.

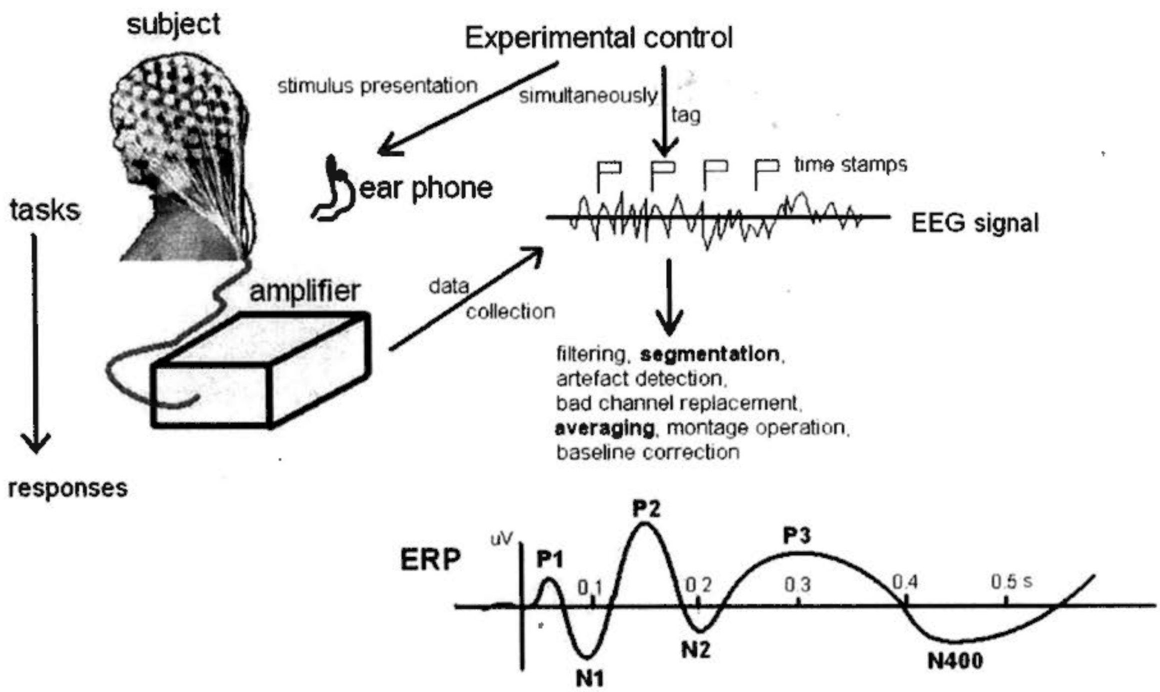


Figure 3.1: The procedures of ERP experiments

3.2 ERP experiment on DL

In Chapter 2, DL has been introduced. In this section, I will summarize the previous ERP studies on DL and narrate my DL experiment on tone lateralization.

3.2.1 Motivations

Followed by the behavioral DL experiments that show the lateralization in the auditory modality, the ERP methods are used to explore the brain lateralization under the DL paradigm [15, 67].

Eichele et al.'s study examines the N1 component of the ERP waves during the stop-consonant DL [15]. They examine the electrodes in the left and right temporal regions, and find that the latency of the N1 component in the left hemisphere is 15ms shorter than that of the right homologue electrode ($p < 0.01$).

In behavioral experiments, it is a standard to use the six stop-consonants /b, d, g, p, t, k/ with an /a/ to form CV (consonant-vowel) syllables to detect the ear advantage. And the results consistently show a REA in population [30]. Although Eichele et al. have not found a significant amplitude difference between the left and right homologous regions, the shorter latency of the left hemisphere is consistent with the REA in behavioral experiments, which reflects a more quickly response of the left hemisphere in perceiving stop-consonants. In a MEG study, "the results suggest that auditory impulses originated from the ear may first arrive at the contralateral temporal cortex and then return to the ipsilateral temporal cortex mediating through the corpus callosum (p483, [45])". Although the reason for these results is unknown, at least it provides evidence that the contralateral auditory pathways transpose signals quicker than the ipsilateral pathways under the monaural presentation [45]. These results confirm Kimura's modal on DL that the contralateral pathways surpass the ipsilateral ones, and the left hemisphere has an advantage in processing certain speech sounds.

Wioland et al. explore DL of pitch perception [67]. Since it is hard to name the pitch, they use the dichotic monitoring task, which requires subjects to discriminate the 'rare' stimuli rather than to identify the stimuli in the original DL experiment. (Arbitrary labeling of pitches verbally or with symbols needs additional training for subjects, and it involves language tasks other than pitch perception itself.) It is an oddball design. In their experiment, subjects hear diotic pitches at 500Hz in 85% of all trials. The pitch in the left or the right ear changes to 2000Hz (left target or right target). Each type of these changes occupies 5% of the trials. The input to the other ear remains at 500Hz. These two conditions are dichotic conditions. In the rest 5% of the trials, subjects hear diotic 2000Hz pitches (diotic target). Once the subjects hear the 'rare' pitch, they will give a response by pressing the button without caring about in which ear they hear the pitch change. The statistical analysis reveals that in the two dichotic conditions, the N2 component has higher amplitude when the tone change is in the left ear than in the right ear. Their "findings bring strong electrophysiological support to Kimura's structural model for dichotic perceptions with a right hemisphere prevalence in a pitch discrimination task" (p516, [67]).

ERP experiments on DL have consistent results as the ear advantage results in the behavioral tests, for CV syllables and pitch materials. However, it has not been used to explore tone lateralization. Previous behavioral DL experiments on tone have inconsistent ear advantage results, while ERP measurement may provide more direct evidence regarding the hemispheric specialization. Since tone is a part of the language system, it is possible to label and name the tones as in the stop-consonant DL task. The tone patterns do distinguish meaning, but they also form the phoneme units which are called tonemes in certain tone languages. In this dissertation, the discussion of tone lateralization also considers tonemes.

3.2.2 Experimental design

In the current DL ERP experiment on tone lateralization, the two factors considered here are the linguistic role and the physical property. It is a two-by-two design. The linguistic role refers to the semantic function of the tone. There are two levels in this factor: syllables with characters that bear meaning and those having no correspondent characters. They are called real syllables and pseudo-syllables, respectively. The physical property refers to the acoustic features of the tone, compared with the other phonemes such as the stop-consonants. The pitch changes in tones are around 200–300ms long and the changes are finegrained in the frequency range, while the formant-transitions in the CV syllables are about 20–40ms within a wider frequency band. Stop-consonant and tone are the two levels in the factor of the physical property.

3.2.3 Materials

There are four conditions in this two-by-two design. The sample materials are listed in Table 3.1. Mandarin syllables are used in the experiments.

Table 3.1: The four conditions in the first DL experiment and the sample materials in these conditions

Conditions	REAL SYLLABLE	PSEUDO-SYLLABLE
Consonant dichotic trial	(bāo), (dāo)	(duá), (buá)
Chinese Character sample	包，刀	,
Tone dichotic trial	(báo), (bāo)	(buā), (buá)
Chinese Character sample	雹，包	,

In the real syllable dichotic trials, the two syllables both have correspondent characters in Mandarin. When one syllable has correspondent characters, the semantics of these characters is activated. For example, when the syllable (bāo) is heard, it is natural for subjects to think of 包, which means the 'bag'. In case there are multiple correspondent characters for a single syllable, each of these homophones has its own meaning, and the semantics will be involved as well. In the pseudo-syllable consonant dichotic trials, both syllables are made of valid consonants and diphthongs. But when they are combined together, there are no correspondent characters for these syllables. In both real syllable and pseudo-syllable cases, there are consonant dichotic and tone dichotic trials. In the real syllable dichotic trials, subjects hear two syllables with different initial consonants. Other components in these syllables are the same. In the tone dichotic trials, the only difference between the left and the right ears is the tone, and the two syllables have the same consonant and diphthong.

In this experiment, the stop-consonants used are phonemes (b) and (d) in Mandarin (/p/ and /t/ in IPA notation), and the diphthongs are (ao) and (ua) (/au/ and /ua/). The tones are tone one (the high level tone) and tone two (the high rising tone). Eight syllables are constructed with these phonemes and tonemes: (bāo), (báo), (dāo), (dáo), (buā), (buá), (duā), and (duá), which form eight pairs of dichotic trials. If the order of left and right ear presentations is counted, there are sixteen trials in total. All materials are listed in Appendix (Table A.1).

The sound materials are recorded from a female Mandarin native speaker in a sound-proof booth, using Shure SM10A microphone and Sony PCM-2700A audio recorder. The sampling rate is 44100Hz during recording. Twenty samples of each syllable are recorded. The sounds are edited using the Praat software after recording. Four real syllables having the same length are chosen, with the mean duration of 300ms. Four pseudo-syllables having the same length are also chosen, with the mean duration of 350ms. The intensity of each of these sounds is adjusted to 75dB. In the end, sixteen pairs of dichotic trials are created by combining two syllables in the left and right channels.

To gain a better experimental control, the pitch of one syllable in a consonant dichotic trial is aligned to the pitch of the other. And one syllable in a tone dichotic trial is made by its original tone contour and the syllable structure of the other syllable in the dichotic trial. The sound waveforms and the spectrograms are shown in Appendix (Figure A.1). These manipulations will remove the acoustical dissimilarity between the left and right channels of the irrelevant phonemes in the dichotic trials, and distinguish the target phoneme contrasts. Only stop-consonant contrasts or the tone contrasts remain in the dichotic trials.

3.2.4 Procedures and experimental settings

Before the experiment, subjects are tested with their hearing abilities using the pure tone analysis method (PTA), and with their handedness using the Edinburgh Handedness Inventory [46]. The sample forms of the PTA recording and the handedness test are shown in Appendix (Figure A.2).

The PTA test is done in a sound-proof room using the GSI-68 diagnostic audiometer. Testing frequencies are 125Hz, 250Hz, 500Hz, 750Hz, 1000Hz, 1500Hz, 2000Hz, 3000Hz, 4000Hz, 6000Hz, and 8000Hz. The sequence of the testing frequency begins from 1000Hz and increases step by step to 8000Hz, and then goes down from 750Hz to 125Hz. The hearing threshold of each subject at each frequency is determined by the automatic program imbedded in the audiometer. Subjects should press a button once they hear a sound. Usually, if the subjects respond to a sound at a certain intensity level for 2 times within 3 presentations, we say they can hear the sound at that intensity level. If the subjects press a button, the sound intensity will go down by 10dB; otherwise, it will bounce back by 5dB. The lowest intensity level at which subjects can respond for 2/3 times is called the hearing threshold at a certain frequency.

If the subject's hearing threshold consistently exceeds 30dB at 3 adjacent frequency levels, his/her data will be excluded from the analysis. Two subjects out of 36 have been excluded due to their hearing abilities, although none of the subjects has previous hearing problems. This hearing ability control is to make sure that subjects can hear stimuli clearly, because during the experiment the intensity of the sound presentation is fixed at 75dB. It is measured by the sound level meter, because the sound intensity measured in the computer is not necessarily to be the output sound intensity.

Other settings of the ERP experiments are listed below. The sampling rate of the EEG recording is 250Hz, and the reference node is vertex. The impedance of all electrodes is adjusted below 50K Ohm at the beginning of the experiment to insure a good contact with the scalp and clear data.

During the experiment, subjects are asked to respond to the consonant and the tone of the heard syllable in one of their two ears. At first, they see a fixation. Four hundred milliseconds later, they hear a dichotic trial. Subjects are asked to listen carefully to the sounds from both ears and try to remember them. The fixation is on when subjects hear sounds. They are asked not to blink or move any body parts while the fixation is on the screen. The fixation disappears at 1000ms after the onset of the stimulus, replaced by the Chinese character indicating "左" (left) or "右" (right). The purpose of the indication is to let subjects to know which side of the syllables they should respond to. The purpose to let subjects hear the stimuli before seeing the indication is not to bias their attention to either ear. The indication is on the screen for 1200ms. Subjects are asked to give the response after seeing the indication. They are given 2000ms more after the disappearance of the indication to respond. The procedure of each dichotic trial is shown in Figure 3.2.

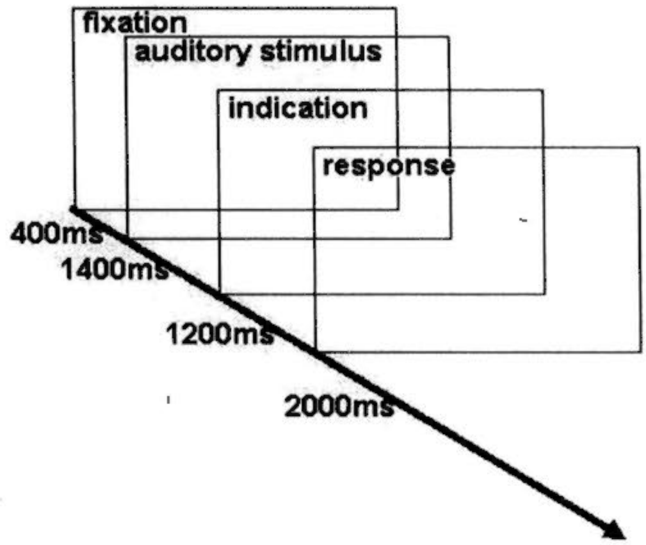


Figure 3.2: The procedure of each dichotic trial

Four buttons are used for response, two for consonants and two for tones. The choices are “B”, “D”, “–”, and “/” representing the consonants (b), (d), tone one, and tone two in Mandarin. After the training of PinYin system for years, the symbols represent different phonemes for subjects for sure. The task is regarded as a language task other than a metalinguistic one. For example, when subjects hear (dāo) and (bāo) in their left and right ears respectively, and they see ”右” (right) as an indication. Then they should respond “B” and “–” by pressing the buttons. Subjects are instructed to respond with the left and the right index fingers, one for the consonants and the other for the tones. For half of the subjects, they use the left index finger to respond to consonants and the right index finger to respond to tones. It is reversed for the other half of the subjects. The left or right hand response to consonants and tones is chosen randomly between subjects. The sequence of the four buttons is adjusted accordingly for each subject.

Each trial lasts 5 seconds. There are 64 trials in each block, lasting 5 minutes and 20 seconds. In total, there are 4 blocks. Between each block, subjects are allowed to take a rest for 2 minutes. The whole experiment lasts about 30 minutes. In each block, the 16 dichotic pairs appear randomly. E-Prime software is used for the stimulus presentation.

3.2.5 The second DL experiment

The basic settings in this DL experiment are the same as in the first DL experiment, except for the materials and additional two diotic control conditions. In the second DL experiment, the consonants used are (d) and (t) (/t/ and /t^h/ in IPA notation), so the contrast in the consonant dichotic trials is the VOT (voice onset time), instead of the formant transition in the stop-consonant CV syllables as in the first DL experiment. The tone materials are tone one and tone four, instead of tone one and tone two as in the first DL experiment. The vowels are /a/ and /œ/, the latter of which does not exist in Mandarin. The syllables composed of /œ/ are called non-syllables. The sample materials are listed in Table 3.2.

Table 3.2: The four conditions in the second DL experiment and the sample materials in these conditions

Conditions	REAL SYLLABLE	NON-SYLLABLE
Consonant dichotic trial	(dā), (tā)	(tœ̀), (dœ̀)
Chinese Character sample	搭，它	–，–
Tone dichotic trial	(tà), (tā)	(dœ̀), (dœ̄)
Chinese Character sample	踏，它	–，–
Diotic trial	(dà), (dà)	(tœ̄), (tœ̄)
Chinese Character sample	大，大	–，–

In composing the stimuli in the second DL experiment, there is no manipulation of the sound waveforms, except for the intensity adjustment. The duration of the syllables is 350ms. The reason for not adjusting the sound waves is that the two sounds in the dichotic trials in the first DL experiment are too similar to each other, which causes difficulty for subjects to identify stimulus in either ear. The behavioral data also indicate a chance level of choice for the average accuracy in the first DL. Although this low accuracy does not deteriorate the lateralization analysis in the behavioral data in the first DL, a better accuracy rate could bring more confidence in the result analysis. A better distinction of the two sounds in a dichotic trial makes the task easier for subjects. The drawback of this consideration is that the differences in the two sounds in a dichotic trial under the two consonant dichotic conditions may also include nuance pitch contrasts. The mean pitch differences between the two sounds in the four consonant dichotic pairs are listed in Table 3.3. According to the d'Alessandro threshold [13], these pitch differences are unnoticeable. For the same reason, the two sounds in each trial in the two tone dichotic conditions may also have small differences in the syllable structures. But the onset of these two sounds can be manually adjusted quite well in Praat to diminish the differences in the onset time. The slight intensity differences inside the sound waveforms between the left and right channels should not affect the result, since each combination will be reversed in the left and right channels for half of the presentations. Slight formant differences between the two sounds in a tone dichotic trial should not affect the result, either. The sound waveforms and spectrograms are shown in Appendix (Figure A.3).

Table 3.3: the mean pitch differences between the two sounds in the four consonant dichotic pairs

Materilas	TONE 1 MEAN FREQUENCY (& RANGE)	TONE 4 FREQUENCY RANGE (& MEAN)
Real syllable	(dā): mean 376.1Hz (372.2–385.2)	(dà): range 369.1–443.0Hz (413.7)
	(tā): mean 376.1Hz (369.9–391.8)	(tà): range 371.7–433.3Hz (407.2)
Non-syllable	(dœ̄): mean 366.2Hz (359.7–382.1)	(dœ̀): range 321.4–442.6Hz (410.3)
	(tœ̄): range 372.2Hz (354.2–385.1)	(tœ̀): range 345.0–458.2Hz (429.0)

The measurement of the pitch is calculated with Praat. Due to lack of pitch points in the beginning and ending parts of (tœ̀) during the measurement, the difference between (dœ̀) and (tœ̀) seems to be greater than it actually is. Even if the difference is as large as shown in the measurement, it does not exceed one semitone of mean frequency value of either (dœ̀) or (tœ̀). And the difference is not obvious in perception.

As in the first DL experiment, each trial lasts 5 seconds. But in the second DL experiment, in order to make subjects feel more comfortable, the number of trials in each block is reduced to 48, which leads to a change of the duration of each block to 4 minutes. There are 6 blocks in the second DL experiment, and the whole session lasts about 30 minutes.

3.3 Word priming

DL is an experimental condition that does not occur often in daily life, and it adds more loads to the forebrain to process two sounds simultaneously [32]. The underlying assumption to use tone or consonant dichotic trials is that the additional processing of two tones or two consonants will increase the load of correspondent brain regions in tone or consonant processing. By comparing different dichotic conditions, the differences in tone or consonant processing are prominent. However, the diotic sound presentation is more natural, and the priming task is one option for the study of tone lateralization.

3.3.1 Motivations and experimental design

Priming is a phenomenon of the acceleration of the responses after repetitions. It has been widely explored in experiments where subjects are exposed to a type of stimuli for more than one time. In this situation, the response time will decrease from the second time subjects encounter the same type of stimuli. It is called facilitation effect if the reaction time decreases, while inhibition also occurs if the reaction time increases.

Previously, in the study of child language acquisition, the phonological priming ERP experiments have been used to explore the changes of the word onset processing along with language experiences [9]. In Bonte and Blomert's experiment, there is a change of the N1 shape and a different N400 component reduction in different language groups when using words or non-words as testing materials. In their experiment, the primes share the first syllable with the target words in half of the trials. In the other half of the trials, the primes share no common syllables with the targets. The materials are all disyllabic Dutch words or non-words.

When exploring the factors affecting tone lateralization, I adopt a similar design as in Bonte and Blomert's work, but use different syllables in the phonological priming tasks, i.e., consonant and tone. The underlying assumption is that the priming effects of tone or consonant will cause different lateralization of the ERP component reduction in the two hemispheres. For example, if the left hemisphere is the dominant hemisphere for the consonant processing, the priming effect should be stronger in the left hemisphere, hence the reduction of the ERP component in the left hemisphere is greater than that of the right hemisphere. However, if the right hemisphere is the dominant hemisphere for the tone processing, the reduction of the ERP component in the right hemisphere should be greater than that in the left homologous sites, which reflects a stronger priming effect in the right hemisphere. I will use these two types of primes to explore the factor of the physical property in my experiment.

Besides, by using real word and pseudo-word targets I explore the different lateralization patterns of the ERP component in these two conditions. According to the previous fMRI studies [44], the semantic processing should be left lateralized. The working hypothesis in the current experiment is that the ERP component correspondent to semantic processing should be more left lateralized. This effect could be indicated by higher amplitudes in the left electrodes than in the right.

In sum, the factor of the physical property is reflected in the different types of priming effects, and the factor of the linguistic role is examined in the different types of target words. These two factors are explored in different time windows in the ERP data, and the experimental design is a three-by-two design including two control conditions. In the factor of the physical property, there are three levels: consonant primes, tone primes, and non-primes. In the factor of the linguistic role, there are two levels: real words and pseudo-words.

3.3.2 Materials and procedure

The sample materials are listed in Table 3.4.

Table 3.4: the sample materials in the second ERP experiment

Conditions	PRIME	TARGET
Real word Consonant prime	(qué)	(qì chē)
Chinese Characters	瘸	汽车
Pseudo-word Consonant prime	(jìng)	(jiāo běn)
Chinese Characters	静	交本
Real word Tone prime	(hōng)	(xiāng gǎng)
Chinese Characters	烘	香港
Pseudo-word Tone prime	(qún)	(guó mèn)
Chinese Characters	群	国闷
Real word Non-prime	(fā)	(xué zhě)
Chinese Characters	发	学者
Pseudo-word Non-prime	(lún)	(yǐng fèng)
Chinese Characters	轮	影缝

There are 6 conditions, and 60 trials are formed under each condition. In total, there are 360 trials. The full list of the materials is listed in Appendix (Table A.2, A.3, A.4, A.5, and A.6). In the consonant priming conditions, the prime syllable shares the same consonant as the first syllable in the target word; in the tone priming conditions, the tone of the prime syllable is the same as the tone in the first syllable of the target word. Real words are the disyllabic words in Mandarin; pseudo-words are created by connecting two valid syllables, but the combined syllables do not form a meaningful word in Mandarin.

In the experiment, subjects first hear the prime. The duration between the onset of the prime and the fixation is fixed at 600ms. The mean duration of the primes is 383.06ms (49.71) (The number in bracket represents the standard deviation), and the maximum length is 591ms. (The minimum length is 251ms.) The sound intensity of the primes is set to 55dB and the subjects are asked to ignore the sound played before the fixation.

The purpose of presenting primes at low intensity and the instructions to subjects is to make sure that the priming effect is strong [40]. Target syllables are adjusted to 75dB. After the prime, the fixation appears on the screen. Four hundred milliseconds later, the target word is presented in both ears. The OSA (onset asynchrony) between the prime and the target is fixed at 1000ms. Target length is 619.58ms (52.05) on average, and the longest target is 751ms and the shortest one is 510ms. After 1000ms after the onset of the target word, the fixation disappears. Subjects should not blink or move any body parts during the appearance of the fixation, and not to respond until the fixation disappears. They are given 3000ms to respond. One trial lasts 5 seconds. There are 60 trials in each block with 10 randomly chosen stimuli from each condition. Each block lasts 5 minutes. Subjects are allowed to rest for 2 minutes between two blocks. The experiment includes 6 blocks and lasts about 40 minutes in total. The procedure of each priming trial is shown in Figure 3.3.

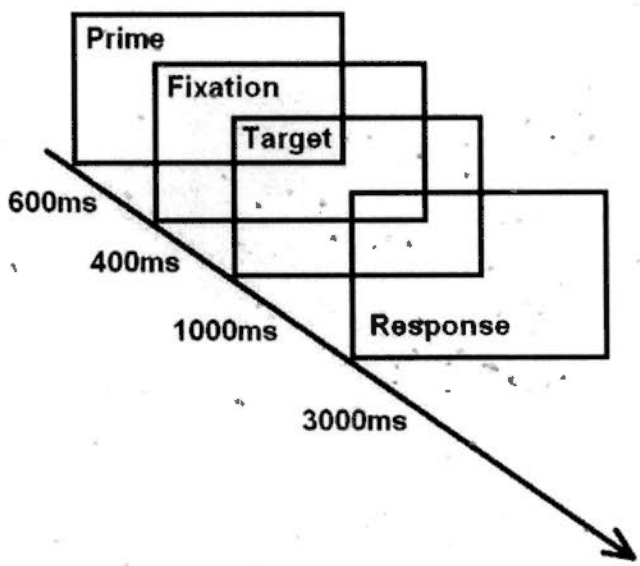


Figure 3.3: The procedure of each prime trial.

The task in the experiment is to judge whether the target word is a real word or not. Subjects press the 'Y' button if they think the word is a real word, and the 'N' button otherwise. One half of the subjects respond to 'Y' with their left index finger and 'N' with their right index finger. The other half do the reverse. The left or right response order is determined randomly between subjects.

3.4 Semantic violation in sentences

3.4.1 Motivations

The first ERP experiment exploring language processing is the work on semantic violation [39]. They have found that the N400 component is more negative when the meaning of the target word does not integrate well with previous context. N400 component and semantic processing have been extensively explored ever since then. I use the semantic violation paradigm to explore the tone lateralization in my ERP experiment.

3.4.2 Experimental design

In this experiment, the physical property and the linguistic role are squeezed together. I change the tone or the consonant in the final syllable of a sentence to induce the semantic violation. Although the last syllable is a valid monosyllabic word in Mandarin, it does not fit in with the sentence context. There is a strict control of the sentence length and the syntactic structure; each sentence contains 11 characters, and the sentence structure of the last two syllables is always a verb followed by an object. Examples of the stimuli are shown in Table 3.5.

Table 3.5: the three conditions of the third experiment and the example sentences in those conditions

Conditions	SAMPLE SENTENCES
Normal sentence	(zǎo chén yì qǐ lái, 早晨一起来, tā jiù kāi shǐ shū tóu). 他就开始梳头。
Consonant induced semantic violation	(xià wǔ méi yǒu kè, 下午没有课, nán shēng dōu qù tī yóu (qiú)). 男生都去踢油（球）。
Tone induced semantic violation	(ná dào xué wèi hòu, 拿到学位后, tā huì mǎ shàng huí guò (guó)). 他会马上回过（国）。

3.4.3 Materials and procedure

There are 60 sentences in each condition, and there are 180 sentences in total. The average duration of the sentence from the onset of the first syllable to the onset of the last one is 3206.1ms (156.1). During the experiment, the fixation is shown on the screen for 400ms before the auditory presentation of the sentences. It disappears at 1000ms after the onset of the last syllable. So the sentence duration is 4206.1ms (156.1) on average. The blank screen remains for 2000ms before the next trial starts. The length of each trial varies according to the length of the stimuli between the onset of the sentence and the end of the second last syllable. The average length of each trial is 6606.1ms (156.1). The intensity of the imbedded sentence and that of the target syllable are all adjusted to 75dB. Each block contains 40 sentences consisting of 10 randomly chosen sentences from each of the three conditions, and 10 additional filler sentences. The usage of the filler sentences is to make the positive and negative feedbacks have equal chances. There is no violations in the filler sentences. They also contain 11 characters each but the sentence structure is not controlled. Each block lasts about 4 minutes. There are 6 blocks in total. Subjects can take a 2 minutes break between blocks. The whole experiment lasts about 30 minutes. The materials are listed in Appendix (Table A.7, A.8, A.9, and A.10). The procedure of each sentence trial is shown in Figure 3.4.

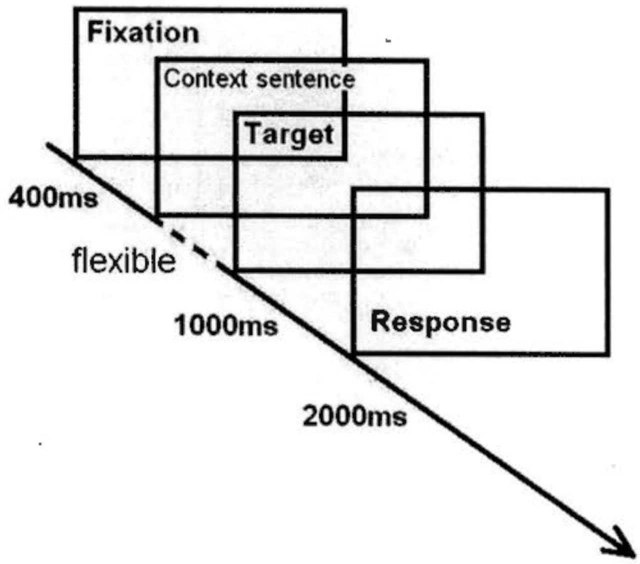


Figure 3.4: The procedure of each sentence trial

Subjects are asked to judge whether the heard sentence is a normal sentence or not. Subjects should press 'Y' button if there is no violation and press 'N' button otherwise. One half of the subjects respond to 'Y' with their left index finger and 'N' with their right index finger. The other half do the reverse. The left or right response order is randomly assigned to the subjects. Usually the violation appears toward the end of the sentence. Subjects are instructed not to blink or move their body parts toward the end of the sentences.

3.5 Subjects and four experimental procedures

Thirty-four subjects participated in the experiments, whose average age is 27 (4.2). All are university graduate or undergraduate students, with mother tongue as Mandarin. Eighteen subjects are male and 16 are female. After their PTA test, two male subjects with their thresholds consistently higher than 30dB below 4000Hz are excluded from the data analysis. Since the energy beyond 4000Hz is relatively low for speech sounds, it is not necessary to exclude subjects with higher thresholds in that range.

The handedness score of each subject is listed in Appendix (Table A.11). The scale is from -100 to 100, -100 representing extreme left hander and 100 extreme right hander. The average score is 83.1 (26.0). The independent-sample T-test shows no significant difference in the handedness scores between male and female subjects ($t(27) = -1.6$, $p = 0.12$). The average handedness scores of males and females are 76.8 (31.7) and 90.1 (15.7). There is a greater variance in male subjects, and their average score is less than that of female subjects. The greater right handedness score for the female subjects may increase the possibility of a left hemisphere advantage of language in them, noticing that females may be more bilateral in the language functions, while males usually have the left hemisphere dominance [12].

The four experiments are finished in two separate days for subjects taking them all. (A few subjects attend 2 out of 4 experiments within one day.) In each testing day, there are two sessions of experiments. Subjects take a rest for 10 minutest between the two sessions. On the first day, subjects do the first DL experiment. There is a short practice block before the experiment which has a half length as the testing blocks. The materials are the same as in the experiments. Subjects can practice for twice to get familiar with the dichotic experiment. The first DL experiment lasts around half an hour. In the second session, the word priming experiment is tested. There are 12 trials in the practice block, using different testing materials from the practice block, with two trials in each condition. All subjects perform well in the practice block. The length of the experiment is around half an hour. On the second day, subjects take part in the second DL at first. It also takes about half an hour. The practice session includes 32 trials with the same testing materials as in the formal test. After taking a 10 minutes rest, subjects continue to do the sentence semantic violation experiment. The practice block of semantic violation includes 9 sentences, with 3 sentences in each condition. The practice sentences are different than the testing materials. Subjects respond with high accuracy during the practice. In each day, it takes about one and a half to two hours to finish the two experiments, including the preparation time for the experiment, e.g. putting on the net and adjusting the impedance.

In sum, the first three experiments use the factorial design, with the semantics and the acoustic property as two factors. In the factor of the linguistic role, real word and pseudo-word are the two levels. In the factor of the physical property, tone and stop-consonant are used as the two levels. In the last experiment, the factor of the physical property is combined with the linguistic role, namely semantics.

□ **End of chapter.**

Chapter 4

Data analysis

Summary

In this chapter, the behavioral and ERP data from four experiments are analyzed. The first two are DL experiments. The ear advantages are calculated based on the accuracy of the two ears. In the word priming and sentence semantic violation experiments, the reaction time and accuracy rate are shown. The effects of the linguistic role and the physical property on lateralization of the ERP waveforms are tested in all four experiments.

4.1 Behavioral data

Among the four experiments, the behavioral data of two DL experiments can be used to analyze the ear advantages. In these experiments, it is hard to analyze the response time, since the subjects have to give two responses sequentially within one trial. Therefore, only the accuracy is considered. In the word priming and semantic violation experiments, both the accuracy and response time are analyzed. Since the presentation is diotic in these two experiments, the behavioral data do not reflect ear advantages, but they can be used to justify both the priming effects, by checking the reduction of the response time, and the semantic violation effects, by examining the length of the response time.

4.2 ERP data processing

The recorded brain waves are continuous EEG signals, and the electronic signals reflecting certain cognitive functions are embedded in various kinds of noises. These noises may come from the other activations inside the brain, the muscle movement, or the outside equipment. There are two assumptions in the ERP study. The first one is that the signals of the electrical potential of certain cognitive function are time-locked to the onset of the stimuli, while noises are not; the second one is that the signals and noises are additive to each other. Considering these two assumptions, if we align multiple chopped EEG segments with their onset times and average them together, the noises will cancel out themselves and the useful signals will be preserved [41].

The working principle of the ERP is that the averaged time-locked EEG segments of a certain type of stimuli reflect the cognitive function that underlies it. Different types of the stimuli may trigger different cognitive functions, hence incurring different shapes of ERP waves. That is why this type of experiment is called the event-related potential. The statistical analyses of the ERP waves can reveal the significant differences between the waveforms in different conditions, and these differences reflect different cognitive processes.

The processing of the ERP data in my four experiments follows the 7 steps suggested by the manual of the EGI NetStation software, and the data analyses all go through the similar procedures.

1. Filter. It is the first step in the data processing. The

default filter is a 40Hz low-pass filter. There are three reasons to set this value: 1) this filter can exclude the 50Hz line noise; 2) the power of the frequency band beyond 40Hz is small; and 3) the most important cognitive functions are related with the frequencies below 40Hz. During the recording, the high pass filter is set to 0.1 Hz by default. After the low-pass filtering, the frequency range of the signal is between 0.1 and 40Hz.

2. Segmentation. In my experiments, the fixation usually appears 400ms before the stimulus onset and disappears 1000ms after the onset. Subjects are asked not to blink during the fixation period, because the EOG (electroculography) of blink will cause electrical potential changes 10-20 times greater than the ERP waves. In the segmentation setting, I focus on the waveforms from 200ms before the stimulus onset to 900ms after the onset. It allows sufficient time for the data analysis after the stimulus onset and a wider time window before the onset for the artefact detection. During the experiments, the presentation program records what type of stimuli the subjects hear during the EEG recording. This is done by adding time stamps with different tags in the waveforms. After the segmentation, different types of segments can be averaged in later steps.

3. Artefact detection. EEG signal is prone to be affected by eye blinks, eye movements, or body movements. The artefact detection is to exclude these bad segments out of analysis. In my experiments, I set a strict threshold for the artefact detection: if the amplitude exceeds -100uV or 100uV in a segment, it is marked as a bad segment. The other parameters are kept the same as in the default setting. This step can also detect bad channels inside a segment. If the contact of the electrode and the scalp is not good in some channel (each corresponds to one electrode), the signal recorded will have abnormal high amplitude. Such channels are marked as bad channels by the artifact detection.

4. Bad channel replacement. This step is to recover the data with bad channel tags. The working principle is that the electrical potentials of adjacent electrodes are very similar. Therefore, the average of all adjacent channels should equal or approach the real value of the electrical potential of a certain electrode. Each electrode corresponds to one channel here.

5. Averaging. This step is to average all good segments in every channel of each condition of each subject. After this operation, the data size decreases a lot. For each subject, the number of the dimensions of the data shrinks to 3 (conditions × time points × channels).

6. Montage adjustment. This manipulation is to make an adjustment of the electrical potentials, conceptually similar to the averaging operation in the bad channel replacement. It corrects the electrical potential errors when the electrodes in the net are placed with unequal distances to each other. This is a necessary step after the averaging to make sure of an even spatial distribution of the data from all channels.

7. Baseline correction. Electrical potentials between different conditions must be compared under the same criteria. The baseline correction adjusts the average electrical potential to zero in a small time window right before the stimulus onset. (If the electrical potential before the onset is a flat line, we can set the electrical potential to zero at the onset time point. However, the ERP wave is not a line before the onset.) Usually, the time window for the baseline correction is from 100ms before the onset to the onset time point.

After the above 7 steps, the ERP of each subject is ready for later analyses. Both of the wave amplitude and the latency can be analyzed. Amplitude includes the peak amplitude (height of the peak value) and the averaged amplitude within a certain time window. Latency is referred as the peak latency of a certain component here. It is a measurement of the time lag of the peak from the stimulus onset. In the statistical analysis, one amplitude or latency measurement of all subjects forms a vector. Each number within the vector comes from one subject. Considering different conditions or electrode locations, data vectors form a multiple dimension matrix. For example, if the experiment follows a two-by-two design (four conditions), and the electrodes are separated to the left or right homologue sites, the dimension of the data matrix could be two-by-two-by-two. If the results show a significant interaction between the left/right factor (lateralization) and different conditions as designed in the experimental manipulation, we say the experimental factor affects lateralization (Figure 4.1).

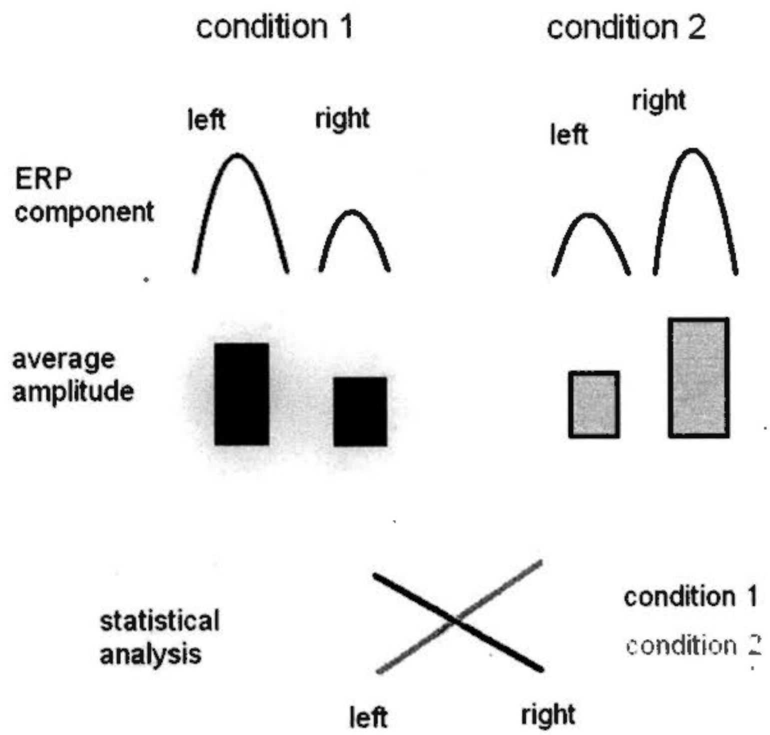


Figure 4.1: An illustration of the expected result.

In the following sections, I will present the data of each experiment, including both the behavioral and ERP data. The ERP results may not have the exactly the same lateralization pattern as shown in Figure 4.1, but there is also a significant interaction effect.

4.3 Dichotic listening

4.3.1 Behavioral data

In every trial of this experiment, subjects have to respond with both the consonant and the tone of the heard syllable in their left or right ear. They are asked to give the response after the indication appears on the screen. The response before the indication is not recorded in the experiment. The behavioral data of one subject are excluded, since this subject always guesses the answers before seeing the indication and the total number of recorded responses is very low. Two other subjects are excluded due to their high hearing thresholds. In total, there are 31 subjects' data available for the analysis out of 34 participants.

The percentage of the responses for each subject is listed in Appendix (Table A.12), and the average percentage of responses is 95.7% (9.2); the accuracy rate of each subject is listed in Appendix (Table A.13), and the average percentage of the accuracy is 50% (21.6). Although the overall correctness is at a chance level, it should not hinder the analysis of the ear advantages. In the consonant conditions, the rate of correctness of the left ears is 48.2% (14.2), and that of the right ears is 51.7% (12.4); in the tone conditions, the rate of correctness of the left ears is 71.1% (17.0), and that of the right ears is 72.5% (16.4). The rates of correctness in the left and right ears in the four conditions are shown in Figure 4.2. Having a longer duration, the tones always show a higher correctness than the consonants, although both of them are phonemes.

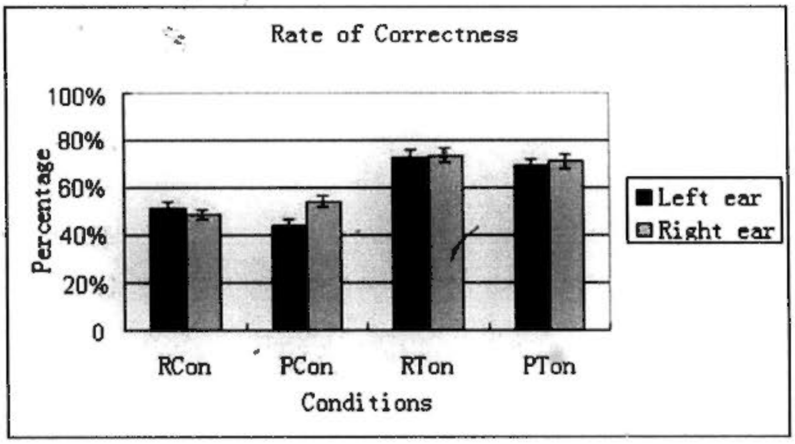


Figure 4.2: The rates of correctness of the left and right ears in the four conditions. 'RCon': real syllable consonant DL condition; 'PCon': pseudo-syllable consonant DL condition; 'RTon': real syllable tone DL condition; 'PTon': pseudo-syllable tone DL condition.

In Figure 4.2, the rate of correctness of each ear in each condition is shown. 'RCon' means the real syllable consonant DL condition. 'PCon' means the pseudo-syllable consonant DL condition. 'RTon' and 'PTon' mean the real syllable tone DL and the pseudo-syllable tone DL conditions respectively. Each error bar represents one standard error.

An often used method to calculate the ear advantages is called POE (percentage of errors). The formula to calculate POE is shown below:

$$\frac{L_{error}}{L_{error} + R_{error}} * 100\% \tag{4.1}$$

In formular 4.1, L_{error} and R_{error} represent the numbers of errors in the left and right ears respectively. If L_{error} equals to 50% of the total number of errors, there is no ear advantage. If a POE exceeds 50%, it indicates that the right ear gets fewer errors than the left ear, i.e., a right ear advantage. A left ear advantage corresponds to a POE less than 50%. POE, as a rough measure, has been widely used in calculation of ear advantages in previous literatures of DL experiments [63]. In my experiment, the values of POE under consonant and tone conditions are 51.7% (11.4) and 50.8% (15.7) respectively.

A statistical test of POE in each condition is shown in Table 4.1. In order to test the right ear advantage, we calculate POE using the one-tail (right-tailed) T-test.

Table 4.1: The right ear advantage test based on POE in each condition

t-value and p-value	REAL SYLLABLE	PSEUDO-SYLLABLE
Consonant DL	t(30) = -1.095, p = 0.859	t(30) = 2.306, p < 0.014
Tone DL	t(30) = -0.350, p = 0.636	t(30) = 0.973, p = 0.169

Only the pseduo-syllable consonant DL condition shows a significant difference, and the sign of the t value indicates that the left ear gets more errors than the right ear, and there is a right ear advantage. The reason for the real syllable consonant DL condition not to have an ear advantage is that the sound (bao) and (dao) are quite similar. Subjects report that the pseudo-syllables (bua) and (dua) are slightly easier to distinguish than (bao) and (dao).

The paired T-test is also used to confirm the ear advantages. It is used to examine whether the correctness of one ear is significantly different from that of the other ear. The reason to use this post-hoc test is that the POE may have extreme high or low values when the number of errors is small. The direct comparison of the left/right correctness is more stable. The test results based on the correctness of the two ears are listed in Table 4.2.

Table 4.2: The paired T-test results of the left and right ear correctness in the first DL

t-value and p-value	REAL SYLLABLE	PSEUDO-SYLLABLE
Consonant dichotic trial	t(30) = 0.908, p = 0.814	t(30) = -2.319, p < 0.014
Tone dichotic trial	t(30) = -0.380, p = 0.353	t(30) = -0.884, p = 0.192

A 3-way repeated measures ANOVA reveals a three-way interaction between the physical property, the linguistic role, and the ear advantage ($F(1,30) = 5.506$, $p < 0.026$). A two-way interaction between the linguistic role and the ear advantage is also found ($F(1,30) = 7.782$, $p < 0.009$), and there is a significant main effect of the physical property ($F(1,30) = 53.042$, $p < 0.001$). Post-hoc analysis of the consonant dichotic trials reveals a significant interaction between the linguistic role and the ear advantage ($F(1,30) = 8.943$, $p < 0.006$). This interaction may be caused by the similarity between the two real syllables in the consonant dichotic trials, so that the ear advantage of the real syllable consonant dichotic trials is not significant. This is also shown in the t-test of the ear advantage in Table 4.1 and 4.2. In the tone dichotic trials, there is a significant main effect of the linguistic role ($F(1,30) = 5.206$, $p < 0.030$).

The slightly higher percentage of correctness of the left ear than that of the right ear may be caused by the slightly better hearing ability of the left ears than that of the right ears of the testing subjects. Although the statistical test of the left and right ear hearing threshold differences does not reach a significant level ($p = 0.097$), there are 6 subjects having significant left ear advantage (the hearing threshold differences exceed 5dB between left and right ears) across the frequency in the PTA test. One subject has a significant right ear advantage, but his behavioral data are excluded in the ear advantage analysis, since the early responses before the indication are not recorded. For the other subjects, there are no significant differences between the hearing abilities of the left and right ears.

4.3.2 ERP data

The 129 channels in EGI system have correspondent electrodes in the 10-20 system according to the electrode coordinates (see Figure 4.3).

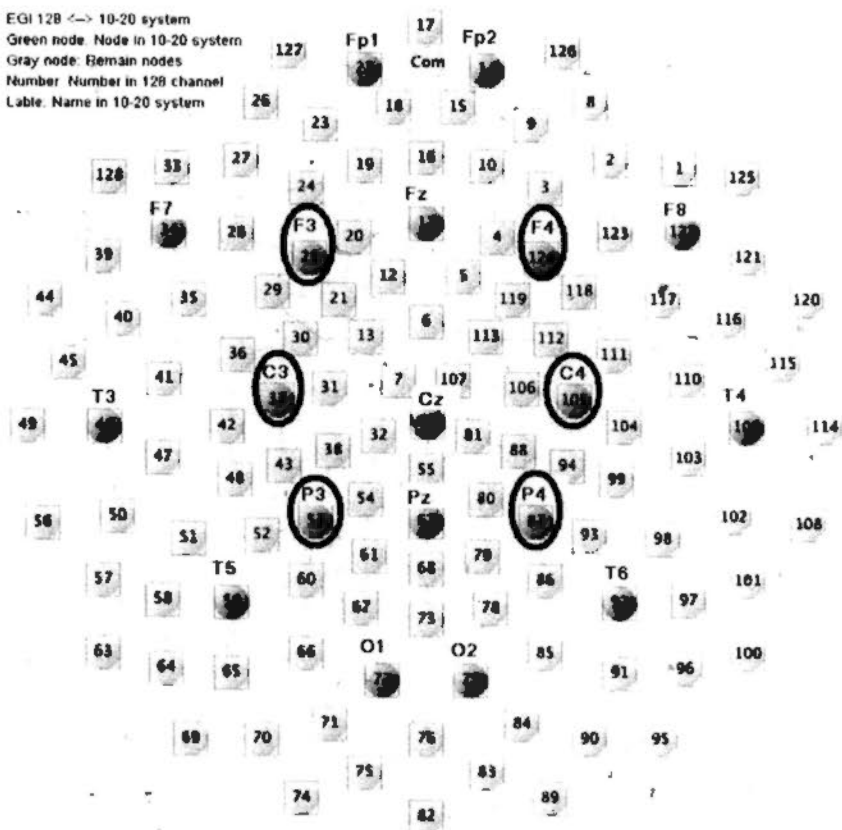


Figure 4.3: The 129-channel EGI electrodes coordination and the 10-20 system

In Figure 4.3, each node represents the location of one electrode. The locations of electrodes of the 10-20 system are marked above the correspondent nodes. ([33] The electrodes are distributed of 10% or 20% along the longitudinal and the latitudinal line on the head. F for frontal, C for central, T for temporal, P for parietal, O for occipital. Odd numbers refer to the left hemisphere, and even numbers refer to the right hemisphere.) The top of the figure is toward the nose. 'VREF' electrode in the center is set as the reference during the recording. Pairs of homologue electrodes representing frontal, central, and temporal regions are shown in Figure 4.3.

The waveforms of the C3 and C4 electrodes in each condition are shown in Figure 4.4.

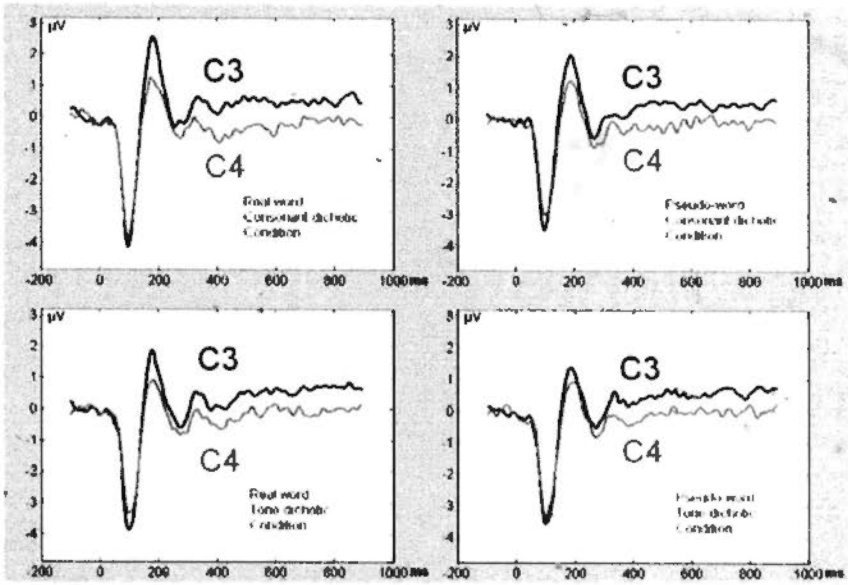


Figure 4.4: Waveforms of the C3 (left) and C4 (right) electrodes in each condition

In Figure 4.4, the waveforms averaged over all subjects between 100 ms before the stimulus onset and 900 ms after the onset are shown in each condition. 'C3' is the electrode in the left central region, and 'C4' is the one in the right homologous region.

In order to compare the results with previous ERP experiments on tone lateralization, I choose the P2 component. In Luo et al.'s work, they examine the MMN at around 200ms after the stimulus onset. The P2 component in their DL experiment has a peak value around 200ms. The average amplitudes between 152ms and 248ms in each condition in the C3 and C4 electrodes are shown in Figure 4.5.

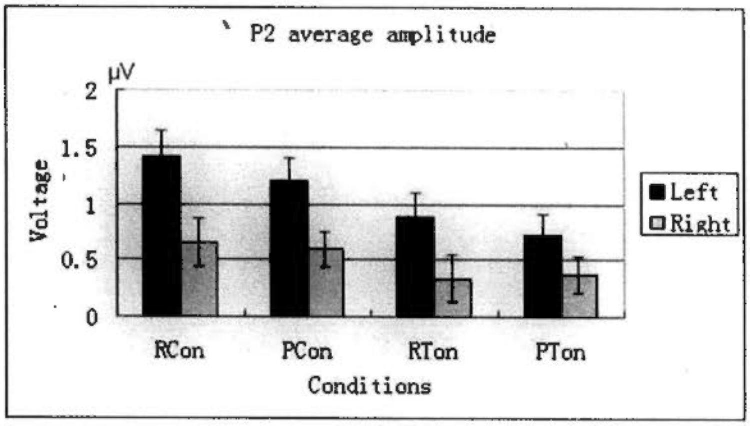


Figure 4.5: The average amplitudes in 152-248 ms at the C3 (left) and C4 (right) electrodes

In Figure 4.5, the averaged P2 amplitude is shown, which is calculated from the amplitude of each subject between 152-248 ms. Each error bar in Figure 4.5 represents one standard error.

The topological map at the averaged peak latency is shown in Figure 4.29 at the end of this Chapter. Since the distribution of the P2 component is central frontal, the C3 and C4 homologue electrodes are chosen to perform the statistical analysis. The *peak amplitude* instead of the average amplitude between 152ms and 248ms for each subject is used for the statistical analysis at first.

The 3-way repeated measures ANOVA is conducted. The lateralization, the physical property, and the linguistic role are the 3 factors in this analysis. There are 32 subjects' data in the analysis. Two significant two-way interactions are found: one is the interaction between the physical property and the lateralization ($F(1,31) = 7.199$, $p < 0.012$); the other is the interaction between the linguistic role and the lateralization ($F(1,31)$

= 10.219, $p < 0.003$). Another three main effects of the three factors are found as well (lateralization: ($F(1,31) = 13.549$, $p < 0.001$; the physical property: ($F(1,31) = 23.785$, $p < 0.001$; the linguistic role: ($F(1,31) = 5.228$, $p < 0.029$). These results indicate that both the linguistic role and the physical property interact with the lateralization in the same time period.

In order to compare with the later experiments, I also conduct the statistical test on the averaged amplitude between 152ms and 248ms. The result shows a significant interaction between the physical property and the lateralization ($F(1,31) = 5.554$, $p < 0.025$) and an interaction between the linguistic role and the lateralization at a marginal level ($F(1,31) = 3.468$, $p = 0.072$). The lateralization ($F(1,31) = 13.957$, $p < 0.001$) and the physical property ($F(1,31) = 22.708$, $p < 0.001$) have the main effects.

The latencies of the P2 peaks in each condition are shown in Figure 4.6. The three-way repeated measures ANOVA is conducted, and only a main effect of the linguistic role is found ($F(1,31) = 7.889$, $p < 0.009$).

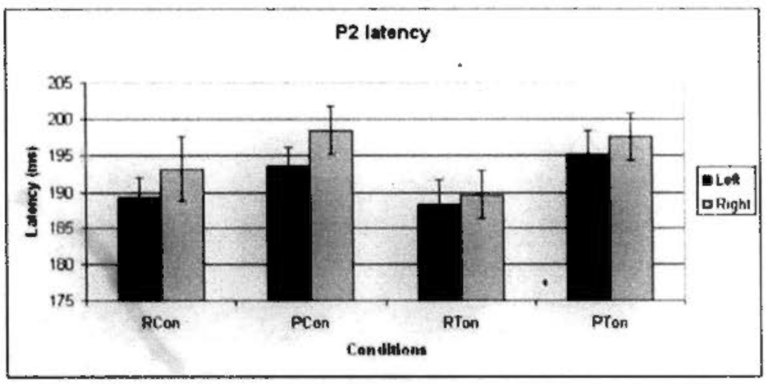


Figure 4.6: The P2 latencies in each condition at the C3 (left) and C4 (right) electrodes

In Figure 4.6, the average peak latency of P2 component is calculated from the ERP waveform of each subject between 152 and 248 ms. Each error bar represents one standard error.

The main finding of this DL experiment is that the P2 peak amplitude shows significant interactions both between the physical property and the lateralization, and between the linguistic role and the lateralization. The result indicates that both the physical property and the linguistic role of the stimuli affect lateralization. From the values of the amplitude, the consonant conditions have a greater extent of left lateralization compared with the tone conditions, while the real syllable conditions have greater extent of left lateralization than that of the pseudo-syllable conditions.

4.4 The second DL experiment

4.4.1 Behavioral data

Thirty-one subjects' data are collected for the analysis. The overall response rate is 98.3% (4.6), and the rate of correctness across all subjects is 74.3% (21.2). The individual response rate and the percentage of correctness are listed in Appendix (Table A.14 and A.15). In the consonant conditions, the rates of correctness of the left and right ears are 58.9% (23.8) and 74.7% (16.5) respectively; in the tone conditions, the rates of correctness of the left and the right ears are 78.8% (20.0) and 84.7% (14.4) respectively. The rates of correctness of the left and right ears in the four conditions are shown in Figure 4.7. Consistent with the first DL experiment, the correctness in the tone dichotic conditions is higher than that in the consonant dichotic conditions, and the right ear advantage is greater in the consonant conditions, which is shown in the following analyses.

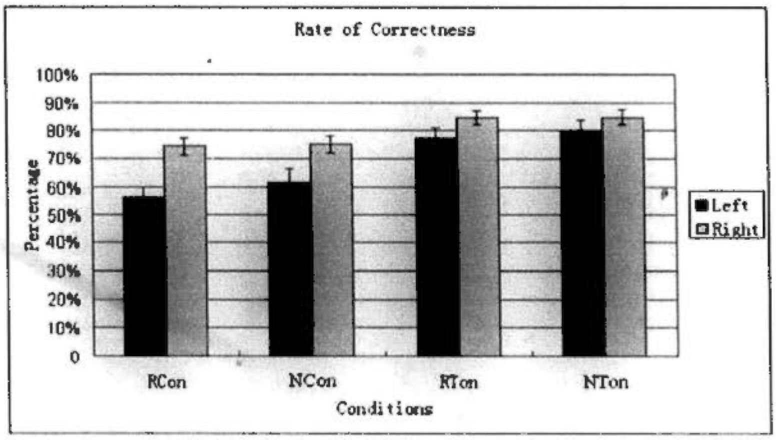


Figure 4.7: The rates of correctness in the four conditions in the second DL experiment. 'RCon': real syllable consonant DL condition; 'NCon': non-syllable consonant DL condition; 'RTon': real syllable tone DL condition; 'NTon': non-syllable tone DL condition.

In Figure 4.7, the rate of correctness of each ear in each condition is shown. 'RCon' means the real syllable consonant DL condition. 'NCon' means the non-syllable consonant DL condition. 'RTon' and 'NTon' represent the real syllable tone DL and the non-syllable tone DL conditions respectively. Each error bar represents one standard error.

The POE in the consonant condition is 62.3% (18.2), and that in the tone condition is 56.5% (22.5). The T-test result reveals significant differences in the percentage of correctness between the left and right ears in the real syllable consonant DL condition ($t(30) = -4.833$, $p < 0.001$), the non-syllable consonant DL condition ($t(30) = -3.341$, $p < 0.002$), and the real syllable tone DL condition ($t(30) = -3.010$, $p < 0.005$). There is no significant difference between the left and right correctness in the non-syllable tone DL condition.

A 3-way repeated measures ANOVA shows a significant interaction between the physical property and the ear advantage ($F(1,30) = 8.351$, $p < 0.007$). There is a marginal significance for the interaction between the linguistic role and the ear advantage ($F(1,30) = 3.063$, $p = 0.09$). In addition, there are three main effects for all three factors (the ear advantage: ($F(1,30) = 20.740$, $p < 0.001$); the physical property: ($F(1,30) = 43.111$, $p < 0.001$); the linguistic role: ($F(1,30) = 4.788$, $p < 0.037$)). The interaction between the physical property and the ear advantage is consistent with the ERP data shown in the following data analysis.

4.4.2 ERP data

Since there are fewer trials in each condition in the second DL experiment than in the first DL experiment, the ERP waveforms are not as smooth as those in the first DL experiment, both for the averaged data and individual data. Therefore, the data analysis is based on the time-averaged values between 152ms and 248ms. The averaged ERP waveforms at the F3 and F4 electrodes through all subjects in the three conditions are shown in Figure 4.8. The topographic maps of the time-averaged value between 152 and 248 ms in the three conditions are shown in Figure 4.30 at the end of this chapter.

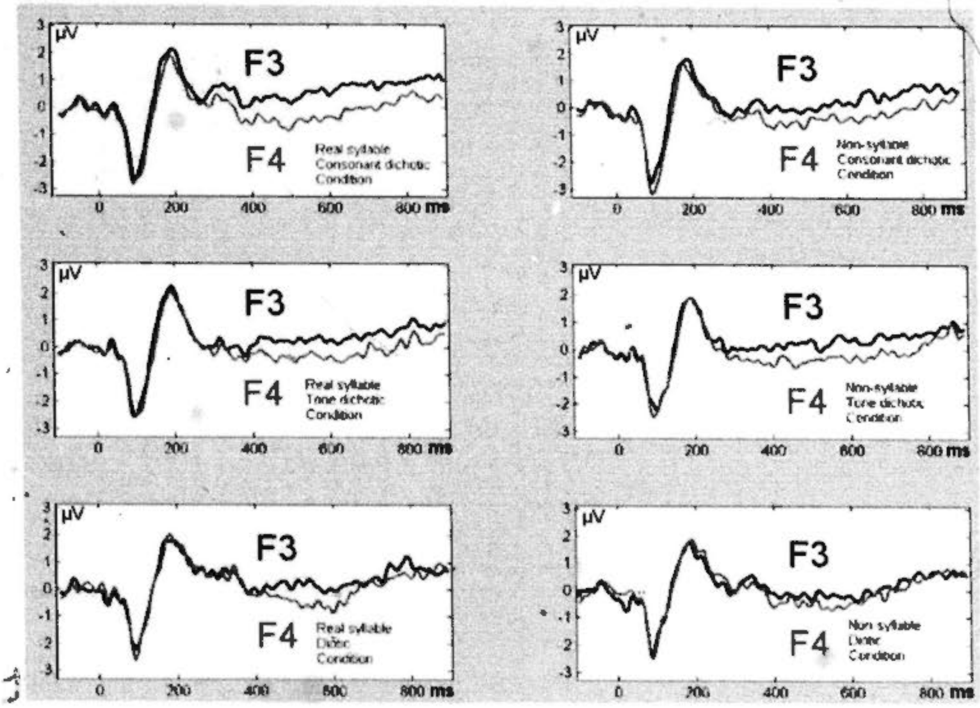


Figure 4.8: The averaged ERP waveforms at the F3 (left) and F4 (right) electrodes in the three conditions

In Figure 4.30, the waveforms averaged over all subjects between 100 ms before the stimulus onset and 900 ms after the onset, are shown in each condition. 'F3' is the electrode in the left frontal region, and 'F4' is the one in the right homologous region.

After the time averaging, the mean values of the amplitudes within the time window of 152-248ms at the F3 and F4 electrodes are shown in Figure 4.9. The reason to choose the frontal sites for the data analysis is that the frontal lobe is highly involved when both the dichotic and diotic stimuli are presented [32].

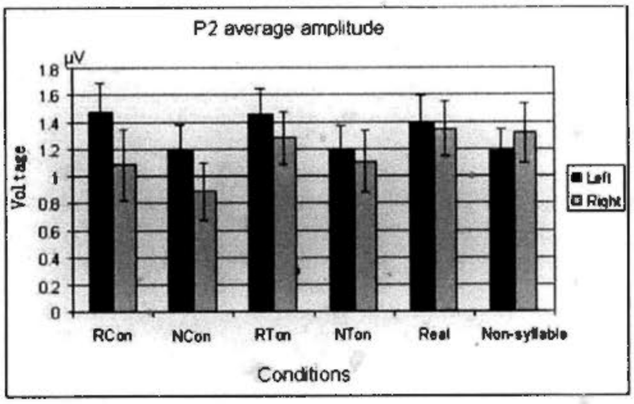


Figure 4.9: The time average values between 152 and 248ms at the F3 (left) and F4 (right) electrodes in all conditions. 'RCon': real syllable consonant DL condition; 'NCon': non-syllable consonant DL condition; 'RTon': real syllable tone DL condition; 'NTon': non-syllable tone DL condition; 'Real': real syllable diotic condition; 'Non-syllable': non-syllable diotic condition.

In Figure 4.9, the averaged P2 amplitude is shown, which is calculated from the time averaged amplitude of each subject between 152-248 ms. Error bar in Figure 4.9 represents one standard error. 'Real' means the real syllable diotic condition. 'Non-syllable' means the non-syllable diotic condition. The other notations have the same meaning as in Figure 4.8.

A 3-way repeated measures ANOVA is conducted to analyze the data. The linguistic role, the physical property, and the lateralization are the three factors. In the linguistic role, the real syllable and the non-syllable are the two levels. In the physical property, the levels of the consonant DL trials and the tone DL trials are compared with the diotic trials as a third level. The F3 and F4 electrodes in the left and right sites are the two factors in the lateralization.

The interaction between the physical property and the lateralization is found ($F(2,60) = 9.288$, $p = 0.001$), and the linguistic role has a main effect at a marginal level ($F(1,30) = 4.252$, $p < 0.048$). The post-hoc analysis based on merely the dichotic conditions has a similar result. The physical property interacts with the lateralization significantly ($F(1,30) = 4.933$, $p <$

0.034) and the linguistic role has a main effect ($F(1,30) = 4.316$, $p < 0.046$). The average amplitudes in the three conditions are shown in Figure 4.10.

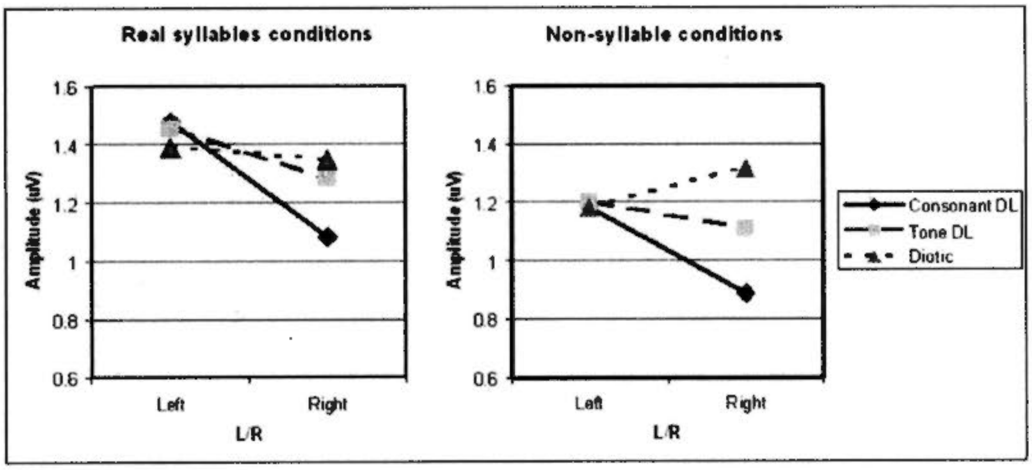


Figure 4.10: The average amplitudes in 152-248ms at the F3 (left) and F4 (right) electrodes

In Figure 4.10, the average amplitudes of the real syllable and non-syllable conditions are shown. The values equal to those in Figure 4.9.

The interaction between the linguistic role and the lateralization does not reach a significant level, perhaps because the diotic conditions are added or the materials in the dichotic trial are less similar than those in the first DL experiment. Subjects may pay more attention to the physical property differences during the second experiment compared to the first DL experiment. Although the statistical analysis does not reach a significant level, the average value in the real word conditions shows a greater degree of lateralization than that of the non-word conditions, as shown in Figure 4.11.

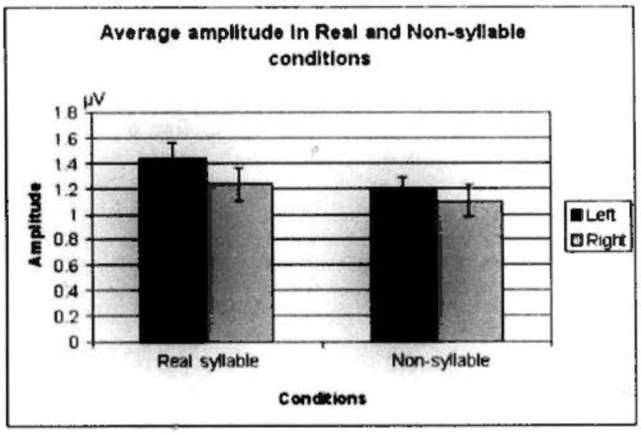


Figure 4.11: The average values in the real and non-syllable conditions at the F3 (left) and F4 (right) electrodes

In Figure 4.11, the average amplitudes of real syllables are calculated in the three real syllable conditions, and the average amplitudes of non-syllables are calculated in the three non-syllable conditions. Each error bar represents one standard error.

The main finding of the second DL experiment is that the physical property affects lateralization significantly, which is shown by the P2 averaged amplitude. This result is consistent with the ear advantages of the behavioral data. Although the interaction between the linguistic role and the lateralization is not significant in the ERP data, it reaches a marginal significance level in the behavioral data. It is interesting that in the behavioral data, the two consonant dichotic conditions and the real syllable tone dichotic condition show significant REAs, while there is no significant REA in the non-syllable tone dichotic condition. In the tone dichotic condition, it seems that without a strict control of the stimulus the REA increases a lot when the first and the second DL experiments are compared, although the correctness is comparable in these two experiments. But there is still no significant REA in the non-syllable tone dichotic condition, which indicates that the semantics causes the REA in tone perception other than the physical property.

4.5 The word priming experiment

4.5.1 Behavioral data

Thirty-one subjects' data are analyzed in this experiment. The overall response rate is very high, 99.9% (0.5), and the accuracy rate is also high, 96.0% (8.9). The response rate and the accuracy rate of each subject are listed in Appendix (Table A.16 and A.17). Only one subject gets some confusion about the real word conditions. The variance in the real word conditions is relatively higher than that in the pseudo-word conditions. The average accuracies in all conditions are shown in Figure 4.12.

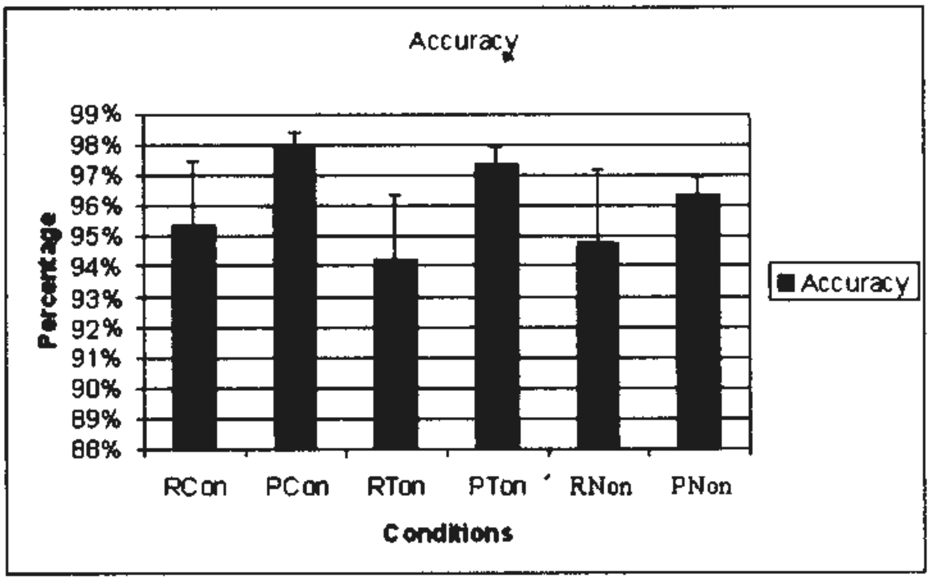


Figure 4.12: The average accuracies in all conditions. 'RCon': real word consonant priming condition; 'PCon': pseudo-word consonant priming condition; 'RTon': real word tone priming condition; 'PTon': pseudo-word tone priming condition ; 'RNon': real word non-priming condition; 'PNon': pseudo-word non-priming condition.

In Figure 4.12, the rate of correctness in each condition is shown. 'RCon' means the real word consonant priming condition. 'PCon' means the pseudo-word consonant priming condition. 'RTon' and 'PTon' represent the real word tone priming and the pseudo-word tone priming condition respectively.

'RNon' means the real word non-priming condition, and 'PNon' represents the pseudo-word non-priming condition. Each error bar represents one standard error.

A 3-way repeated measures ANOVA shows a significant main effect of the priming effect ($F(2,60) = 4.778$, $p < 0.013$), and the consonant priming conditions have significantly higher accuracy rate than the non-priming conditions ($F(1,30) = 9.137$, $p < 0.005$). The marginal means in the three conditions are shown in Figure 4.13.

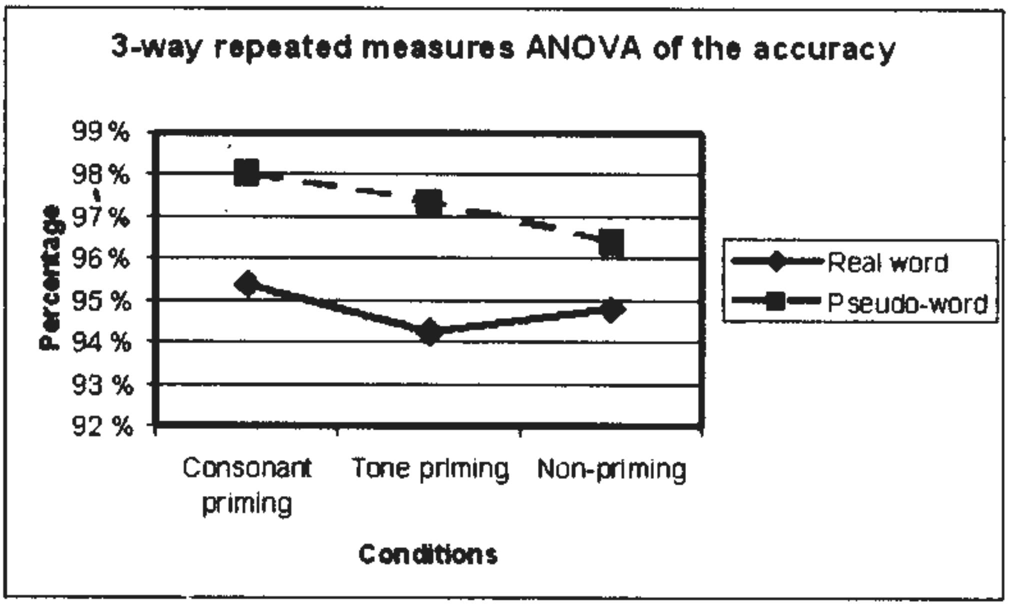


Figure 4.13: The average accuracies in all conditions

In Figure 4.13, the average values of the accuracy in the real word and pseudo-word conditions are shown. The values equal to those in Figure 4.12.

The averaged reaction time over all conditions is 962.72ms (159.99). The reaction times of each subject in all conditions are listed in Appendix (Table A.18). The reaction times in all the conditions are shown in Figure 4.14.

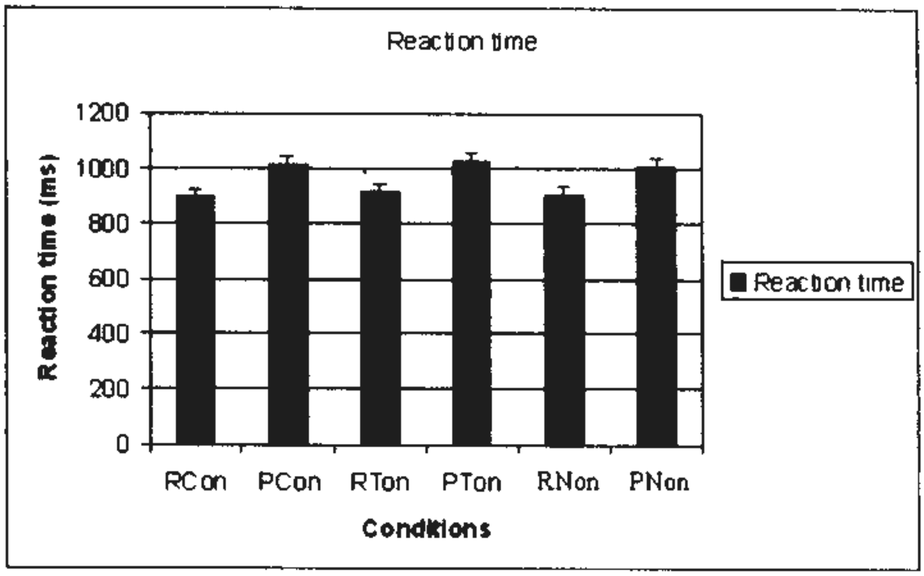


Figure 4.14: The reaction times in all conditions

In Figure 4.14, the average reaction time in each condition is shown. Each error bar represents one standard error.

A 3-way repeated measures ANOVA reveals a significant main effect of the real and pseudo word conditions ($F(1,30) = 78.350$, $p < 0.001$). The priming conditions have a main effect ($F(2,60) = 8.503$, $p = 0.001$), and there is a marginal level interaction effect between the real/pseudo-word conditions and the priming/non-priming conditions ($F(2, 60) = 2.899$, $p = 0.074$). The means of the reaction time in the three conditions are shown in Figure 4.15.

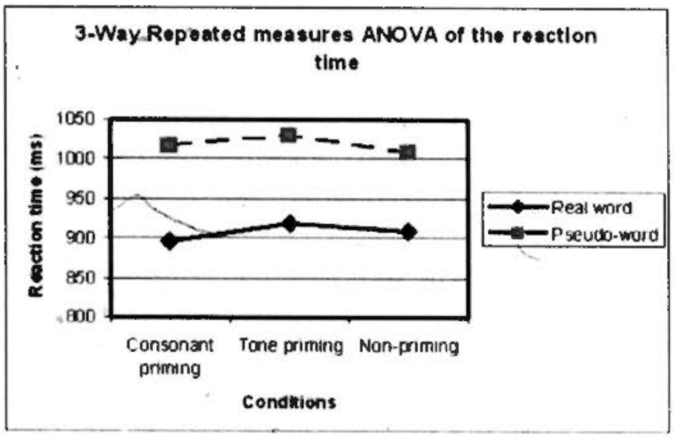


Figure 4.15: The means of the reaction time in all conditions

The average reaction times in the real word and pseudo-word conditions are also shown in Figure 4.15. The values equal to those in Figure 4.14.

Although the reaction times in the real word conditions are significantly shorter than those in the pseudo-word conditions, it does not mean that the accuracy rates are higher in the real word conditions. The statistical test indicates that the real and pseudo word conditions do not show significant differences in the accuracy rate, even without the data from the subject who has the lowest correctness rate in the real word conditions. The priming conditions increase the accuracy rate, especially in the consonant priming condition. However, the facilitation effect (reduction of the reaction time) only exists in the real word consonant priming condition at a marginal level ($t(30) = -1.993$, $p = 0.055$, two-tailed). The tone priming conditions always have an inhibition effect (increasing of the reaction time): the real word tone priming condition has an inhibition effect at a marginal level ($t(30) = 1.822$, $p = 0.078$), and the pseudo-word tone priming condition has a significant inhibition effect ($t(30) = 2.524$, $p = 0.017$). This inhibition effect of the tone priming conditions is consistent with the previous phonological priming experiments involving the Cantonese Character reading tasks [68]. The time differences between the priming and non-priming control conditions are shown in Figure 4.16. The real and pseudo-word priming conditions are contrasted with the real and pseudo-word non-priming conditions respectively, in calculation of the time difference of each subject.

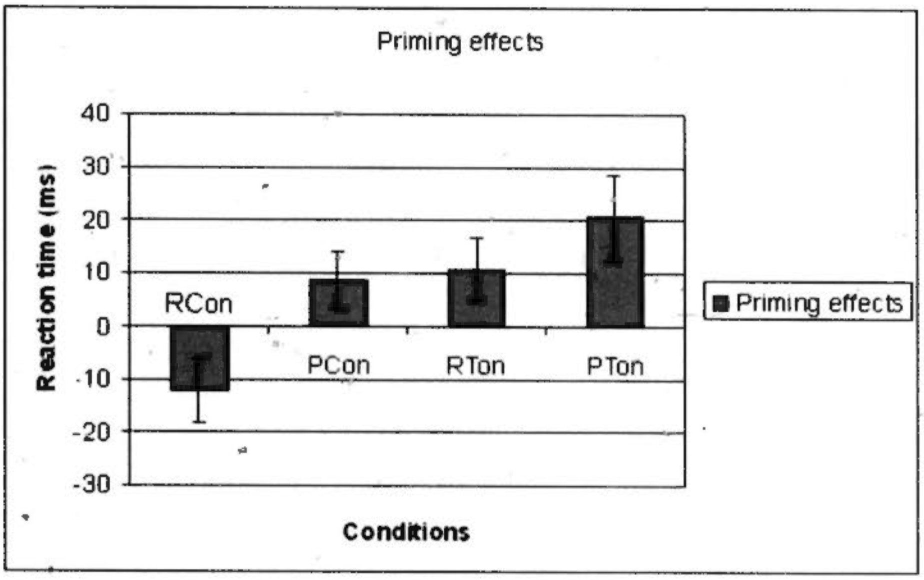


Figure 4.16: The time differences between the priming and non-priming conditions. 'RCon': the time difference between the real word consonant priming condition and the real word non-priming condition; 'PCon': the time difference between the pseudo-word consonant priming conditions and the pseudo word non-priming condition; 'RTon': the time difference between the real word tone priming condition and the real word non-priming condition; 'PTon': the time difference between the pseudo-word tone priming condition and the pseudo-word non-priming condition.

In Figure 4.16, the average time differences between the priming and non-priming conditions are shown. 'RCon' represents the time difference between the real word consonant priming condition and the real word non-priming condition. 'PCon' represents the time difference between the pseudo-word consonant priming conditions and the pseudo word non-priming condition. 'RTon' represents the time difference between the real word tone priming condition and the real word non-priming condition. 'PTon' represents the time difference between the pseudo-word tone priming condition and the pseudo-word non-priming condition. Each error bar represents one standard error. The facilitation or inhibition effects were illustrated in the previous paragraph.

4.5.2 ERP data

The ERP waveforms at the P3 and P4 electrodes in each condition are shown in Figure 4.17.

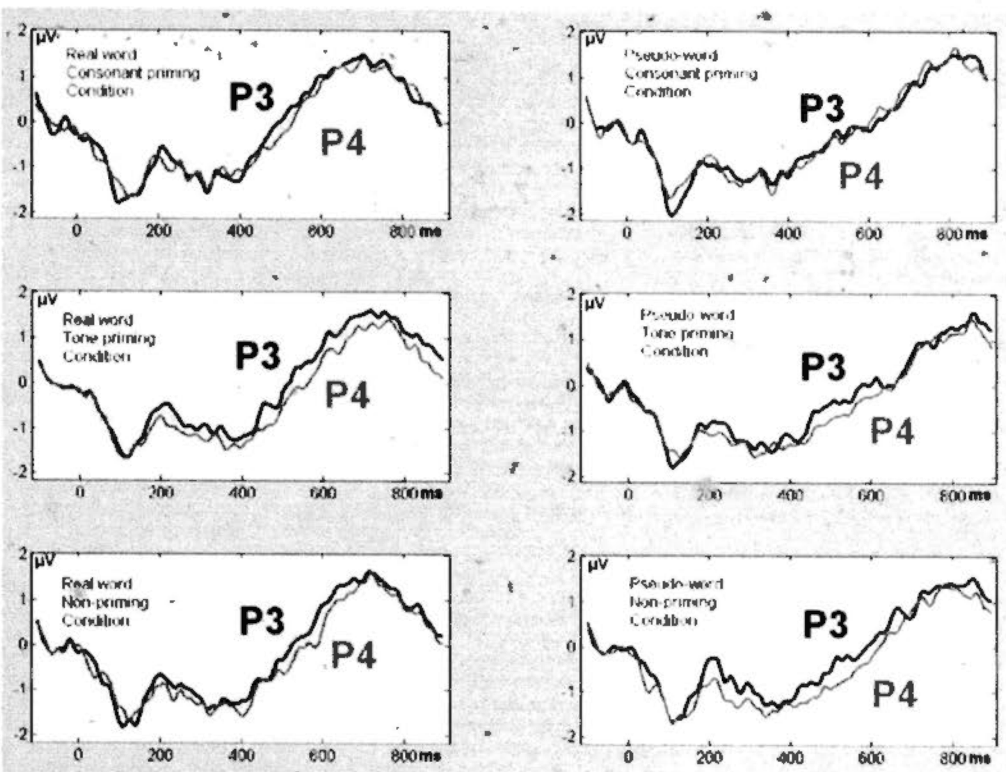


Figure 4.17: The ERP waveforms at the P3 and P4 electrodes in the three conditions

In Figure 4.17, the waveforms averaged over all subjects between 100 ms before the stimulus onset and 900 ms after the onset, are shown in each condition. 'P3' is the electrode in the left parietal region, and 'P4' is the one in the right homologous region. Based on the left/right differences in the waveforms, I will focus on the P2 component in analyzing the data in the later parts for this pair of electrodes.

The original ERP waveforms at the F3 and F4 electrodes are shown in Figure 4.18.

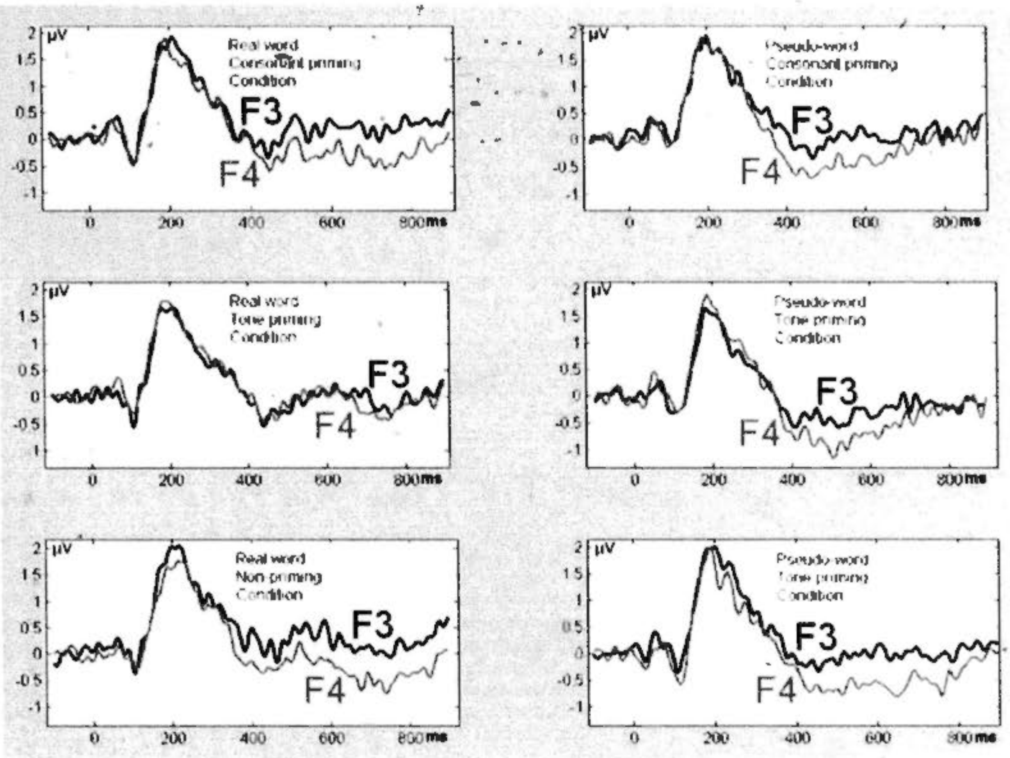


Figure 4.18: The average ERP waveforms at the F3 and F4 electrodes

The waveforms at the F3 and F4 electrodes are also shown in Figure 4.18. The waveforms are averaged over all subjects between 100 ms before the stimulus onset and 900 ms after the onset. 'F3' is the electrode in the left frontal region, and 'F4' is the one in the right homologous region. Based on the left/right differences in the waveforms, I will focus on the time window around 400 ms in analyzing the data in the later parts for this pair of electrodes.

The topographic maps between 152ms and 248ms and those between 400ms and 448ms in the three conditions are shown in Figure 4.31 and Figure 4.32 at the end of this chapter. The analysis on the effects of the physical property and the linguistic role is based on the two time windows. Since in previous neuroimaging studies, the auditory priming effects correlate with the haemodynamic changes in the superior temporal lobe and inferior frontal lobe [5], and the haemodynamic changes are caused by the neuronal changes in the same brain region [29], the data analysis is carried out at parietal and frontal electrode sites. The auditory pathway arrives at the superior temporal gyrus at first, so that in the early time window the P3 and P4 electrodes at the posterior region are analyzed. And in the late time window, the F3 and F4 electrodes at the frontal region are analyzed.

In the early time window between 152 and 248 ms, a 3-way repeated measures ANOVA reveals significant 2-way interactions between the physical property and the lateralization ($F(1,30) = 4.810$, $p = 0.036$) and between the linguistic role and the lateralization ($F(1,30) = 5.636$, $p < 0.024$) based on the waveform differences between the priming conditions and the non-priming control conditions. The average amplitudes reductions between 152 and 248ms at the P3 and P4 electrodes in the four conditions are shown in Figure 4.19.

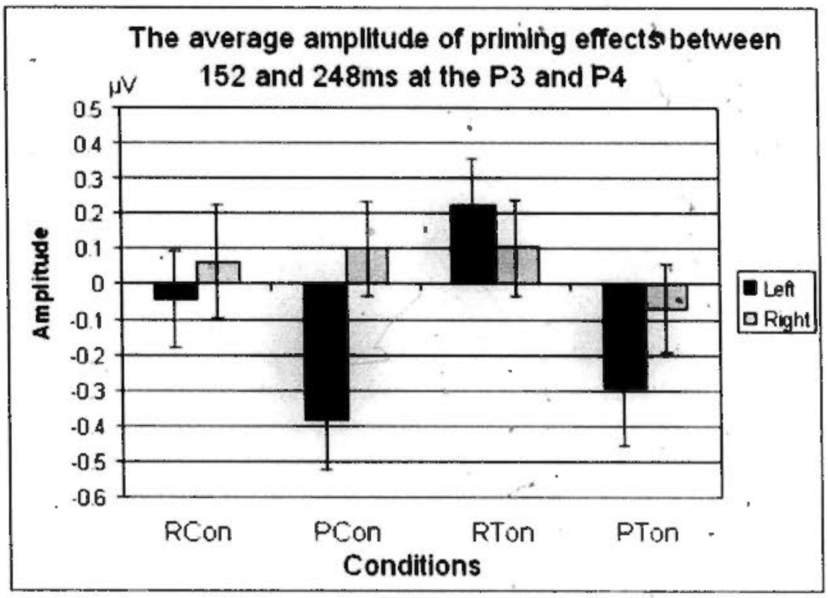


Figure 4.19: The average amplitudes of the priming effects between 152 and 248ms at the P3 (left) and P4 (right) electrodes in the four conditions. 'RCon': the differences between the real word consonant priming condition and the real word non-priming condition; 'PCon': the differences between the pseudo-word consonant priming condition and the pseudo-word non-priming condition; 'RTon': the differences between the real word tone priming condition and the real word non-priming condition; 'PTon': the differences between the pseudo-word tone priming condition and the pseudo-word non-priming condition.

In Figure 4.19, the average values of the differences between the priming conditions and the non-priming conditions between 152 and 248 ms are shown. 'RCon' means the differences between the real word consonant priming condition and the real word non-priming condition. 'PCon' means the differences between the pseudo-word consonant priming condition and the pseudo-word non-priming condition. 'RTon' means the differences between the real word tone priming condition and the real word non-priming condition. 'PTon' means the differences between the pseudo-word tone priming condition and the pseudo-word non-priming condition. Each error bar represents one standard error.

This result indicates that the consonant and the tone primes affect the lateralization significantly. From the mean amplitude differences shown in Figure 4.20, we can see that in both real word and pseudo-word conditions, there is a greater negativity in the left electrode than in the right electrode in the consonant priming conditions. This result reflects a greater left lateralization of the consonant processing than the tone processing.

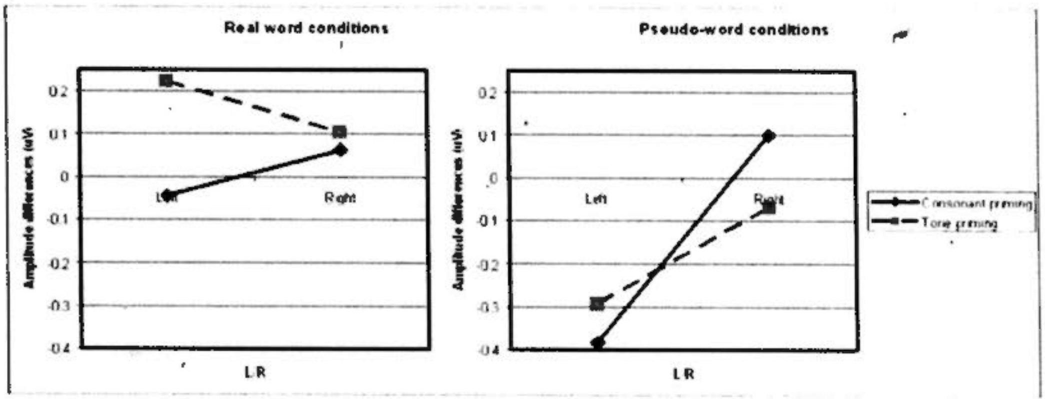


Figure 4.20: The average values of the amplitude differences between the priming and non-priming control conditions between 152-248ms at the P3 and P4 electrodes

In Figure 4.20, the average values of the amplitude differences between the priming and non-priming conditions are shown. The values equal those in Figure 4.19. There are both significant interactions between the real/pseudo word conditions and the lateralization, and between the consonant/tone conditions and the lateralization.

In the real word conditions, however, the amplitudes of the left hemisphere are lifted, compared with those in the pseudo-word conditions (Paired T-tests are conducted. In the left hemisphere, $t(30) = 1.836$, $p = 0.076$ for the real and pseudo-word consonant priming conditions, and $t(30) = 2.174$, $p < 0.038$ for the real and pseudo-word tone priming conditions. In the right hemisphere, there are no significant differences of the amplitude between the real and pseudo-word conditions in both the consonant and tone priming conditions). This effect appears immediately after the presentation of the second syllable in the target disyllabic word. According to the analysis of the sound materials, the earliest appearance of the second syllable is at 191ms after the onset of the first syllable. The mean starting time of the second syllable is at 284.64ms (40.28). The starting time does not differ significantly between the real (mean: 283.32ms (38.27), minimum: 191ms) and pseudo-word (mean: 285.96ms (42.27), minimum: 196ms) conditions. The consistency of the second syllable in the situations where the first syllable is a whole word or not affects the lateralization of the priming effects significantly. The higher amplitude in the real word conditions than in the pseudo-word conditions only existing in the left electrodes indicates a left lateralization of the semantic processing. It is surprising that this effect appears at such an early time window. According to Friederici ([18]), the effect of the semantic integration should appear around 300-500 ms after the stimulus onset. It seems the top-down linguistic effects run parallel to the early stage acoustic processing.

An analysis is also carried out at a later time window between the 400 and 448ms after the onset of the first syllable based on the F3 and F4 electrodes. This time window is about 120ms to 170ms, later than the average starting time of the second syllable. The result shows that there is also a significant interaction between the linguistic role and the lateralization ($F(1,30) = 10.440$, $p=0.003$). This analysis is based on merely the four priming conditions without subtraction to the control conditions. If the non-priming control conditions are subtracted, there is still a significant interaction between the linguistic role and the lateralization ($F(1,30) = 4.389$, $p < 0.045$). There is a marginal level interaction between the physical property and the lateralization ($F(1,30) = 3.468$, $p = 0.072$). This interaction is the same with and without subtracting the control conditions.

It reflects the existence of the priming effect even in a late time window after 400ms after the stimulus onset. The mean amplitude differences at this late time window with subtraction of the control conditions are shown in Figure 4.21. A relative greater negativity of the tone priming conditions than consonant priming conditions reflects a stronger priming effect for tones in the late time window. This could be caused by the longer duration of the tones, compared with that of consonants.

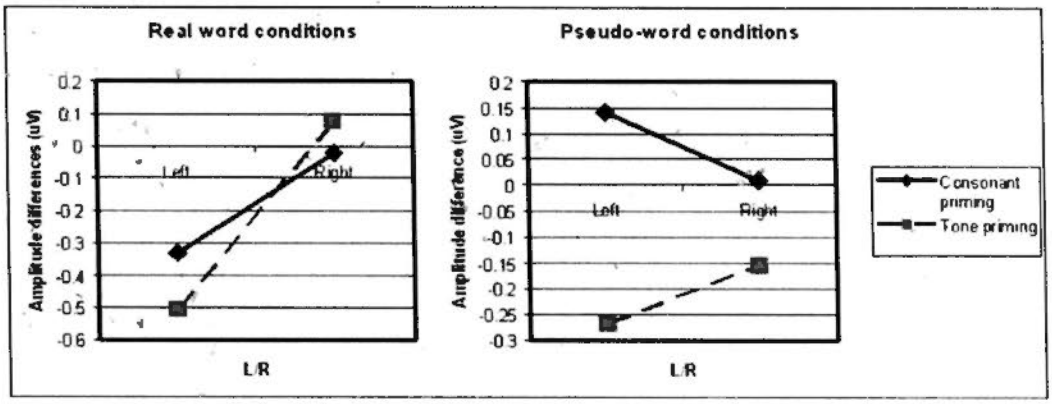


Figure 4.21: The mean of the amplitude differences between the priming conditions and non-priming control conditions between 400-448ms at the F3 and F4 electrodes

In Figure 4.21, the average values of the amplitude differences between the priming conditions and non-priming conditions are shown. The interaction between the lateralization and the consonant/tone conditions is not obvious, especially in the real word conditions. The interaction between the real/pseudo-words and the lateralization is still apparent.

The major finding of this experiment is that in the time window of P2 component, both the linguistic role and the physical property affect the lateralization significantly, which is shown by examining the priming effects of the amplitude in the ERP waveforms.

4.6 Sentence semantic violation

4.6.1 Behavioral data

The overall response rate is 99.98% (0.18) and the rate of accuracy is 94.3% (3.2). The average response time is 854.13 ms (186.61). The individual response rate, accuracy rate, and response time in each condition are listed in Appendix (Table A.19, and A.20). The average rates of accuracy and reaction time in the three conditions are shown in Figure 4.22 and Figure 4.23.

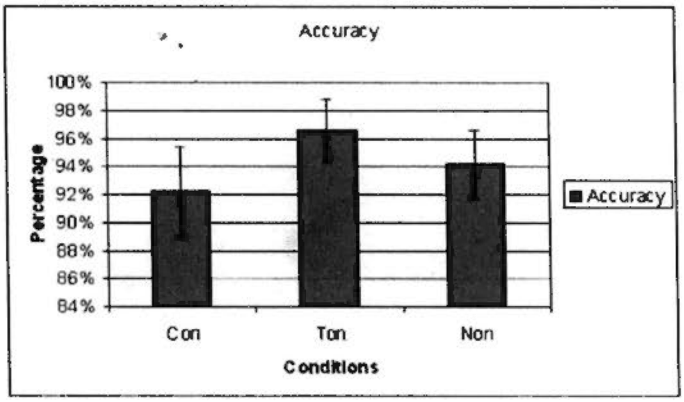


Figure 4.22: The average rates of accuracy in the three conditions in the sentence semantic violation experiment. 'Con': the consonant violation condition; 'Ton': the tone violation condition; 'Non': the non-violation condition.

In Figure 4.22, each error bar represents one standard error. 'Con' means the consonant violation condition. 'Ton' means the tone violation condition. 'Non' means the non-violation condition.

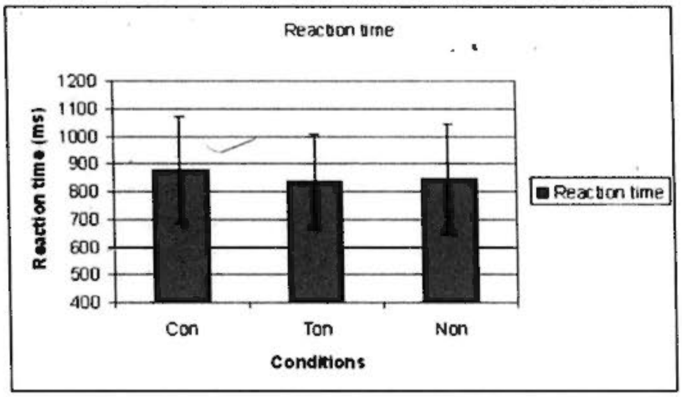


Figure 4.23: The average reaction times in the three conditions in the sentence semantic violation experiment. 'Con': the consonant violation condition; 'Ton': the tone violation condition; 'Non': the non-violation condition.

In Figure 4.23, each error bar represents one standard error. 'Con' means the consonant violation condition. 'Ton' means the tone violation condition. 'Non' means the non-violation condition.

The accuracy rates in the three conditions differ among each other. The 1-way repeated measures ANOVA on the reaction time shows a significant main effect of the different conditions (F(2,56) = 22.923, p < 0.001). The contrast between the consonant violation and non-violation control conditions (F(1,28) = 7.787, p < 0.009) indicates that these two conditions are significantly different. The contrast between the tone violation and non-violation conditions is also significant (F(1,28) = 16.834, p < 0.001). A post-hoc paired T-test reveals a significant difference in the accuracy rate between the consonant violation and tone violation conditions (t(28) = -6.705, p < 0.001). From the results of the mean accuracy (see Figure 4.24) and the statistical testing, the consonant condition has the lowest accuracy, while the tone violation condition has the highest accuracy, even greater than that of the non-violation condition.

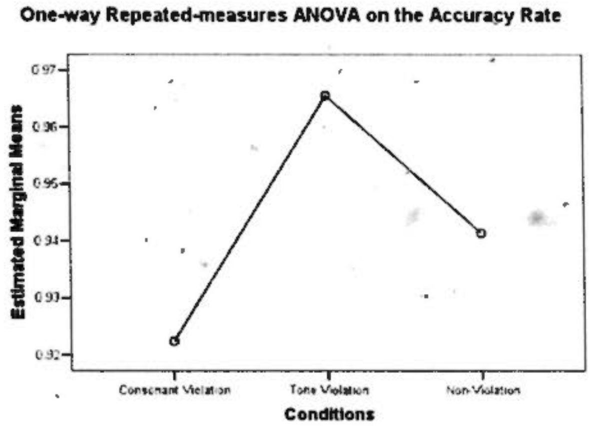


Figure 4.24: The mean accuracies in the three conditions

In Figure 4.24, the mean values of the accuracy of the three conditions are shown. The values equal to those in Figure 4.22.

The accuracy differences shown above are also reflected in the reaction time. The consonant violation condition has the longest reaction time, while the tone violation condition has the shortest (see Figure 4.25). The 1-way repeated measures ANOVA on the reaction time shows a significant main effect of the different conditions ($F(2,56) = 7.155$, $p < 0.002$). The contrast between the consonant violation and non-violation control conditions is significant ($F(1,28) = 7.290$, $p < 0.012$). There is no significant difference between the tone violation and non-violation conditions. A post-hoc paired T-test shows a significant difference between the consonant and tone violation conditions ($t(28) = 4.040$, $p < 0.001$).

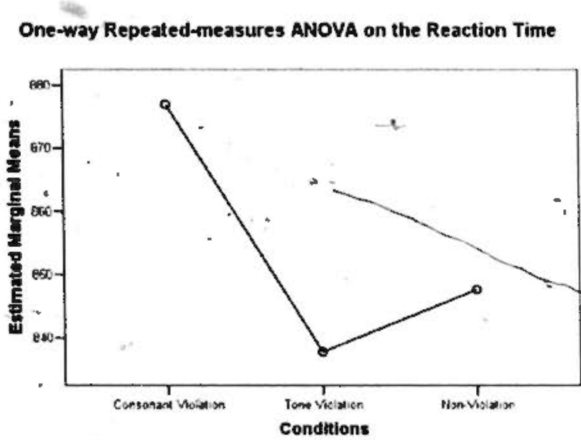


Figure 4.25: The mean reaction times in the three conditions

In Figure 4.25, the mean values of the reaction time of the three conditions are shown. The values equal to those in Figure 4.23.

It seems that the tone violation condition is the easiest to judge with the shortest reaction time and highest accuracy, while the consonant violation condition is the opposite. It is consistent with my previous experiments of word priming in which the consonant and tone processing are different.

4.6.2 ERP data

The averaged ERP waveforms of the F3/F4, C3/C4, and P3/P4 electrodes in the three conditions are shown in Figure 4.26.

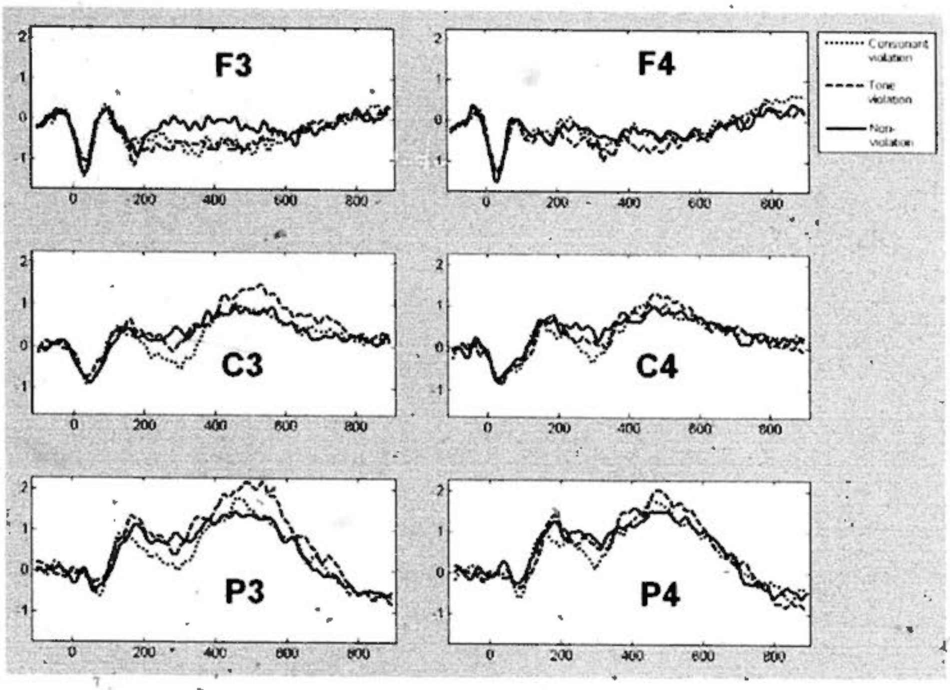


Figure 4.26: The averaged ERP wavefoms of the three conditions in three pairs of electrodes

In Figure 4.26, the waveforms averaged over all subjects between 100 ms before the stimulus onset and 900 ms after the onset, are shown in each condition. 'F3' is the electrode in the left frontal region, and 'F4' is the one in the right homologous region. 'C3' is the electrode in the left cental region, and 'C4' is the one in the right homologous region. 'P3' is the electrode in the left parietal region, and 'P4' is the one in the right homologous region. Comparing the violation conditions and the non-violation condition, the differences are shown in time windows around 300 ms to 500 ms after the stimulus onset.

Since it is a semantic violation task, the N400 component contrasting the semantic violation and non-violation conditions is the target component to be analyzed. It has been mentioned that the inferior frontal cortex has haemodynamic changes in the semantic violation tasks and it should be the source of the N400 ERP component [23]. The frontal electrodes F3 and F4 are chosen to be analyzed at first. In the consonant conditions, the

N400 component is significantly left lateralized ($t(28) = -2.2$, $p = 0.036$) in the frontal sites. There is no significant lateralization for the tone violation N400 component. A 2-way repeated measures ANOVA based on the average amplitude between 400ms and 448ms at the F3 and F4 electrodes is also conducted. There is a significant interaction between the physical property and the lateralization. ($F(1,30) = 4.343$, $p < 0.046$). It reflects that the physical property affects the lateralization of the N400 component significantly. The average amplitude differences between the violation and non-violation conditions at the F3 and F4 electrodes between 400ms and 448ms are shown in Figure 4.27.

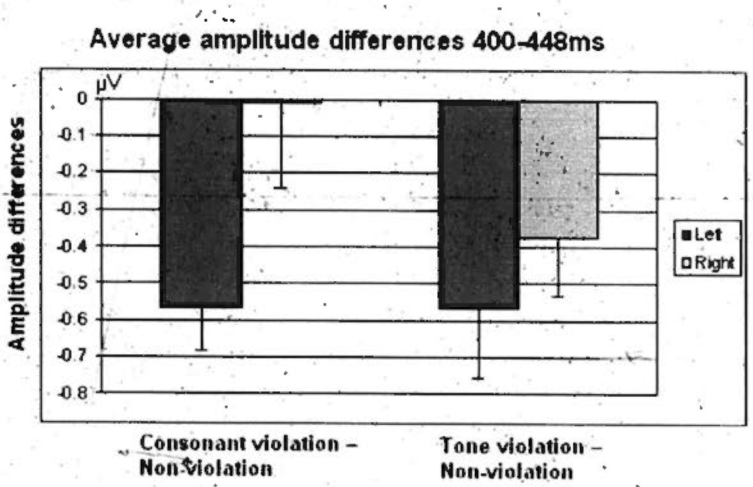


Figure 4.27: The amplitudes of the N400 component in the consonant and tone violation conditions at the F3 (left) and F4 (right) electrodes

In Figure 4.27, each error bar represents one standard error. The differences between the left and right homologue regions show a great difference between the two violation conditions, which indicates that the lateralization of semantic processing in the late time window is also affected by the physical property factor.

At the central-parietal electrodes, there are clear negativities around 300 ms after the stimulus onset. Since in this time range, the amplitude differences between the violation and non-violation conditions match the topographical distribution of previously described N400 component [39], the post-hoc statistical analysis is also conducted at the C3 and C4 electrodes between 252ms and 348ms (Figure 4.33 at the end of this Chapter). In Schirmer et al.'s exploration [50] of Cantonese tone processing using the semantic violation tasks and ERP methods, they also do the analysis in the time window between 200 ms and 450 ms after the stimulus onset.

The upper row in Figure 4.33 shows the topographic maps of the three conditions and the bottom row shows the contrasts of different conditions. The contrast between the consonant violation and non-violation conditions has a central-parietal distribution, while the tone violation versus non-violation conditions is more frontal distributed with a clear right lateralization of the negativity. A direct comparison of the consonant and tone violation conditions shows a left lateralization at the central parietal sites.

A 3-way repeated measures ANOVA reveals a significant interaction between the physical property and the lateralization ($F(1,30) = 5.990$, $p < 0.021$). This result matches the analysis done in the 400ms-448ms time window. (see Figure 4.28).

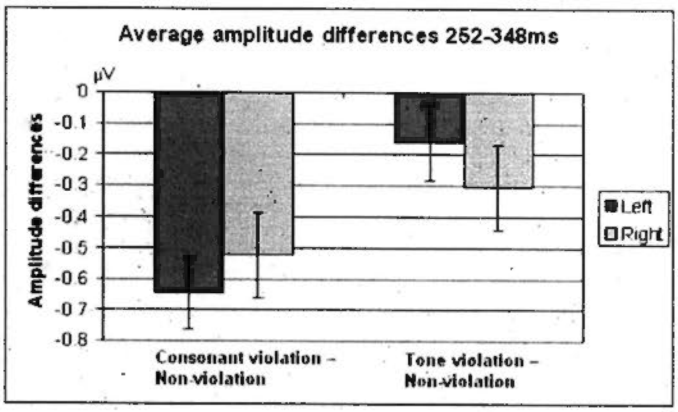


Figure 4.28: The average amplitudes between the semantic violation and non-violation condition at the C3 (left) and C4 (right) electrodes between 252ms and 348ms

In Figure 4.28, each error bar represents one standard error. The opposite lateralization patterns for the consonant and tone violation conditions shows clearly.

In both the 300ms and 400ms time windows, the N400 component is more left lateralized in the consonant violation condition than in the tone violation condition. In the 300ms time window, the average amplitude of the negativity is even right lateralized. In both cases, the physical property interacts with lateralization significantly, even in the late N400 component of the semantic violation task. By themselves, the ERP waveform differences between the semantic violation and non-violation control conditions reflect the semantic processing. My experimental results show that this effect is significantly left lateralized when the semantic violation is introduced by the consonant abnormality, while there is no significant left lateralization in the tone violation condition.

4.7 Summary

In the four ERP experiments, the factors underlying tone lateralization are analyzed. Both the physical property and the linguistic role affect tone lateralization. In the DL experiment, these effects take place in the same time window at around 200ms after the stimulus onset in the ERP data. From the behavioral data, a general trend is that the consonant DL conditions have a greater REA than that of the tone DL conditions. The real syllable consonant DL condition in the first DL experiment has two syllables too similar to each other, which diminishes the REA in the behavioral data. However, the LHA (left hemisphere advantage) which is correspondent to the REA in the behavioral data is obvious in the ERP results. In the ERP data, a clear result of the interactions between the linguistic factor and the lateralization, and between the physical property factor and the lateralization exist in the first DL experiment. The physical property factor also interacts significantly with lateralization in the second DL experiment, however the linguistic factor does not interact significantly with lateralization probably because of the increasing of the number of conditions or the acoustical similarity of the non-syllable material to other real syllables in Mandarin or Cantonese (Mandarin subjects may become familiar with the Cantonese phoneme /œ/ after coming to Hong Kong). In general, the results support that the tone processing is more right lateralized (or less left lateralized) than that of the consonant processing, and the semantic processing is left lateralized when comparing words with meaning and without meaning.

In the word phonological priming experiment, both factors interact with the lateralization of the ERP waveforms in the priming effects at the early time window. This result is consistent with the DL experiment. Other than the interactions between the two factors and the lateralization, the pseudo-word conditions have greater negativity in the ERP amplitude, which may have similar underlying mechanisms as in the sentence semantic violation experiment. This negativity is more significant in the left hemisphere, which indicates that the left hemisphere has an advantage in semantic processing. And the ERP reduction (negativity increasing) of the left hemisphere is greater than that of the right hemisphere, which supports that the tone is more right lateralized (less left lateralized) than the consonant in perception.

In the sentence semantic violation experiment, the physical property interacts with the lateralization in late time windows around 300ms to 400ms after the stimulus onset. Although the linguistic factor is combined with the physical property factor, in the sense of semantic violation, the phoneme violation of tones or consonants should not differ from each other significantly, especially in the late time windows. However, my experimental results indicate that the physical property affect lateralization in the late time window, during the semantic violation task.

Combining the above results, both the linguistic factor and the physical property affect lateralization. Tone is toward bilaterally processed because its slow varying physical property, while the semantics when tone is used to distinguish lexical meaning makes it more left lateralized when compared with tonemes (or tone patterns) that has no meaning. These processes are parallel existing both in the early and late time windows.

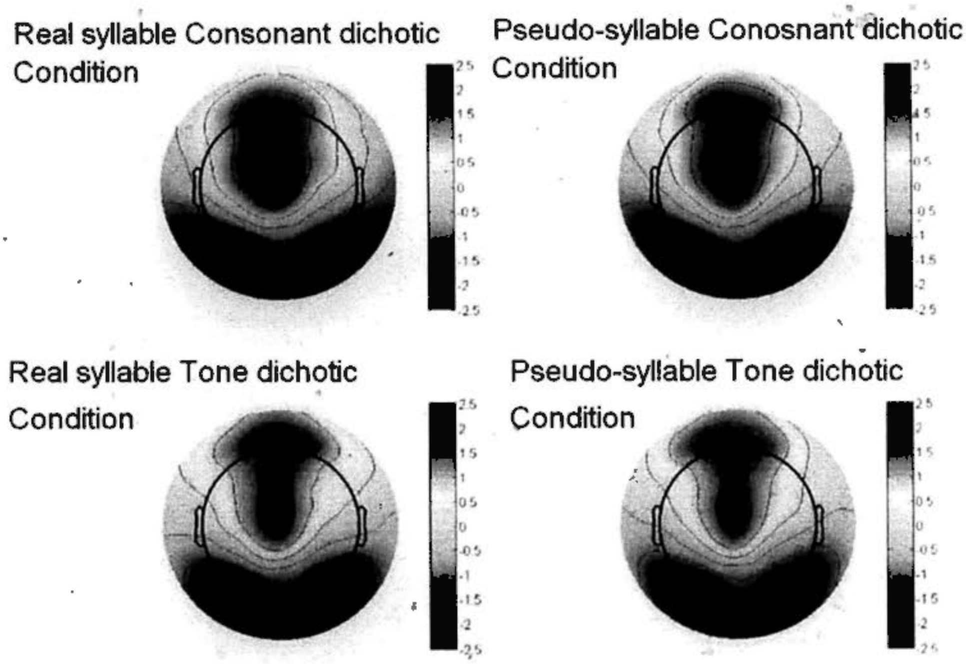


Figure 4.29: The topographic map of the average amplitude in 152-248ms in each condition, in the first DL experiment.

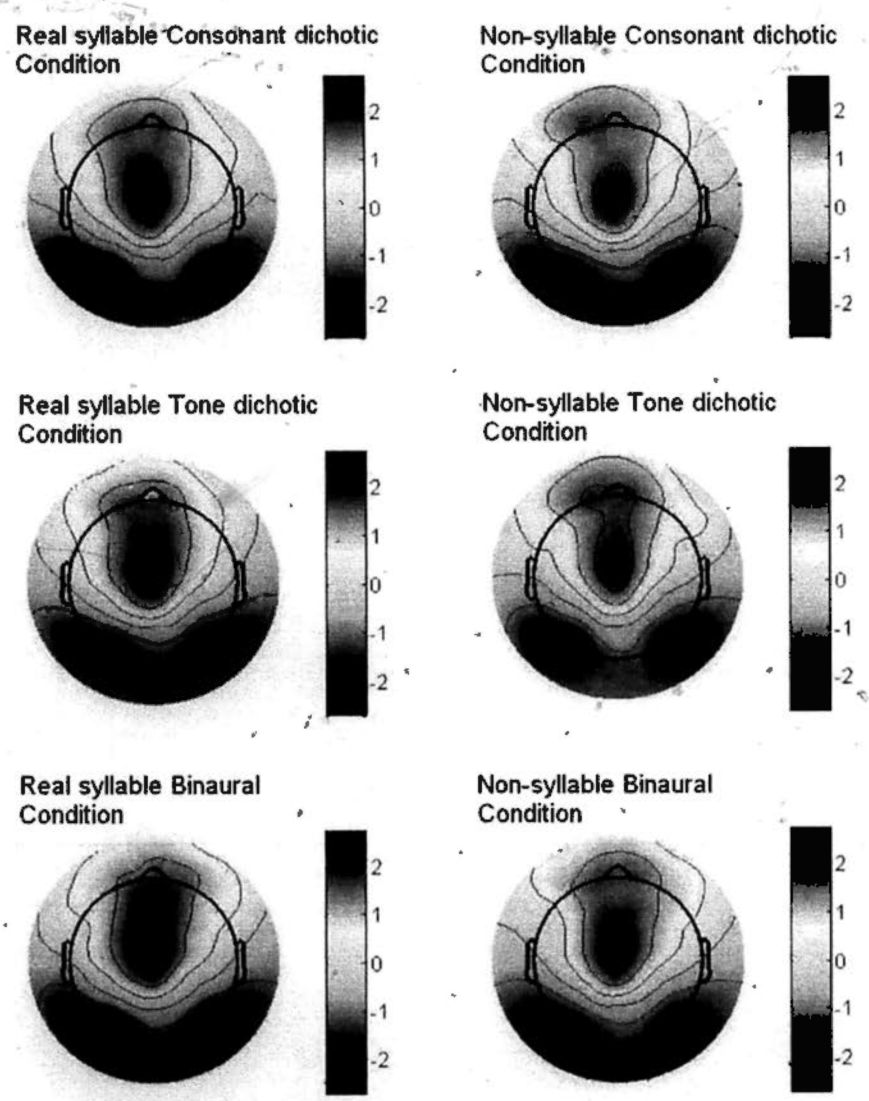


Figure 4.30: The topographic maps of the average amplitude in 152-248ms in each condition, in the second DL experiment.

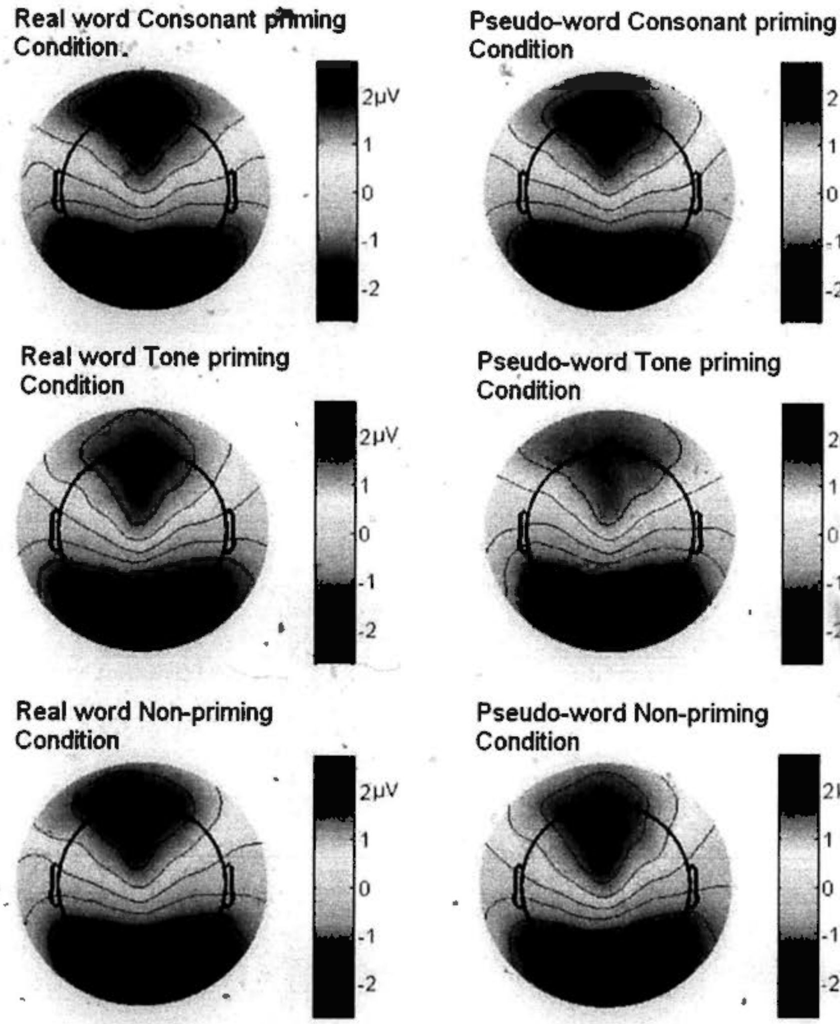


Figure 4.31: The topographic maps of the averaged amplitude in 152-248ms in each condition, in the word priming experiment.

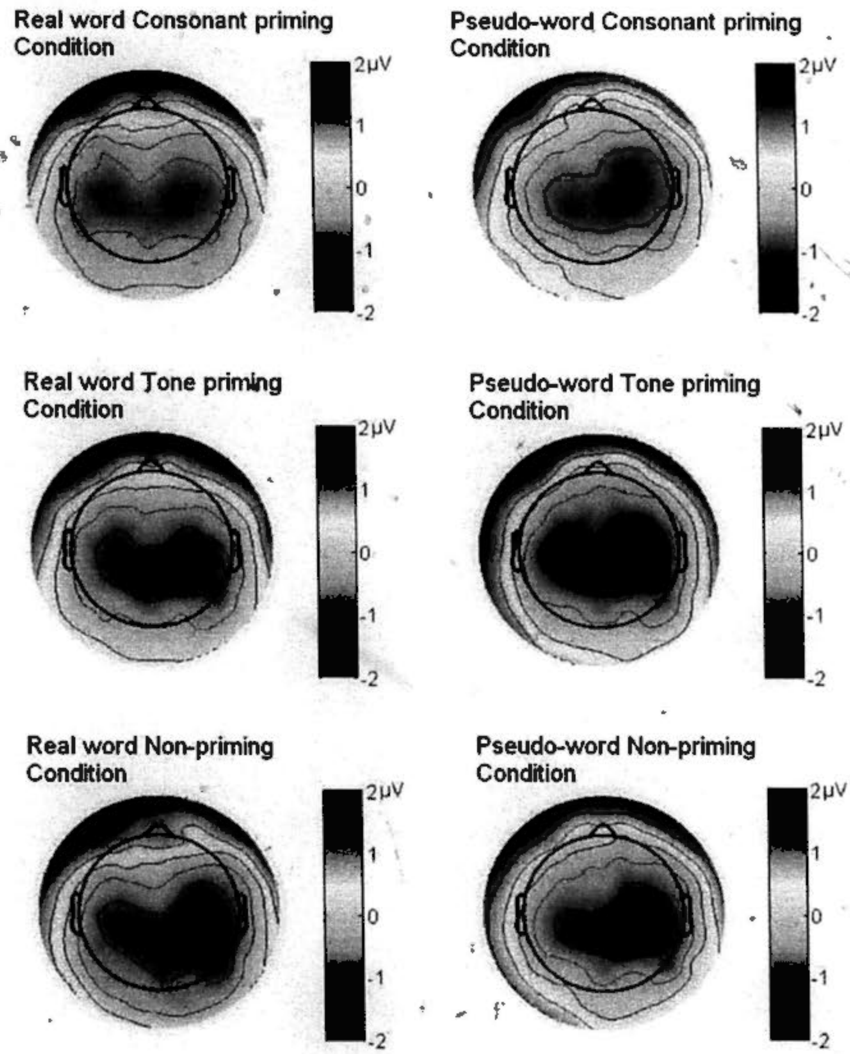


Figure 4.32: The topographic maps of the averaged amplitude in 400-448ms in each condition, in the word priming experiment.

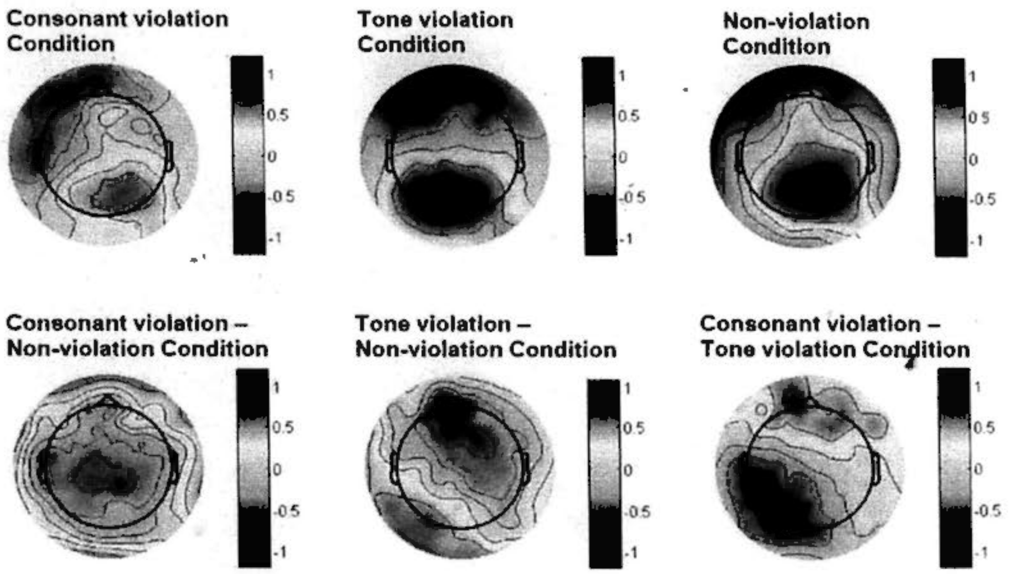


Figure 4.33: The topographic maps of the average amplitudes in 252-348ms in each condition and the amplitude differences between different conditions, in the sentence semantic violation experiment.

□ **End of chapter.**

Chapter 5

Tone lateralization under noisy conditions

Summary

This chapter discusses the DL experiment on the perception of Mandarin tones under clean and noisy conditions, and examines the enhancing role of noise on the lateralization patterns of tones. It is shown that the lateralization patterns of different tones are inconsistent: the perception of tone 1 exhibits a left ear advantage, while that of tone 2 or tone 4 has a right ear advantage. These different patterns are ascribed to different tone features and the fast or slow change of the tone pitch. A gender difference in tone perception is also detected from the results.

5.1 Motivation

The behavioral DL experiment on tone lateralization was first conducted by Van Lancker and Fromkin on Thai tones [57]. In their experiment, the ear advantages of Thai tones in both Thai and English speakers are compared and a right ear advantage for

Thai tones in Thai speakers has been discovered. This is supportive evidence for the "function" view of tone lateralization. However, the empirical results of later behavioral DL experiments do not show a consistent right ear advantage for tones. For example, Baudoin-Chial has failed to find any ear advantage on Mandarin tones [3]. Wang et al.'s DL experiment has revealed a right ear advantage for Mandarin tones in Mandarin speakers, but no ear advantage in English speakers [63]. Although, a right ear advantage in tone language native speakers and no ear advantage in non-tonal language speakers have been found in both Van Lancker and Fromkin's [57] and Wang et al.'s experiments [63], the experimental conditions in these DL experiments are different between native and non-native speakers. In the former experiment, two consecutive dichotic trials are used for native Thai speakers in half of their trials; while for non-native speakers, only isolated dichotic trials are used. In the latter experiment, the white noise with -10dB S/N ratio is introduced for native Mandarin speakers, but non-native speakers only hear clean speech. Without a systematic study of the tone lateralization patterns under noisy conditions, directly introducing noise may affect the lateralization results, since the noise may act as a confounding variable. In addition, both experiments have not reported the hearing ability differences in left and right ears of subjects.

Considering these, I propose a DL experiment on tone lateralization under clean and noisy conditions. It begins with a test of the hearing ability of subjects in left and right ears. In addition, instead of simply inducing errors as in Wang et al.'s experiment, I find that the noisy condition actually enhances the REA slightly from the clean condition to -10dB S/N ratio, though the effect is different for different tones. Moreover, the experimental results show that subjects exhibit different lateralization patterns toward different tones, and two factors can be used to explain these various lateralization patterns. Finally, the individual and gender differences among subjects are discussed, which is one of the significant factors to study the variety in human behaviors [16] and is usually neglected in some previous studies.

5.2 Methods

In order to find the effect of noise on tone lateralization, I embed the tone dichotic trials in white noise under three different S/N ratios, and compare the lateralization patterns in noisy dichotic trials with those in clean dichotic trials.

Two groups of subjects are tested. In one group, both the balance of the hearing abilities of the two ears and the environmental noise are controlled. In the other group, these two conditions are not strictly controlled as the same as in [63]. The purpose of doing this is to investigate whether these control conditions affect REA in the tone dichotic listening experiment.

5.2.1 Participants

In the first group, 25 native Mandarin speakers are enrolled in the experiment. Eleven of them are qualified to take the experiment based on the Edinburgh Handedness Test [46], the Hearing Threshold Level (HTL) test and the pretest. These 11 subjects include 5 males and 6 females, whose average age is 25.36 (2.25), and all of them are strongly right-handed.

In the second group, 11 native Mandarin speakers with no history of hearing impairment are enrolled in the experiment. All of them are strong right-handed, tested by the Edinburgh Handedness Test. There are 6 males and 5 females in this group, whose average age is 25.82 (2.82).

5.2.2 Stimuli

In this experiment, the testing materials consist of 16 monosyllabic Mandarin words, as shown in Appendix (Table A.21), which are formed by four syllables (fan), (guo), (hui) and (shi) combined with 4 tones (adopted from [63]). The F0 contours of the four Mandarin tones are shown in Figure 5.1. The stimuli are recorded from a female native Mandarin speaker and the tone contours are analyzed by Praat software.

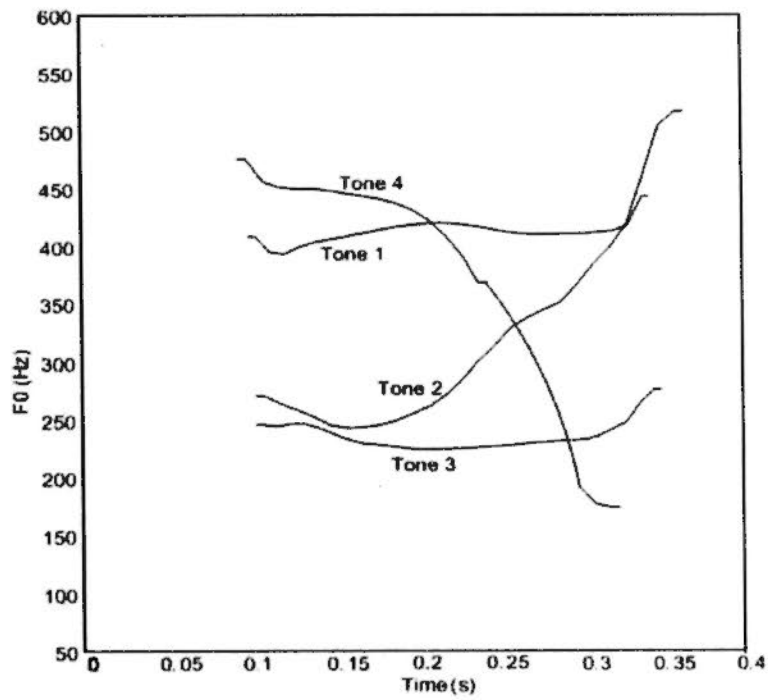


Figure 5.1: The F0 contours of the four Mandarin tones, each of which is carried by the syllable /fan/.

The recording is done in a sound-proof room in a digital speech processing lab using a SHURE microphone and digitized with a MACKIE 12-channel mixer at 44.1 kHz. Each word is produced separately. The lengths of the four tones of the same syllable are roughly the same, which are chosen from the three repeated recordings of each tone of this syllable.

Each target word lasts about 400ms. The target stimuli in each dichotic trial are either clean or embedded in white noise.

The length of the noise is 1000ms. The three noisy conditions include 0dB, -10dB and -20dB S/N ratios, and the S/N ratio is measured during the 400ms in which the target word is presented (0.3ms 0.7ms in the noise sound file). The intensity profile of the noise is shown in Figure 5.2. After the target word has been embedded in the white noise in the three noisy conditions, the intensity of the whole sound file is adjusted at 75dB using Praat software.

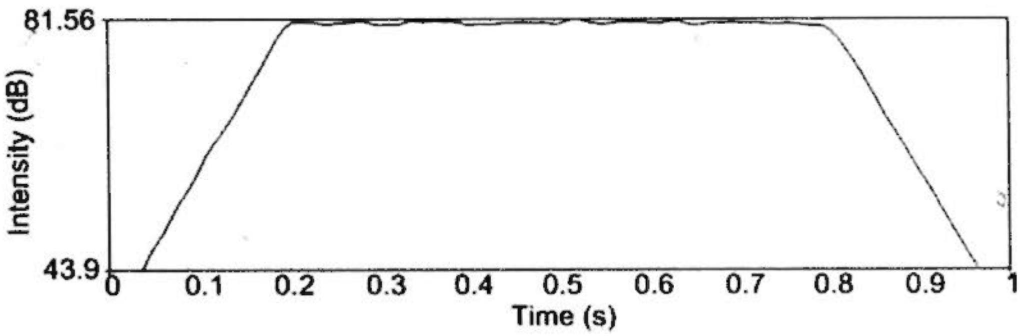


Figure 5.2: The intensity profile of the noise.

The Inter-Stimuli Interval (ISI) is set to 2 seconds. A total of 192 dichotic pairs (12 pairs × 4 syllables × 4 conditions) are generated using MATLAB. Each pair contains two words with the same syllable but different tones. There are 4 blocks in the experiment, each consisting of a randomization of these 192 pairs of stimuli.

5.2.3 Procedure

For the first group, the experiment is conducted in a sound-proof booth. All participants are tested individually with a headphone (SENNHEISER HD 280 Pro). Before the experiment, participants are given the handedness test. Those strongly right-handed participants are allowed to take the HTL test (1 of the 24 participants, not strongly right-handed, is excluded). They are tested of their hearing ability under 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Participants whose left and right ears' HTLs differ more than 10dB or either of them exceeds 25dB at any frequency are excluded (6 of the 23 participants fail to meet this criterion). Participants who pass the HTL test are given the pretest. During the pretest, participants are tested using 48 trials randomly chosen from the 192 dichotic trials in the real test. Participants who reach more than 50% correctness in both left and right ears are allowed to take the real test (7 of 17 participants do not pass the pretest). In the real dichotic test, four blocks are presented, each containing 192 randomized trials. The output volume of the two channels of the headphones is calibrated at 75dB using a sound level meter. Subjects are instructed that they will hear two different words (only differ in tones) simultaneously in their two ears. They need to identify the tones of both stimuli and write them down on an answer sheet using the four tone marks. Left ear and right ear response rows are counterbalanced across blocks to avoid order bias. Each block lasts around 8 minutes. Between the first two and the last two blocks, there is a 30-second rest. The two channels between these blocks are counterbalanced. Between the second and third blocks, there is a 2-minute break for the subject to take a rest and prepare for the reversed order of ear response rows in the answer sheet. The whole experiment lasts approximately 35 minutes.

For the second group, the experiment is conducted in the office environment. Right-handed subjects with no previous hearing deficits are recruited. There is no HTL test in this group. In the formal DL test, all procedures are the same as in the first group.

5.2.4 Data analysis

The Percentage of Errors (POE) is calculated to indicate the lateralization, including the POE of all stimuli and POE of each of the four Mandarin tones.

5.3 Results and Discussion

The overall correctness of the 384 stimuli (192 pairs) is 75.7%. The average POE of the 22 subjects is 52.3%, which is lower than the POE (57%) reported in Wang et al.'s experiment. However, Wang et al. have not reported the hearing ability differences in left and right ears as in my experiment, and there is a possibility that the unbalanced hearing ability may affect the ear advantages. Besides the overall correctness and POE, the correctness and POE under the clean and three noisy conditions are listed in Table 5.1.

Table 5.1: The Correctness and POE under the clean and noisy conditions

Condition	CORRECTNESS (%)	POE (%)
Clean	82.6	52.1
0dB	80.7	52.9
-10dB	76.4	53.4
-20dB	63.1	50.7

As shown in Table 5.1, POE increases in the noisy conditions, compared with the clean condition, though in the -20dB S/N ratio noisy condition, the increase of POE is not as obvious as that in 0dB or -10dB S/N ratio condition. This is because that in the -20dB condition subjects may not clearly identify the tones in both ears, which is indicated by the abrupt drop of correctness compared with the other three conditions.

In order to find the lateralization patterns, Wang et al. introduce the white noise at -10dB S/N ratio to increase errors and to avoid ceiling effect. However, they do not notice that the noisy condition may affect the result of lateralization. My experimental results suggest that a certain degree of white noise can increase the POE value in a certain degree in the tone DL experiment. Although the effect does not reach the statistical significance level, the white noise may still act as a confounding when ear advantages of tonal and non-tonal speakers in Wang et al.'s experiment are compared. There is functional neuroimaging evidence supporting that the low S/N ratio increases the left hemisphere activation in speech processing [6, 72]. These fMRI results show that Broca's area has an enhanced activation when the S/N ratio decreases (Binder et al. 2004), and under a very low S/N ratio, only the left BA44 area activates significantly compared with other regions that correlate with speech processing [72]. The possible explanation of this phenomenon is that the Broca's area may compensate for the loss of the sensory information by enhancing the internal speech sound presentations and serve to improve performance under low S/N ratio. The above evidence that the left hemisphere activates more under low S/N ratio is consistent with my finding that the left lateralization increases when the S/N ratio decreases.

There are no significant group difference between group 1 and group 2. However there are significant noise level and gender interactions ($F(3,54) = 4.266$, $p < 0.012$) (Figure 5.3).

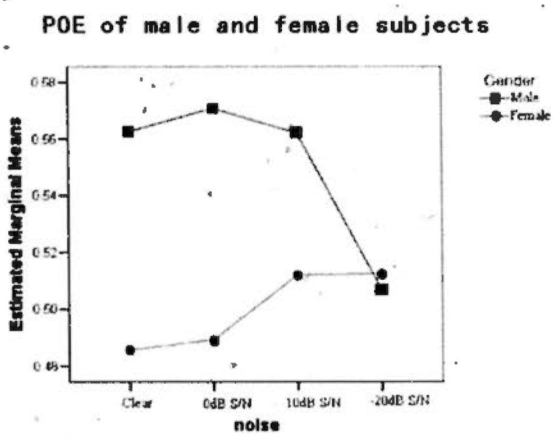


Figure 5.3: Noise level and gender interactions of the POE values

5.4 POE of the four tones

Subjects show different lateralization patterns with respect to the four tones. The one-way ANOVA shows the main effect of tone ($F(3,54) = 6.202$, $p < 0.003$). Table 5.2 lists the POEs of the four tones, in which tone 1 exhibits a left ear advantage; tones 2 and 4 have a strong right ear advantage. Tone 3 has a right ear advantage under -10dB S/N ratio noisy condition, a left ear advantage in the clean condition, but in the 0dB and -20dB S/N ratio noisy conditions, the ear advantages are inexplicit.

Table 5.2: The POE of four tones under different conditions

Condition	TONE 1	TONE 2	TONE 3	TONE 4
Clean	41.9%	56.3%	48.7%	56.7%
0dB	41.7%	61.4%	49.4%	54.3%
-10dB	41.9%	58.6%	52.7%	59.9%
-20dB	47.8%	50.8%	50.5%	56.4%

I propose two explanations for the different tone lateralization patterns. The first explanation deals with the feature differences of these 4 tones. According to the 7 features that Wang [61] assigned for different tones (CONTOUR, HIGH, CENTRAL, MID, RISING, FALLING and CONVEX), tone 1 differs from the other 3 tones in CONTOUR, and tones 2 and 4 differ from tone 3 in HIGH. The different tone features may cause different lateralization patterns of the four tones. This explanation and my experimental results may further reveal a neural mechanism in the auditory system that works similarly as that in the visual system. For instance, in the primary visual cortex of cat, there are "complex" cells that only respond to specific orientation of light bars [28], indicating that certain neurons in the visual cortex can extract different orientation features from the visual stimuli. Similarly, my experiment shows that different pitch contours in tones may correspond to different brain mechanisms. However, whether there are such pitch contour feature extraction neurons in the auditory cortex of humans or other animals remains unknown.

My second explanation concerns the fast or slow changes of the tone contours. As shown in Figure 5.1, the tone contour of tone 1 is flat and its frequency throughout the whole word changes slowly, however tones 2 and 4 have fast frequency changes throughout the pitch contours. Our results indicate that the fast or slow changes of the fundamental frequencies of different tones may cause different lateralization patterns, such that tone 1 has a left ear (right hemisphere) advantage while tone 2 or tone 4 have a right ear (left hemisphere) advantage during the perception. This finding partially matches Poeppel's hypothesis on the lateralization [49], which states that the left hemisphere is more sensitive to the fast physical property changes and the right hemisphere is more sensitive to the slow physical property changes, though the time window in this hypothesis does not exactly match that of mine. As for tone 3, its pitch contour undergoes a falling rising change, but this change is not fast enough compared with that of tone 2 or tone 4. Therefore, the lateralization pattern of tone 3 in the clean condition is similar to that of tone 1 (left ear advantage). However, in the -10dB S/N ratio noisy condition, the lateralization patterns of tone 3 are reversed, which is consistent with my argument that a certain degree of white noise can increase the right ear advantage. It is also consistent with the finding in Wang et al.'s experiment that tone 3 has a strong right ear advantage in noisy conditions.

5.5 Individual difference and gender difference

The individual and gender differences among subjects are indicated by the individual POE. Table 5.3 lists the correctness and POE of each subject, in which 'M' indicates male subjects and 'F' indicates female subjects. As shown in Table 5.3, different subjects show different degrees of lateralization, one male and four female subjects even have reversed lateralization patterns compared with others. In addition, the average POE of all male subjects is 54.76% (3.52) and the average POE of all female subjects is 51.0% (6.0). In the first group that is strictly controlled, the average POE of male subjects is 56.84% (3.41) and the average POE of female subjects is 48.93% (5.43). Based on a T-test in the first group, a significant gender difference of the POE is detected ($t(9) = 2.937$, $p < 0.018$). In the sum of group 1 and group 2, gender difference reaches a marginal significance level ($t(20) = 1.788$, $p = 0.093$). This gender difference indicates that tones are more bilaterally processed by females than males. A similar gender difference has also been found in some other studies [52, 64].

Table 5.3: The correctness and POE (percentage of errors) of each subject

Subjects	CORRECTNESS (%)	POE (%)
Group 1		
M1	89.6	56.0
M2	69.1	54.9
M3	54.4	58.8
M4	65.4	52.9
M5	76.1	61.6
F1	71.0	51.5
F2	68.6	38.6
F3	80.7	52.9
F4	64.3	47.3
F5	85.4	52.4
F6	88.5	50.9
Group 2		
M1	93.3	49.1
M2	52.1	55.4
M3	74.2	52.7
M4	87.1	56.8
M5	50.9	51.4
M6	72.8	52.8
F1	66.0	47.6
F2	78.7	62.6
F3	68.3	52.9
F4	69.1	47.8
F5	87.4	56.5

5.6 The ear advantages of tones change with noise

In this chapter, I report a Mandarin tone DL experiment to study tone lateralization under clean and noisy conditions. Based on a hearing test, the subjects of the experiment are well controlled of their left and right ears' HTLs. Apart from the clean condition, three noisy conditions are introduced, and the lateralization patterns of the four Mandarin tones under these conditions are compared. The results show that certain noisy conditions such as those under the 0dB and -10dB S/N ratios may limitedly increase the average POE. In addition, subjects show different ear advantages for different tones: the perception of tones 2 and 4 shows a right ear advantage, while that of tone 1 shows a left ear advantage. Two physical properties, the tone features such as CONTOUR and HIGH, and the fast or slow changes of the fundamental frequencies of different tones, may cause these different tone lateralization patterns. Moreover, a gender difference of POE is revealed, which suggests that there could be differences in the underlying mechanisms of tone perception between male and female speakers. In this experiment, the lateralization pattern of tone 3 is different in clean and noisy conditions, which cannot be explained by the above two physical properties. In addition to these physical properties, other factors may play a role in affecting the lateralization pattern of tone 3, and the exploration of these linguistic or nonlinguistic factors remains as the future work.

□ **End of chapter.**

Chapter 6

Discussion

Summary

In this chapter, I will discuss the results of my ERP and behavioral experiments, and link them with previous work regarding tone lateralization. My main finding is that the linguistic role and the physical property both affect tone lateralization. I will also discuss a general pattern of tone lateralization and link my results of ERP studies with previous brain structure studies. In the end, a general view about the neural bases of language is discussed, the major contribution of my ERP studies to tone lateralization is summarized, and some future work is mentioned.

6.1 Discussion of the results

The purpose of my **ERP experiments** is to test the underlying factors that affect tone lateralization. By nature, the physical property and the linguistic role of tones should be analyzed, because the tone is the use of pitch to distinguish lexical meanings. In addition, the lateralization of tonemes should also be considered, because when tones are used in certain language, their patterns become the phonetic units in the language, even they are not used to distinguish lexical meanings. Furthermore, it is not necessary to be restricted to real words with specific meanings. The use of pseudo-syllables and pseudo-words is a novel character of my ERP studies, which has never been discussed in previous literature.

In Van Lancker and Fromkin's experiment [57], they have found that there are no ear advantages of hums. They use the hums as a control, without considering the lateralization of tonemes. However, tone patterns should be considered since they are part of the phonological system in certain language. Although the result of lacking REA for hums compared with tone words is consistent with my ERP results, they do not consider the underlying factors. The REA for tone words compared with hums may be caused by both the semantics and the physical properties. There is no strict control to separate these two factors in their experiment.

In the previous studies of tone lateralization, two views on lateralization, the "task-dependent" and the "cue-dependent" hypotheses, are proposed, each focusing only on one side of the two basic properties of the tone. With the biases and presumptions about tone lateralization, some specific experiments can certainly find evidence to support each of these two conflicting hypotheses.

In the behavioral experiments and PET or fMRI neuroimaging studies [20, 21, 27, 38], the materials are all real words and contain physical properties such as the fast formant transitions within 20-40ms. Tone patterns presented in the hums without fast changing acoustical cues are not considered as part of the facts of tone lateralization. The results of behavioral or neuroimaging studies reflect the tone lateralization as the final outcomes of the whole tone processing without caring about the precise temporal resolution of the neural activities. However, in the experiments of speech perception, the temporal domain is important and the perception process is online.

In the previous ERP experiment on tone lateralization [42], no specific language tasks are involved, and the right lateralization of tone reflects the lateralization pattern on its physical property. The merit of that and my ERP experiments is that the temporal resolution is high and it is crucial to look inside the time course of tone processing. In Luo et al.'s experiment, they only examine the ERP component around 200ms, because of the MMN paradigm. In my ERP experiments, the components within 1000ms after the onset can all be analyzed.

The results of my four ERP experiments show that in early and late time windows, the physical property and the linguistic role both affect tone lateralization. The early and late time windows are defined around P2 and N400 components. In previous ERP studies, the functions of the P2 and N400 components have been extensively explored. Based on the serial model of auditory sentence processing [18], P2 is assumed to be related with word category processing which is after the phonological processing at the N1 component . N400 component has long been associated with semantic processing and it will increase when the material does not integrate with the context. Although it has been assumed that different functions are represented in different ERP components and the processing is mainly serial other than parallel, the results of my experiments indicate that different functions are presented in both early and late ERP components. In the two DL experiments, the two factors affect the lateralization of the P2 components, and in the word priming experiment, both factors interact with P2 component as well. The linguistic role also affects the lateralization around the 400ms time windows after the onset of the first syllable in the disyllabic pseudo-words. In the sentence semantic violation experiment, the deviation of tone or consonant interacts with the N400 lateralization around 300 ms–400 ms after the onset of the target syllable. In sum, it is hard to dissociate the effects of these two factors in the time course. They may be dissociated in the spatial distribution in later studies, which indicates different neural sources of these two factors.

The result of the **behavioral experiment** shows an increasing trend of the REA in the 0dB and -10dB S/N conditions, compared with that in the clean condition. In the -20dB S/N condition, the REA decreases compared with that in the -10dB S/N condition, shown by an abrupt decrease of the correctness (See Table 5.1). The error rate in the -20dB S/N condition matches that in Wang et al.'s study at -10dB S/N ratio [63]. However, the effect of the REA is much weaker than their results when the POE values are compared.

I reproduce the same set of stimuli used in Wang et al.'s study and use the similar procedures as them [63]. I have a strict control of the hearing ability difference of the recruited subjects in group 1 and the environmental noise, which has not been reported in detail in their study. In my experiment, the hearing ability difference between the left and right ear of each subject is not greater than 10dB, at 7 frequency levels from 125 to 8000Hz. My test is done in a sound proof booth with the environmental noise around 40–45dB. The different experimental results between these two studies may be caused by the different experimental controls. The differences of the hearing abilities between the left and right ears may cause different ear advantages in the DL experiment, even in the normal hearing subjects.

At least, my data show that the -10dB S/N ratio increases the POE compared with that in the clean condition. This result infers that the white noise increases the REA in the tone DL experiment. Therefore, the comparison between the testing results of Mandarin subjects in noisy condition and those of English subjects in clean condition is unfair, not to mention when the hearing ability is not strictly controlled. And the claim of the REA of the lexical tone in Mandarin native speakers may not be true in the previous tone DL experiment.

6.2 Is tone bilaterally processed?

Although I do not argue for an absolute lateralization of tone processing, the general trend of the lateralization could be discussed. Since the two underlying factors of tone processing are toward the opposite directions, tone perception must include the interhemispheric communications and the two hemispheres should both carry out parts of the processing. In this sense, tone is processed bilaterally.

In my ERP data, because the testing materials always have fast changing acoustic cues, the general pattern of lateralization of ERP components is always toward the left side. It is impossible to dissociate the base syllables from tones in tone language when distinguishing lexical meanings. The relative lateralization pattern of tones in different conditions is examined by manipulating various factors, and it is hard to dissociate a pure contribution of the tone processing in my ERP experiments. In my opinion, there is no way to determine the tone lateralization alone without considering the underlying factors. The linguistic processes in the brain are broadly distributed among all four lobes, and there is no 'language' center in the brain. It is reasonable to assume joint operations in different parts of the brain for tone processing. The relative contribution of each underlying factor could be explored in future studies.

6.3 Structural differences in the two hemispheres

In Zatorre et al's review on language and pitch lateralization, they have mentioned a cytoarchitectural difference between the left and the right superior temporal gyri. The cellular composition differences may predict different functions in the two hemispheres. Left hemisphere has large and heavily myelinated cells, which suggests a fast conduction of the electrical signals. This mechanism may allow a better temporal resolution of the auditory signals, since the cells could detect the signal changes that happen in a short time window. However, the cells in the right hemisphere are relatively small in size and have less myelin sheath. The function of the myelin sheath is to make the signal transform quickly inside axons. The lack of this structure could result in a slow conducting rate of the signals in the right hemisphere. But this slow response may raise another advantage in the signal detection. Since the signal is transformed slowly, it will be preserved much longer, and the signal changes that happen after a long time can be detected easily. However, for a continuously changing signal which varies slightly along a relatively longer time window, the fast conductive cells may not detect these small differences.

A good analogue of this temporal and spectral trade-off effect is the Fourier transform. In the engineering signal processing methods, a better temporal resolution in a shorter time window always causes a sacrifice of the spectral resolution, and the precision in the narrower frequency band needs a longer time window to be analyzed. The neural system may have similar general patterns, although the details of the neural processing of information are not yet clear. The advantages of temporal and spectral resolutions in the left and right hemispheres may be caused by either the different properties of single cells or the emerging property that sum up all feedbacks from neuronal function groups.

The above structural differences between the two hemispheres may predict the functional differences when different stimuli with fast or slow changing acoustical properties are perceived.

There is another kind of structural difference between the two hemispheres which may predict functional lateralization of semantics. In Parker et al.'s DTI (diffusion tensor imagning) studies, dorsal and ventral language pathways are examined. They find a greater lateralization in the ventral pathway connecting the superior temporal gyrus, middle temporal gyrus to the inferior temporal gyrus. In previous neuroimaging studies, the middle temporal gyrus is associated with the semantic processing [7, 14], and it is left lateralized. The results of these functional neuroimaging studies are direct proofs of the left lateralization caused by the linguistic role of tones. And the structural differences between the left and right white matter volumes are consistent with the trends of those functional neuroimaging studies.

Further discussion about how my study of tone lateralization links with a broader view of the neural bases of language and brain functional localization will be discussed in the following section.

6.4 'Language as an interface'

In the study of the functional organization of human brains, a basic assumption is that each of the cognitive functions is segregated in certain brain regions. It is a recent trend to study the functional integration of the cognition [19, 43]. However, in the theory of the cognitive bases for language, it has been a long history since the integrated view was proposed.

The basic assumption in my ERP studies of tone lateralization is that the language functions involve various more basic cognitive functions. As in the 'mosaic theory' proposed by William S-Y. WANG in 1967, "*language is regarded as a kind of 'interface' among a variety of more basic abilities. These abilities underlie nonlinguistic processes as well, and involve the perception of patterns in the frequency and temporal domains, the coding and storage of events and objects at different levels of memory, the manipulation of various hierarchical mental structures.*" (p116, [60])

In my ERP studies, the results support that the pitch perception and the semantic processing both contribute to the tone perception and affect the functional lateralization of it. Although the ERP experiments can not localize precisely the region of the functions of the underlying cognitive processes, lateralization is a rough measurement of the localization, and the influences of the semantics and the acoustic cues are consistent with other behavioral and neuroimaging studies.

By looking at the language functions as integrated neural processes, other than the historical view that the Broca's area is the site for speech production, the Wernicke's area is the site for speech perception, and the left hemisphere is language dominant hemisphere for all language functions, the puzzles of tone lateralization could be resolved.

6.5 Tone lateralization puzzle

The current ERP studies on tone lateralization propose a fresh view different from previous studies. It has been discussed recently that the tone lateralization should be dissected into different conditions, knowing that both the 'task-dependent' and the 'cue-dependent' hypotheses only tell parts of the truth. However, there were no specific solutions to this intriguing question. Although previous studies have already cumulated consistent results regarding lateralization of semantics and pitch perception, no previous work has analyzed them in the frame work of tone lateralization. Since the nature of the tones covers these two basic factors, it is reasonable to explore the effect of pitch and semantic processing on tone lateralization.

6.6 Brain is a dynamic system

The ERP results reflect that certain brain function may have multiple hierarchies, and the functional lateralization is not fixed. Different brain regions work together to process the complex cognitive function such as language. Tone study is a good example of it. The changes of the acoustical properties or the semantics of the materials alone may affect brain lateralization, during the same type of tasks using similar sounds.

To further explore the functional localization of the basic cognitive functions, other experimental methods such as fMRI should be used in future studies, which will provide further evidence of the current ERP studies.

6.7 Future work

An interesting question raised in Chapter 5 is that whether different tones have different lateralization. According to Poeppel [49], the fast changin acoustic cues are left lateralized, while the slow changing acoustic cues are right lateralized. If the pitch changes of the contour tones are detectable within several dozens of milliseconds, it might be categorized to the 'fast changing' sounds and be left lateralized. This is supported by the data in Chapter 5. It may also predict that the low rising tone in Cantonese has a less left lateralization than the high rising tone. Further neuroimaging evidence needs to be found.

Other experimental methods such as fMRI study need to be used to confirm these findings in my studies, although the temporal resolution of fMRI is not as good as ERP. In previous fMRI studies the comparison between pseudo- and real-words has not been examined on tone perception. The precise spatial localization of this contrast is an interesting question, and could be compared with the same comparison when the vowels or consonants are changed. If the regions are the same, it will indicate that the semantic processing is in certain brain regions irrelevant of the acoustic cues. Otherwise, it will confirm that different types of acoustic cues have different brain mechanisms and each has a specific phonetic and semantic interface.

Moreover, the Mandarin phoneme and toneme auditory processing has not been studied thoroughly in the previous work. The relation between non-linguistic cues and specific linguistic phonological contrasts should be examined more carefully. This will help us understand better the neural bases of language.

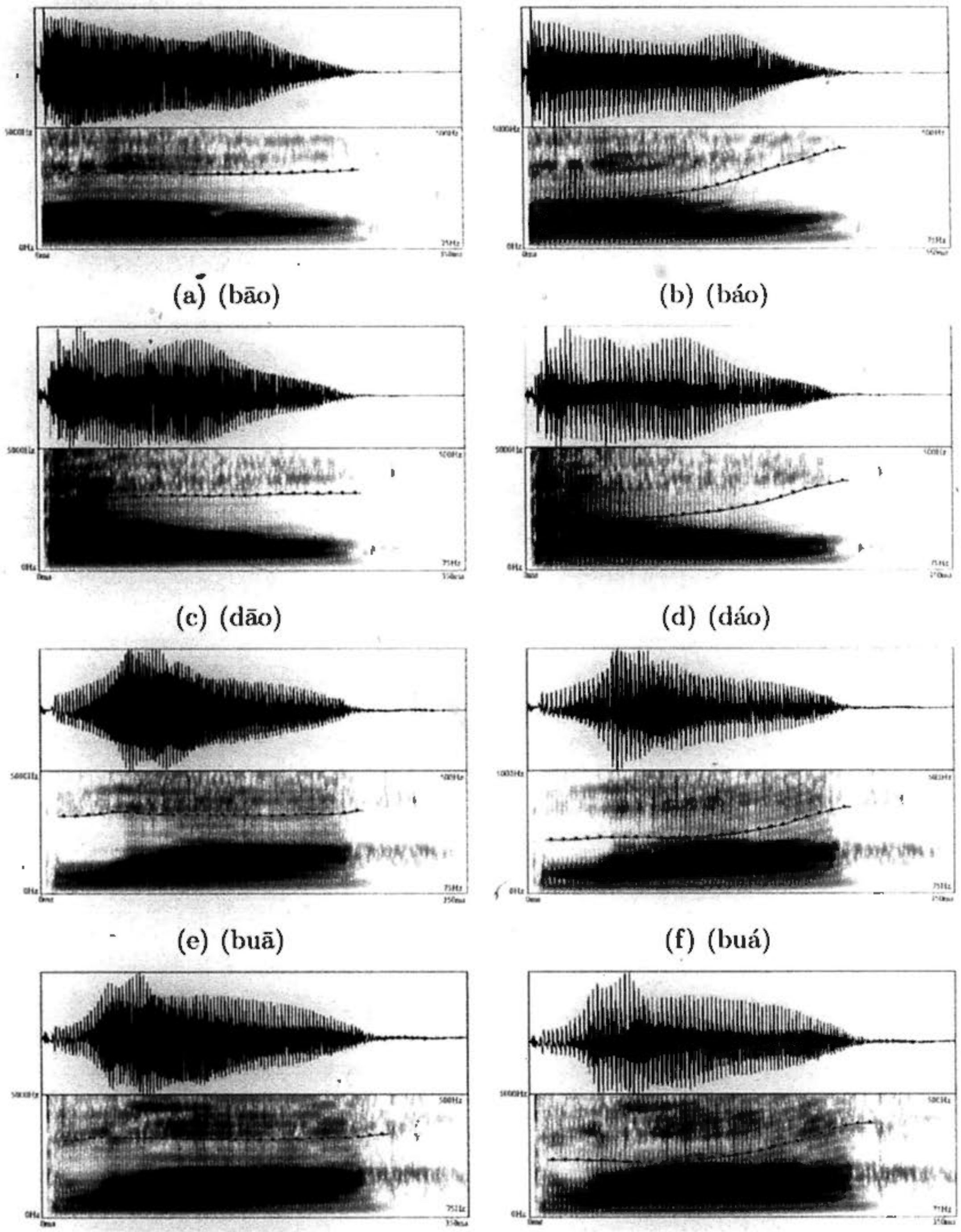
□ **End of chapter.**

Appendix A

Supplementary materials

Table A.1: Stimuli of the first DL experiment

Dichotic trials	REAL SYLLABLES		PSEUDO-SYLLABLES	
Consonant dichotic trials	(bāo), (dāo) 包, 刀	(dāo), (bāo) 刀, 包	(buā), (duā)	(duā), (buā)
and Chinese Characters	(báo), (dáo) 雹, 捯	(dáo), (báo) 捯, 雹	(buá), (duá)	(duá), (buá)
Tone dichotic trial	(bāo), (báo) 包, 雹	(báo), (bāo) 雹, 包	(buā), (buá)	(buá), (buā)
and Chinese Characters	(dāo), (dáo) 刀, 捯	(dáo), (dāo) 捯, 刀	(duā), (duá)	(duá), (duā)



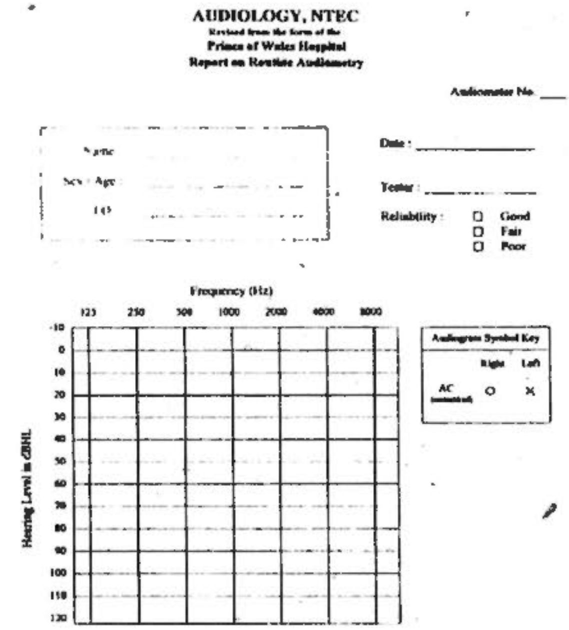
(a) (bāo) (b) (báo)

(c) (dāo) (d) (dáo)

(e) (buā) (f) (buá)

(g) (duā) (h) (duá)

Figure A.1: Sound waveforms and the spectrograms (0–5000Hz) of the first DL experiment. The pitch contours are also shown in the spectrograms (75–500Hz).



(a) PTA form

惯用手趋势调查

名字__________ 出生日期__________ 性别________

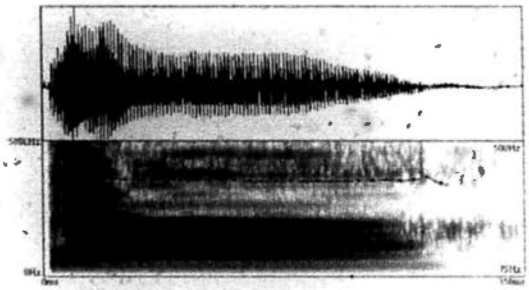
在下面的表格中，根据您的用手习惯填写您做某种动作时的常用手，***在相应的表格用✓表示***
有一些动作需要双手，在这些动作中，请填写括号中的物体/动作的用手习惯
填写时请注意：“总是”表示除非强迫情况下，否则总是。“有时”表示两只手没有区别，选择“有时”则左右栏都填上，选择“总是”则另外一栏请填上“从没”。
请回答所有的问题，当且仅当您从来没有做过这个动作时才在相应的表格留下空白。

		左			右		
		总是	有时	从没	总是	有时	从没
1	写字						
2	绘画						
3	投掷						
4	使用剪刀						
5	使用牙刷						
6	使用刀(不与叉同用的情况下)						
7	使用勺子						
8	使用扫把(放在上面的那只手)						
9	划火柴(拿火柴的那只手)						
10	开瓶子(拿盖子的那只手)						
i	踢东西的使用习惯用哪只脚?						
ii	只用一只眼睛看东西的时候习惯哪一只?						

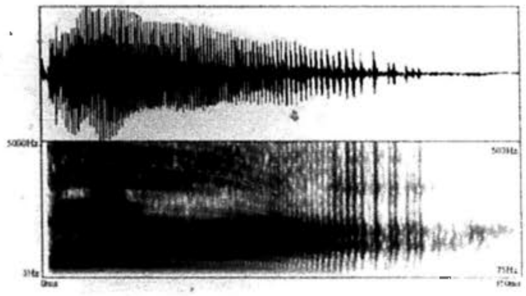
Adopted from Oldfield, 1971
Made by Zheng Hong-Ying
Revised by Shuai Lan

(b) Handedness test

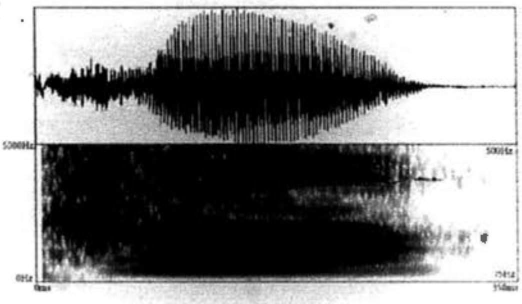
Figure A.2: The PTA form and the handedness test form used in the ERP experiments.



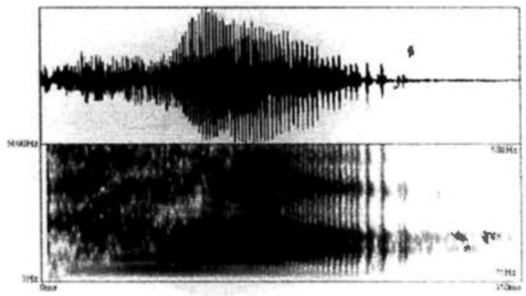
(a) (dā)



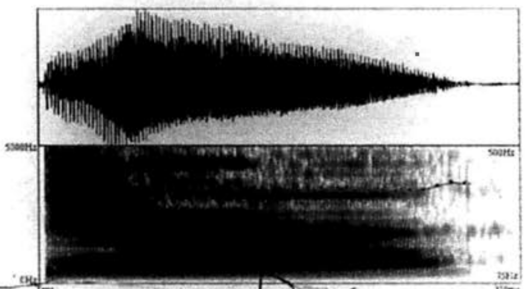
(b) (dà)



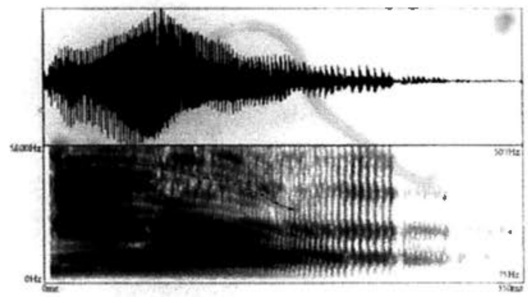
(c) (tā)



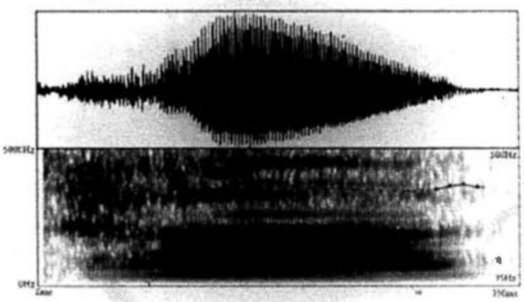
(d) (tà)



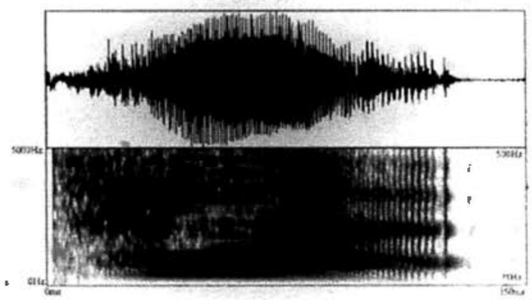
(e) (dǣ)



(f) (dæ̀)



(g) (tǣ)



(h) (tæ̀)

Figure A.3: Sound waveforms and the spectrograms (0–5000Hz) of the second DL experiment. The pitch contours are also shown in the spectrograms (75–500Hz).

Table A.2: Materials of the word priming experiment, real words, part 1

Consonant Primes	Real Word Targets	Tone Primes	Real Word Targets	Non-Primes	Real Word Targets
古	功能	花	风格	肯	官员
假	精神	分	公园	躺	居民
肯	科学	匹	家庭	落	心情
旭	新闻	期	生活	热	中华
祖	资源	荒	需求	尺	青年
笨	标准	灯	基础	父	商品
故	工厂	温	家长	停	说法
啥	身体	妈	思想	现	歌曲
徐	心理	烘	香港	情	焦点
敌	单位	风	观点	盖	经理
福	方式	低	方向	鼻	观众
汞	规划	乌	工作	惭	经验
局	阶段	瞻	经费	轮	商业
卡	科技	蛙	生命	惹	宗教
纸	专业	需	压力	渠	资料
彻	长期	阳	国家	比	劳工
马	民间	图	人家	客	时期
热	人生	徐	时间	饭	投资
特	台湾	局	文章	汉	学生
宇	员工	国	河川	密	研究
赤	成本	红	成果	八	媒体
豁	环保	文	结果	发(fā)	学者
润	人口	兰	民主	燕	词典
逼	博士	拔	男子	度	成长
喝	环境	夹	读者	车	情感
努	能力	祥	程度	凯	情绪
赏	食物	爬	结构	边	时代
挖	文化	程	情况	呼	条件
须	协会	仆	学术	秋	习惯
新	学院	玩	行政	关	责任

(continued on next page)

Table A.3: Materials of the word priming experiment, real words, part 2 (Following Table A.2)

Consonant Primes	Real Word Targets	Tone Primes	Real Word Targets	Non-Primes	Real Word Targets
拔	北京	缓	本身	群	厂商
锯	警方	坎	老师	算	母亲
鱼	眼睛	渴	小说	和	早期
过	感觉	产	女生	佩	演出
眯	美国	写	景观	屯	法规
问	我国	五	感情	批	老人
西	小时	粉	美元	劝	小孩
勒	理由	底	委员	潘	主题
奋	法国	鼠	以前	又	主席
班	比例	宝	旅游	闷	警察
吃	产业	懒	比赛	渣	土地
接	角度	渴	法律	隔	网络
拿	女性	谱	理念	期	主任
他	体育	土	品质	心	考试
吴	晚上	瓦	以后	福	统计
此	措施	万	地方	我	画家
德	地区	乐	父亲	否	细胞
局	竞争	罪	目标	仆(pú)	卫生
傻	社区	墨	亚洲	团	作家
瘸	汽车	客	教师	躲	特征
逼	部门	特	病人	泼	范围
底	大学	万	课程	餐	少年
哥	过程	裤	去年	女	校园
举	价值	去	问题	喊	论文
哪	内容	故	自然	扑	太阳
博	办法	落	记者	直	电脑
读	电影	裤	历史	泼	市场
分	妇女	抱	下午	图	校长
须	系统	辣	重点	洋	政府
租	自己	布	作品	掐	自我

The real words are chosen from the Sinica Corpus of the Academia Sinica (http://elearning.ling.sinica.edu.tw/eng_jindai.html). The average rank of the real words is 827.4. The highest rank of these words is 45 and the lowest rank is 1,956. All real words are within the top 2,000 most frequently used words in the corpus. The average frequency of occurrences of the words is 1,194.5 with the highest frequency of 9,059 and lowest frequency of 302. All words are disyllabic noun words.

Table A.4: Materials of the word priming experiment, pseudo-words, part 1

Consonant Primes	Pseudo-Word Targets	Tone Primes	Pseudo-Word Targets	Non-Primes	Pseudo-Word Targets
杜	当文	汪	今除	竟	工拔
锯	将佛	充	机岩	上	经挪
哑	英谭	温	公题	某	邀驼
涨	中痕	晕	期达	赫	规无
发(fà)	分罗	君	危同	谱	医峦
嘎	高鲁	胚	今暖	国	生鲁
静	交本	昆	发喜	乐	开本
客	空土	堪	公北	麻	妻葛
啥	双者	弯	公裸	轮	机瓦
正	专伟	黑	基损	驻	方傻
扯	差兔	喷	公密	把	都扩
葛	官弱	多	八混	人	规卖
杰	机袜	拉	区塑	土	机赖
霞	需切	金	声罪	娃	因妹
怎	资怒	芳	中个	渴	砖拓
染	如拉	强	人昆	苦	昨奔
马	民突	才	文租	瓦	民桌

(continued on next page)

Table A.5: Materials of the word priming experiment, pseudo-words, part 2

(Following Table A.4)

Consonant Primes	Pseudo-Word Targets	Tone Primes	Pseudo-Word Targets	Non-Primes	Pseudo-Word Targets
曲	全纠	凡	原插	显	男哥
弱	人杯	婆	族蛙	笨	情拉
躺	同风	痕	来夫	挂	人花
叶	银组	华	明土	散(sàn)	同有
飞	房马	寻	国扯	晕(yūn)	行反
黑	孩鲁	蛮	德卡	定	传解
拍	朋卡	人	集伟	混	农砍
她	团亩	茄	哲几	拉	成喜
染	人破	全	服挂	苦	成骂
洗	学恰	群	国闷	懒	国凑
楚	城铺	墙	人汉	剪	活客
哥	国入	壳	行铺	慌	节兔
家	决度	存	同价	哭	模漏
泽	组八	扯	管突	罐	扭摸
自	总飞	肯	选憨	恒	软分
触	广泼	马	主喷	凡	小缺
寻	小龛	铆	孔纠	万	整米
亚	影多	府	演温	吐	水餐
那	女迟	虎	老门	奋	选仪
锅	改罚	且	场仆(pú)	客	小活
鸭	语鼻	猛	保卢	遮	女爷
阅	以盆	瓦	女迟	黑	以徐
啥	使陆	痞	表无	半	此罗
栾	理热	某	辅岔	夫	表溃
公	广怒	舍(shě)	好棍	陈	反顿
勒	两或	惹	挑括	包	领在
牙	以诺	渴	古叛	霞	企岁
宅	主破	雪	法或	轮	影缝
比	抱饥	是	变推	和	战昆
读	电发	赫	大熏	瓦	对潘
底	动威	破	地湾	笨	讯山

(to be continued)

Table A.6: Materials of the word priming experiment, pseudo-words, part 3

(Following Table A.5)

Consonant Primes	Pseudo-Word Targets	Tone Primes	Pseudo-Word Targets	Non-Primes	Pseudo-Word Targets
法	费粗	厦	智驹	奴	照乌
夹	技拉	物	会班	胡	内扎
书	社博	旭	个爬	喊	掉娃
渣	这癞	看	塑隔	乌	大魁
熟	社趴	路	是霞	波	日德
舍	是搭	意	建读	选	道谜
塔	特马	爸	训盆	鲁	现毛
施	上予	赫	代裹	颗	父捧
席	项肯	赴	电怎	斯	看扭
鱼	意葛	度	现哪	金	效胆
严	印古	次	叫卡	求	道满
遮	制哪	怕	事腿	爬	色毁

In the following tables, materials used in the sentence semantic violation experiment are listed. All sentences are composed of 11 characters, which are constructed to two phrases with the maximum length of 7 characters and the minimum length of 4 characters. The target word in each sentence is the last character, which is a monosyllabic word. The syntax of the sentence is controlled such that the second last character is the verb and the last character is the object.

Table A.7: The stimuli of the semantic violation in sentences, part 1

Consonant violation	Tone violation	Non-violation
小明在杀鸡， 杀完以后拔曹（毛）。	古时候的婚礼上， 都要拜汤（堂）。	瓦罐导热均匀， 最适合熬汤。
小周买了新房， 很快会搬瞎（家）。	在出国旅行时， 她被人绑家（架）。	想参加考试， 就赶快去报名。
吴会计这次来， 是为了查让（帐）。	他也有难处， 别怪他不帮莽（忙）。	四川有一项杂技， 叫做变脸。
小明说他饿了， 吵着要吃干(gàn)（饭）。	我要接办事处， 请帮忙拨豪（号）。	他不出席审判， 是为了避嫌。
夏天到了， 小刚要每天冲祥（凉）。	秋天到了， 可以去树上捕颤（蝉）。	小陈一边看电视， 一边剥橘。
八达通没钱了， 我得去充池（值）。	经济萧条期， 公司大量裁愿（员）。	这里秩序井然， 没有人插队。
小林刚洗完澡， 现在在穿七（衣）。	小程十八岁了， 今年就参俊（军）。	他正拿着铁锹， 奋力地铲雪。
婷婷很爱面子， 特别怕出抖（丑）。	上班高峰期， 总是很难乘扯（车）。	警察给了他罚单， 因为超速。
这次体能测试， 全体都达教（标）。	外面在下雨， 出去必须撑散（伞）。	他们会月初领证， 月底成亲。
最近几天很冷， 出门要戴涝（帽）。	今天的任务， 是给庄稼除宠（虫）。	明天单位搞活动， 还有抽奖。
你想当秘书， 必须先学打次（字）。	他这人不实在， 就知道吹扭（牛）。	查理来中国， 只是为了传道。
古时候没有电， 晚上得点耕（灯）。	银行涨利息了， 我想去存欠（钱）。	天气太冷了， 冻得她直搓手。
每天早上起床， 我都要叠类（被）。	家里来客人了， 你快去倒插（茶）。	没赶上火车， 他急得直跺脚。
就这一点小事， 不需要动兔（怒）。	编辑告诉小冯， 要注意断举（句）。	小静在暑假里， 帮家里放羊。
他脾气不好， 经常当众发果（火）。	他一句话都不说， 光是翻鼠（书）。	台湾的男青年， 多数要服役。

(to be continued)

Table A.8: The stimuli of the semantic violation in sentences, part 2

(Following Table A.7)

Consonant violation	Tone violation	Non-violation
他被保安打伤， 去医院缝喷（针）。	受到不公待遇， 他只能告装（状）。	刚才的事故， 你要全权负责。
噪音很大， 因为对面在盖揉（楼）。	今晚八点， 整栋楼停止供点（电）。	小虎家养猪， 他得每天割草。
心态非常重要， 得学会感真（恩）。	拿到学位后， 他会马上回过（国）。	王庄离这十里， 中间要过桥。
生产力先进了， 用机器耕钱（田）。	市长接受邀请， 明天来剪猜（彩）。	你不会游泳， 最好别去划船。
今晚有雷暴雨， 要记得关筐（窗）。	因剧情需要， 女主角在减飞（肥）。	要上坡了， 司机会提前换档。
他刚刚运动完， 急着要喝腿（水）。	在提审前， 不允许同他见免（面）。	股市风险很大， 不一定获利。
明星队首场失利， 面临降河（格）。	每次我生病， 总是妈妈煎摇（药）。	下周开始， 我们用英语讲课。
他不好好打球， 倒像是搅渠（局）。	他告诉孩子们， 要谨慎交又（友）。	每天傍晚， 老李都要来浇花。
乒乓球比赛上， 我负责计奔（分）。	他工作绩效很高， 明年加信（薪）。	阿姨特地叮嘱， 要我去接机。
为了生存， 他必须上山砍白（柴）。	小孙有对象了， 想明年结混（婚）。	为了健康着想， 你必须戒烟。
为了选拔人才， 月底会考志（试）。	班长爱动脑筋， 最喜欢解替（题）。	小柯住在乡下， 不经常进城。
他勤劳能干， 积极种树垦庄（荒）。	想强身健体， 可以练练举钟（重）。	颁奖的时候， 他向观众鞠躬。
以前生产面粉， 用驴子拉阔（磨）。	李老师身体不好， 经常看柄（病）。	小吴下周不在， 去北京开会。
银行提供服务， 帮客户理埋（财）。	战争结束后， 他一直在疗上（伤）。	名将刘翔， 从十岁开始跨栏。
因为受贿问题， 市长被免十（职）。	天暗下来， 恐怕下午要落鱼（雨）。	他遇见领导， 总是主动拎包。

(to be continued)

Table A.9: The stimuli of the semantic violation in sentences, part 3

(Following Table A.8)

Consonant violation	Tone violation	Non-violation
他坚持锻炼身体， 每天跑裤（步）。	从春天开始， 我们就在灭稳（蚊）。	想有所作为， 必须从小立志。
小鹏做完作业， 便开始拼足（图）。	饲养公奶牛， 只是为了配钟（种）。	今天你请客， 记得最后买单。
大坝决堤， 解放军赶来抢脸（险）。	为欢迎客人， 村民开始敲顾（鼓）。	村里有规定， 不许自行酿酒。
我们做个分工， 小夏来切太（菜）。	军营纪律严明， 得按时起窗（床）。	小徐常常锻炼， 他喜欢爬山。
这是个紧急任务， 不准请恰（假）。	假期到了， 小陆约我去骑妈（马）。	游完泳之后， 小冯总是揉眼。
在发言之前， 小程习惯清绑（嗓）。	为保平安， 他到寺庙里求浅（签）。	工头吩咐， 今天让大家晒盐。
投票已经结束， 有两人弃原（权）。	他谦虚好学， 常向别人取敬（经）。	为了民众， 烈士们选择受难。
一群小孩打假， 在街上扔端（砖）。	和尚还俗以后， 就可以娶棋（妻）。	按当地风俗， 出殡前要守夜。
今天是劳动日， 我负责扫气（地）。	养鸡的目的， 就是为了生胆（蛋）。	农村条件差， 不能每天刷牙。
小峰六岁了， 今年就能上绝（学）。	小黄的电脑旧了， 需要升技（级）。	连夜抢修之后， 她只想睡觉。
清明节到了， 路边有人烧尺（纸）。	漂流在外的游子， 都很思翔（乡）。	早晨一起来， 他就开始梳头。
小殷把球带起来， 准备射陈（门）。	小王转身就走， 不喜欢抬港（杠）。	人要相信自己， 不能靠算命。
上课要认真， 不能随便说挂（话）。	从小开始， 父亲就教他弹亲（琴）。	他很浮躁， 总是不停的跳槽。
拜年的时候， 大家相互送痞（礼）。	司令在开会， 商量怎样退堤（敌）。	小东戴上耳机， 正准备听歌。
煮饭时间到了， 你快去淘比（米）。	对面要盖楼， 这几天在挖图（土）。	培养好习惯， 不要随地吐痰。

(to be continued)

Table A.10: The stimuli of the semantic violation in sentences, part 4

(Following Table A.9)

Consonant violation	Tone violation	Non-violation
他开了信贷公司，总在讨赖（债）。	小赵唯一的嗜好，就是喂愚(yū)（鱼）。	陈师傅就在村口，帮人修鞋。
他经常去酒吧，跟别人调明（情）。	校长经过时，我们向他问豪（好）。	他已经决定，去少林寺习武。
银行排长队，许多人在提选（款）。	今天任务多，我得很晚下版（班）。	小花猫脏了，晨晨帮它洗澡。
下午没有课，男生都去踢油（球）。	远洋货轮到了，在港口卸豁(huō)（货）。	这次的篮球赛，是为了选秀。
最近经济不错，适合于投思（资）。	这次能得奖，你该好好谢十（师）。	他刚刚出道，还不太会演戏。
暗室里的照片，还没有显饼（影）。	二十年前，人们还经常写心（信）。	明早十点，大家到村口迎宾。
医生开了药方，帮助他消直（食）。	他承受不了打击，开始信脚（教）。	他应该明白，工作必须用心。
水果喷了农药，吃前要削题（皮）。	村里在搞培训，教怎样养灿（蚕）。	谁都知道，这种做法是愚民。
他热爱文学，平时喜欢吟只（诗）。	泰森拳击失利，急得想咬任（人）。	小冯家装修，这几天在砸墙。
刚到新城市，小胡到处找抗（房）。	我们决定，下午去河里游拥（泳）。	果子熟了，小张约我去摘桃。
丈夫去种地，妻子在家织醋（布）。	为了国家的绿化，要多种书（树）。	毕业典礼后，大家都在照相。
玲玲不想回答，于是就装喇（傻）。	为了公平，兄弟俩决定抓九（阄）。	他出车祸之后，便开始拄拐。
每天早上六点，寺里会撞松（钟）。	他去找风水先生，祈求转云（运）。	年轻人爱赶潮流，喜欢追星。
爷爷过生日，儿孙都来祝漏（寿）。	我打电话给他时，他在走卢（路）。	仪式开始了，第一项是奏乐。
为尊重事实，他决定去作缝（证）。	用拼装式家具，就不用钻空（孔）。	小红毕业了，在银行里做事。

Table A.11: The handedness score of the subjects

Male subjects	Handedness score	Female subjects	Handedness score
1	-5	1	50
2	50	2	70
3	60	3	70
4	64	4	71
5	70	5	80
6	80	6	90
7	90	7	100
8	90	8	100
9	90	9	100
10	90	10	100
11	90	11	100
12	90	12	100
13	100	13	100
14	100	14	100
15	100	15	100
16	100	16	100

Table A.12: The response rate of each subject in the first DL experiment

Consonant	dichotic	trial		Tone	dichotic	trial	
Real	syllable	Pseudo-	syllable	Real	syllable	Pseudo-	syllable
Left	Right	Left	Right	Left	Right	Left	Right
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
78%	69%	84%	81%	72%	72%	91%	88%
91%	94%	97%	97%	59%	63%	72%	47%
94%	94%	94%	100%	100%	100%	97%	97%
94%	100%	100%	94%	88%	91%	81%	88%
100%	100%	100%	100%	100%	94%	100%	100%
88%	100%	97%	84%	100%	100%	100%	97%
78%	84%	91%	94%	97%	100%	91%	97%
100%	100%	100%	100%	100%	100%	100%	100%
91%	81%	97%	91%	100%	100%	100%	100%
78%	84%	100%	97%	100%	100%	97%	100%
100%	100%	94%	97%	97%	100%	100%	97%
100%	100%	100%	100%	100%	100%	100%	100%
97%	100%	100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
97%	100%	100%	100%	100%	100%	100%	100%
94%	88%	94%	91%	100%	100%	100%	100%
100%	97%	100%	100%	100%	97%	97%	100%
100%	97%	100%	100%	100%	100%	100%	100%
94%	91%	100%	97%	97%	97%	100%	100%
50%	44%	56%	59%	100%	100%	97%	100%
100%	94%	100%	100%	97%	100%	100%	97%
97%	97%	97%	100%	100%	100%	100%	100%
100%	97%	100%	94%	88%	88%	84%	81%
97%	100%	94%	97%	100%	100%	100%	100%
97%	100%	100%	100%	100%	100%	100%	100%
97%	97%	97%	94%	100%	100%	94%	100%
97%	100%	100%	97%	94%	100%	97%	94%
100%	100%	100%	100%	97%	100%	100%	100%

Table A.13: The accuracy rate of each subject in the first DL experiment

Consonant	dichotic	trial		Tone	dichotic	trial	
Real	syllable	Pseudo-	syllable	Real	syllable	Pseudo-	syllable
Left	Right	Left	Right	Left	Right	Left	Right
72%	56%	44%	47%	97%	97%	97%	91%
38%	53%	28%	78%	88%	97%	91%	91%
69%	38%	81%	28%	88%	88%	81%	91%
24%	55%	44%	62%	61%	39%	48%	46%
55%	53%	48%	65%	42%	60%	43%	67%
57%	50%	30%	66%	88%	78%	74%	74%
67%	28%	53%	63%	39%	52%	35%	39%
66%	47%	41%	47%	84%	83%	75%	69%
71%	47%	39%	56%	63%	81%	63%	81%
44%	52%	28%	47%	58%	53%	48%	55%
44%	53%	34%	53%	72%	88%	72%	72%
45%	42%	23%	66%	91%	78%	94%	69%
52%	48%	25%	61%	100%	97%	87%	100%
56%	59%	40%	48%	61%	66%	63%	55%
50%	50%	50%	50%	66%	66%	69%	66%
61%	63%	56%	81%	53%	53%	63%	50%
41%	44%	50%	50%	53%	47%	50%	47%
19%	38%	13%	75%	75%	78%	81%	69%
50%	61%	40%	52%	41%	88%	38%	56%
63%	55%	53%	47%	59%	58%	61%	56%
47%	61%	53%	31%	81%	91%	75%	84%
50%	52%	44%	48%	90%	90%	72%	78%
44%	71%	33%	47%	94%	81%	74%	88%
47%	53%	41%	66%	77%	75%	78%	90%
65%	26%	65%	28%	78%	72%	72%	81%
44%	32%	53%	80%	54%	43%	63%	65%
45%	47%	63%	45%	97%	97%	88%	94%
61%	53%	63%	56%	78%	75%	63%	84%
55%	45%	42%	53%	81%	59%	83%	72%
74%	28%	50%	52%	90%	78%	87%	80%
34%	53%	56%	44%	55%	75%	69%	53%

Table A.14: The response rate of each subject in the second DL experiment

Consonant dichotic trial				Tone dichotic trial			
Real syllable		Non-syllable		Real syllable		Non-syllable	
Left	Right	Left	Right	Left	Right	Left	Right
100%	100%	100%	100%	96%	100%	96%	100%
100%	100%	100%	100%	100%	100%	96%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	96%	96%	92%	100%	92%	96%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	96%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
96%	100%	100%	100%	100%	100%	100%	100%
100%	92%	96%	96%	100%	100%	100%	100%
100%	100%	100%	100%	100%	92%	96%	96%
100%	100%	100%	100%	79%	79%	83%	79%
100%	100%	96%	96%	83%	96%	100%	96%
100%	96%	100%	100%	100%	96%	96%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
96%	100%	100%	92%	100%	100%	100%	100%
100%	100%	96%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	96%	100%	92%	100%	100%	96%	96%
100%	100%	100%	100%	100%	100%	100%	100%
92%	100%	96%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	92%	100%	96%	100%	100%	100%
92%	100%	92%	96%	100%	100%	100%	100%
100%	100%	96%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%	100%
100%	100%	96%	100%	100%	100%	100%	100%
100%	100%	92%	96%	100%	100%	100%	100%
100%	100%	100%	100%	71%	67%	79%	79%
100%	100%	100%	100%	100%	100%	100%	96%

Table A.15: The accuracy rate of each subject in the second DL experiment

Consonant	dichotic	trial		Tone	dichotic	trial	
Real	syllable	Non-	syllable	Real	syllable	Non-	syllable
Left	Right	Left	Right	Left	Right	Left	Right
54%	71%	79%	88%	78%	92%	91%	100%
21%	58%	46%	63%	79%	79%	78%	83%
88%	100%	100%	100%	100%	100%	100%	100%
17%	96%	4%	83%	73%	92%	64%	96%
29%	50%	38%	63%	88%	88%	67%	83%
92%	96%	92%	96%	92%	100%	100%	100%
54%	71%	70%	67%	83%	92%	83%	96%
58%	71%	71%	71%	88%	88%	96%	92%
61%	75%	71%	92%	88%	100%	96%	92%
38%	77%	35%	57%	50%	54%	54%	50%
88%	92%	88%	92%	92%	95%	83%	91%
38%	67%	8%	67%	37%	79%	70%	84%
38%	63%	57%	48%	30%	70%	50%	57%
100%	96%	92%	100%	100%	100%	96%	100%
54%	63%	63%	54%	96%	88%	100%	67%
71%	75%	75%	83%	83%	96%	100%	96%
87%	96%	79%	82%	92%	96%	100%	96%
38%	79%	65%	50%	58%	46%	67%	58%
83%	54%	92%	63%	96%	79%	88%	88%
46%	57%	21%	59%	33%	67%	30%	70%
63%	96%	75%	92%	92%	96%	96%	92%
55%	46%	87%	75%	79%	92%	75%	88%
42%	42%	38%	67%	67%	75%	54%	71%
83%	88%	82%	83%	83%	92%	83%	96%
36%	83%	59%	87%	79%	88%	96%	88%
50%	67%	61%	88%	88%	92%	92%	71%
71%	71%	75%	92%	75%	58%	75%	88%
67%	92%	74%	100%	88%	92%	96%	92%
50%	71%	50%	48%	88%	92%	96%	96%
42%	58%	50%	54%	41%	63%	26%	58%
29%	88%	21%	71%	83%	88%	88%	91%

Table A.16: The response rate of each subject in the word priming experiment

Real word conditions			Pseudo-word conditions		
Consonant priming	Tone priming	Non-priming	Consonant priming	Tone priming	Non-priming
100%	100%	100%	100%	100%	100%
100%	98%	100%	98%	100%	100%
98%	100%	98%	100%	98%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	98%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	98%	100%	100%	100%	97%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	98%	100%	98%
100%	100%	100%	100%	100%	98%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%
100%	100%	98%	100%	100%	100%
100%	98%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%

Table A.17: The accuracy rate of each subject in the word priming experiment

Real	word	conditions	Pseudo-	word	conditions
Consonant priming	Tone priming	Non-priming	Consonant priming	Tone priming	Non-priming
100%	100%	93%	98%	90%	100%
98%	97%	100%	93%	97%	93%
97%	100%	100%	98%	97%	97%
98%	100%	97%	100%	98%	95%
98%	97%	87%	98%	97%	93%
97%	98%	97%	100%	100%	98%
98%	97%	100%	97%	100%	93%
95%	98%	90%	100%	95%	100%
100%	98%	100%	98%	98%	100%
98%	97%	87%	100%	97%	100%
95%	95%	98%	97%	98%	95%
95%	100%	98%	100%	97%	100%
100%	98%	100%	97%	98%	95%
98%	100%	100%	95%	98%	100%
97%	97%	95%	100%	97%	97%
100%	97%	100%	95%	95%	97%
97%	100%	97%	100%	100%	97%
95%	100%	98%	100%	98%	93%
98%	100%	95%	100%	97%	100%
98%	100%	97%	100%	100%	100%
97%	97%	98%	95%	98%	90%
98%	95%	92%	95%	93%	95%
98%	98%	95%	97%	95%	95%
100%	98%	93%	100%	98%	92%
33%	95%	33%	92%	25%	97%
93%	100%	93%	100%	92%	98%
95%	92%	98%	95%	98%	97%
98%	100%	100%	98%	98%	95%
97%	98%	95%	98%	98%	97%
95%	100%	95%	85%	97%	92%
98%	97%	100%	97%	98%	98%

Table A.18: The reaction time and the priming effects of each subject in the word priming experiment (ms)

Real	word	conditions	Pseudo-	word	conditions
Consonant priming	Tone priming	Non-priming	Consonant priming	Tone priming	Non-priming
951.23	986.20	975.10	979.78	949.52	1017.60
896.18	888.80	906.52	983.80	1066.15	979.83
1186.49	1226.56	1160.49	1494.30	1524.08	1434.03
703.55	732.02	725.98	881.70	885.38	884.30
763.45	793.25	777.42	833.73	859.40	837.68
936.80	951.18	954.80	1032.68	1057.45	1020.13
1116.98	1076.08	1095.78	1144.46	1140.13	1140.15
725.93	745.42	739.05	779.72	803.47	803.03
816.50	834.73	832.22	906.77	905.08	878.33
860.50	953.13	878.42	942.77	944.38	935.57
850.67	899.90	876.97	1042.14	1075.23	1040.86
933.17	948.57	918.05	955.12	970.90	958.02
787.93	814.83	799.62	930.95	931.22	966.50
914.28	929.03	959.88	1145.48	1130.18	1041.58
759.82	763.90	755.92	827.52	831.90	835.05
869.52	889.42	879.23	1098.70	1090.72	1077.37
1223.03	1236.67	1140.37	1275.60	1255.87	1245.25
883.20	927.37	880.37	1045.13	1032.62	1070.10
933.65	917.55	917.15	1023.43	1013.38	1017.82
790.07	800.15	796.58	935.77	942.63	917.50
732.25	754.33	762.93	889.97	902.32	912.15
863.68	855.53	861.13	959.38	977.81	961.92
892.47	1004.33	1023.72	1193.80	1249.48	1171.19
828.82	876.90	847.32	978.85	1008.97	991.62
1339.37	1335.65	1392.58	1338.72	1346.20	1318.88
753.22	746.27	743.93	757.00	770.73	755.90
1010.57	988.42	1040.50	1157.35	1103.73	1103.20
907.97	950.42	923.23	1061.27	1040.30	1047.35
795.50	820.19	819.87	907.18	905.80	865.47
876.00	956.07	913.97	1061.34	1208.22	1037.22
866.37	876.50	845.93	959.47	969.70	990.38

Table A.19: The response rate and accuracy rate of each subject in the sentence semantic violation experiment

Response	rate		Accuracy	rate	
Consonant violation	Tone violation	Non-violation	Consonant violation	Tone violation	Non-violation
100%	100%	100%	87%	100%	92%
100%	100%	100%	93%	98%	92%
100%	100%	100%	95%	98%	98%
100%	100%	100%	90%	98%	92%
100%	100%	100%	95%	97%	97%
100%	100%	100%	93%	95%	97%
100%	100%	100%	97%	98%	93%
100%	100%	100%	93%	97%	98%
100%	100%	100%	92%	100%	93%
100%	100%	100%	87%	97%	95%
100%	100%	100%	95%	97%	95%
100%	100%	100%	92%	93%	95%
100%	100%	100%	90%	93%	95%
100%	100%	100%	87%	93%	92%
100%	100%	100%	97%	100%	97%
100%	100%	100%	92%	98%	95%
100%	100%	100%	92%	97%	92%
100%	100%	100%	90%	100%	95%
100%	100%	100%	95%	98%	92%
100%	100%	100%	92%	95%	95%
100%	100%	100%	88%	93%	93%
100%	100%	100%	88%	93%	95%
100%	100%	100%	97%	93%	90%
100%	100%	100%	93%	95%	95%
100%	100%	100%	88%	95%	92%
100%	100%	100%	93%	95%	97%
100%	100%	100%	93%	98%	97%
100%	100%	100%	95%	95%	88%
98%	100%	100%	97%	98%	95%

Table A.20: The reaction time of each subject in the sentence semantic violation experiment

Reaction	time	(ms)
Consonant violation	Tone violation	Non-violation
926.45	896.28	992.7
695.88	680.93	711.02
1338.13	1304.73	1318.8
687.08	663.02	652.5
897.28	874.42	849.55
964.82	881.7	978.83
750.13	740	803.88
957.05	872.47	872.18
823.18	778.97	707
1028.17	983.72	1023.88
863.55	829.63	803.93
616.9	607.6	536.18
851.47	899.7	852.73
1234.73	1136.52	1251.67
873.65	744.3	752.78
887.95	836.8	902.33
782.95	760.1	756.87
785.55	766.62	687.02
863.4	870.55	937.13
656.75	634.23	664.92
829.68	873.48	842.17
801.42	818.97	803.33
1009.05	919.13	971.3
706.3	666.62	657.57
735.78	721.87	735.77
891.08	894.57	752.33
959.82	872.87	827.48
589.92	553.32	593.88
1423.98	1213.45	1341.25

Table A.21: The 16 monosyllabic words used in the DL experiment under noisy conditions (adopted from [63])

Character	Pinyin	Tone	English
帆	fān	1	sail
烦	fán	2	annoy
反	fǎn	3	reverse
饭	fàn	4	meal
锅	guō	1	pan
国	guó	2	country
果	guǒ	3	fruit
过	guò	4	pass
灰	huī	1	gray
回	huí	2	return
毁	huǐ	3	destroy
会	huì	4	meeting
师	shī	1	teacher
十	shí	2	ten
史	shǐ	3	history
是	shì	4	right

□ **End of chapter.**

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