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English Vowel Production of Mandarin Speakers

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English Vowel Production of Mandarin Speakers

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Dedication

To my parents

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English Vowel Production of Mandarin Speakers

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This study examines acoustic characteristics of Mandarin and English vowels articulated by their native speakers. In addition, the acoustic properties of English vowel production from Mandarin subjects who speak English as a second language are investigated. There are twenty subjects from each language group. All the vowel productions are studied at the syllable level. First formant (F1) and second formant (F2) values of each Mandarin and English vowel are obtained and analyzed.

The acoustic distributions compared in this study are: (1) English vowel production from native speakers of English and Mandarin, and (2) Mandarin and English vowels from Mandarin speakers. The results suggest that there are crossover effects from Mandarin to English in English vowel data from Mandarin speakers. Generally speaking, for the English vowels that have Mandarin equivalents, their acoustic characteristics do not differ significantly from their Mandarin equivalents.

For the English vowels without Mandarin equivalents, the formant values of those vowels and their closest Mandarin equivalents most often do not differ either in F1 or F2. It was noteworthy that the acoustic distribution of English vowels from Mandarin subjects shows that Mandarin subjects do not distinguish English /ʊ/ from /u/ and /ɔ/ from /o/.

The aforementioned findings illustrate features of English spoken with a Mandarin accent. Through examining the properties of a Mandarin accent in English speech, the results of this study can assist ESL teachers or learners in knowing which English vowel pairs are difficult to contrast and serve as a reference on how to position their speech organs to approximate English vowel sounds. Furthermore, the results of this study can provide a basis for future clinical research on the accented English of Mandarin ESL learners and Mandarin speech disorder patients.

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Chapter 1: Introduction

The increasing use of English for communication in business, travel, or education has become important for people with different language backgrounds all over the world. Non-native speakers of English may easily be stigmatized because of their varying degrees of English language skills (Lindemann, 2005). This lack of fluency may result from interference from the sound system of their mother tongue (L1), leading to non-native pronunciation of their second language (L2), English (Best, 1994; Flege, 1995, 2003).

There have been various studies relating L2 language performance to the age of arrival in the L2-dominant country. The methodologies used by the studies have applied to L2 grammatical judgments (Birdsong & Molis, 2001; Johnson & Newport, 1989), perception and production of L2 sounds (Flege *et al.*, 1997), and accent in sentences read aloud (Flege *et al.*, 1999). Among all language skills, pronunciation accuracy seems to be the most difficult skill for L2 learners to achieve (Scovel, 1969). Pronunciation errors may easily occur in phoneme, stress, or intonation. This current study focuses on the English and Mandarin vowels produced by Taiwanese Mandarin speakers at the syllable level (CVC words or sound-sequences in English, and CVCV ones in Mandarin).

1.1 Research Questions and Project Overview

Despite years of studying English as a second language (ESL), Chinese speakers may still have problems pronouncing English vowels accurately. The aim of this project is to determine which English vowels Mandarin speakers do not easily distinguish, and to investigate whether there are crossover effects from their Mandarin to their English. The following questions guide this study:

A. What are the acoustic characteristics of spoken Mandarin vowels?

B. What are the acoustic characteristics of American English vowels as pronounced both by native American English speakers and by Mandarin speakers?

C. Are the vowels used by Mandarin speakers in speaking Mandarin and American English identical with respect to formant values?

To answer these questions, this study analyzed recordings of Mandarin and American English vowels as spoken by native speakers of each language, as well as American English vowels as spoken by native Mandarin speakers[1].

Voice recordings were made of twenty Taiwanese and twenty American students at The University of Texas at Austin (UT). The Taiwanese students spoke both English and Mandarin, while the American students spoke only English. In each case, the speakers were given short words to pronounce (CVC words or sound-sequences in English, and CVCV ones in Mandarin). The first formant (F1) and

[1] In addition, a survey was conducted to evaluate Mandarin speakers' self-perception of their language use in Mandarin and American English (see Appendix A).

second formant (F2) values were obtained for each target Mandarin and English vowel. For the Mandarin words or sound-sequences, the vowel in question is the one in the first syllable. Generally speaking, F1 and F2 values are related to tongue elevation and tongue advancement respectively (Borden *et al*. 2003; Pickett, 1999). The articulatory features of each vowel are observed through formant values. By comparing the articulatory features of vowels from Mandarin and English speakers, the patterns of acoustic distribution for each English vowel phoneme as produced by native speakers of English could serve as references for analyzing the accented English vowel phonemes of Mandarin speakers and further assist Mandarin speakers to adjust their articulations.

1.2 Further Significance of the Work

This study, which explores the results of comparing the English and Mandarin vowel qualities produced by Mandarin speakers, should be able to contribute to the following fields: ESL teaching and learning, speech disorders, and Second Language Acquisition. Teaching or learning Mandarin or English as a second language can be greatly improved by considering the results of this study, which examines the acoustic properties of vowels. These acoustic properties are important because they characterize the physical movement inside the vocal tract (Peterson & Barney, 1952; Lindblom & Sundberg, 1971; Pickett, 1999). Furthermore, data from this study are relevant to speech pathologists. Phonetic descriptions of English vowels from normal Mandarin speakers should be differentiated from Mandarin ESL patients suffering

from speech disorders. The phonetic inaccuracies of English vowels from normal Mandarin speakers can be compared with the phonetic features of Mandarin ESL speakers with speech disorders by speech language pathologists (Chen *et al*., 2001; Langdon, 1999). In addition, the results of this study can be used to test some hypotheses in the field of Second Language Acquisition. All these fields are vital for study because of the onslaught of globalization, with more and more Mandarin speakers needing to learn English for business or education.

Through analyzing the phonetic distribution of Mandarin and English vowels, this author hopes that the results of this study will shed light on the reasons why non-native speakers of English might continue to carry the non-native accent after many years of living in an English-speaking country.

Chapter 2: Literature Review

This section describes literature relevant to the research aims of this dissertation. It is organized into four sub-sections: (1) L2 pronunciation accuracy, (2) English as a second language for Mandarin speakers, (3) English and Mandarin vowels, and (4) postulates and hypotheses for this study.

2.1 L2 Pronunciation Accuracy

Children are generally thought to be better L2 learners than adults. Scovel (1969), basing his observations on the critical period hypothesis (Lenneberg, 1967), proposed that children have the ability to completely acquire their L2 whereas adults only acquire an L2 incompletely. Various individual differences have been investigated to explain why some L2 learners are more successful in pronunciation accuracy than other L2 learners. These have included motivation, attitude, gender, the relative extent of L1 and L2 use, degree of field independence, degree of right hemispheric specialization in relation to accurate pronunciation, age of learning L2, age of arrival in the target language area, and the length of residence in a place where the target language is spoken (Elliott, 1995; Munro, 1993; Piske *et al*., 2001; Flege *et al*., 1997). Other studies have sought to determine the likelihood of having a minimal accent with reference to the sound systems of L1 and L2 (McAllister *et al*., 2002; Riney & Flege, 1998; Major, 1987). Flege *et al*. (1997) mention that attaining native-like pronunciation accuracy for L2 learners may be constrained by the length of time

spent using L2, L2 learners' psychological factors, the influence of other language learners with non-native accents, and assimilation and dissimilation of L2 sounds to or from L1 sounds. All these factors may create difficulties in the perception and production of native-like L2 sounds, especially when the L2 sounds do not exist in the L2 learners' L1 sound system. The difficulties that L2 learners face determine whether they acquire L2 sound signals as meaningfully and accurately, and deliver them as informatively, as native speakers of L2.

Best's (1994) perceptual assimilation model (PAM) and Flege's (1995) speech-learning model (SLM) take the similarity of L1 and L2 sounds into account, revealing the difficulties that L2 learners might encounter and further predicting the sound assimilation patterns that L2 learners might have. Best's (1994) premise is based on whether or not L2 learners can perceive the articulatory gestures in the speech signal. L2 learners fail to catch the discrepancies between similar L1 and L2 sounds if they cannot perceive the articulatory activity producing these sounds. Best (1994) lists four types of perceptual assimilations based on the relationship of gestural properties between learners' L1 and their L2:

A. Two Categories: two "gesturally similar" non-native phonemes are assimilated to two different native phonemes.

B. Single Category: two non-native categories of sound are assimilated to one native category of sound either well or poorly.

C. Category Goodness: two similar non-native phonemes are assimilated to the same single native phoneme, although one is more similar to the native phoneme than the other.

D. Nonassimilable: the gesture properties of a non-native sound category are not assimilated to any native sounds.

Whether L2 learners can successfully contrast non-native phonemes perceptually depends on how well the articulator gestures of non-native phonemes are perceived by L2 learners. The four assimilation patterns in Best's PAM (1994) reflect the two essential difficulties that L2 learners encounter. First, L2 learners often face difficulties in correctly perceiving the articulator gestures of non-native phonemes. Second, the difficulties of forming the speech-sounds of non-native phonemes in their existing sound system result in assimilating non-native phonemes perceptually to either native phonemes or unrecognizable sounds.

Flege's SLM model (1995) suggests one further difficulty—the one that L2 learners encounter in contrasting non-native phonemes. The difficulty of distinguishing L2 speech sounds from the closest L1 sounds is caused by failing to recognize phonetic differences between the two (Best, 1994; Flege, 1995, 2003). Failing to recognize phonetic differences between L2 speech sounds and their closest L1 sounds may result from the L2 learners' L1 phonology. L2 learners are not able to differentiate L2 sound pairs or the sound pairs between L1 and L2 and assimilate to "Single Category" (Best, 1994) because the existing phonology of L1 filters out the important features of L2 sounds that distinguish them from those of L1 and from other L2 sounds (Flege, 1995, 2003).

This dissertation builds on such earlier studies and investigates the degree of similarities between Mandarin and English vowels from speakers of Mandarin and determines if there is interference from Mandarin to English for non-native English speakers from Taiwan. The comparison of the distribution of acoustic properties of subjects' Mandarin and English phonemes predicts the problems of their Mandarin accent in English. Moreover, the results from comparing the acoustic distribution of English vowel phonemes of native speakers of English and speakers from Taiwan should provide information to help Mandarin speakers who speak English as a second language.

2.2 English as a Second Language for Mandarin Speakers

Mandarin speakers who speak English as a second language show some inaccuracies in their English pronunciation (Chen *et al.*, 2001; Flege *et al.*, 1997; H. Wang & van Heuven, 2003; X. Wang & Munro, 1998). Flege *et al*. (1997) investigate how twenty Mandarin subjects' speech production of English /i/, /ɪ/, /ɛ/, and /æ/ are perceived by native speakers of English. For Mandarin subjects who have lived in the U.S. for over the study average of five years, Mandarin subjects' English /ɛ/ is identified as /æ/ and /eˈ/ 27 and 29 percent of the time, respectively, and their English /æ/ is identified as /ɛ/ 23 percent of the time. Mandarin subjects' English /i/ is identified as /ɪ/ 16 percent of the time. Mandarin subjects' English /ɪ/ is identified as /i/ 6 percent of the time. Chen *et al*. (2001) investigate eleven English vowels

produced by forty subjects from mainland China. Chen *et al*. (2001) hypothesize that Mandarin subjects' English vowel production differs significantly from that of native speakers of English for the English vowels which do not exist in Mandarin. According to their definition (Chen *et al*., 2001), these vowels, /ɪ/, /ɛ/, /æ/, /ʌ/, /ʊ/, and /ɔ/, do not exist in Mandarin. The studies of neither Chen *et al*. (2001) nor Flege *et al*. (1997) investigate the relationship between the acoustic properties of Mandarin and English. Therefore, the extent of the interference from Mandarin speakers' first language upon their second language is unknown.

Wang (1997) and Wang and Munro (1998) investigated the English vowel production of fifteen Mandarin speakers from Beijing. They found that Mandarin subjects' English /ɪ/, /ɛ/, /æ/, and /ʊ/ were less well identified by four native speakers of English than these same vowels produced by other native speakers of English, suggesting a relationship between Beijing Mandarin subjects' Mandarin vowel production and their English vowel production, regardless of whether the English vowels had Mandarin equivalents. Wang (1997) analyzed the relationship between the vowel production in Mandarin subjects' L1 and L2. However, as was indicated in discussing the limitations of Wang's study, when comparing the vowels in Mandarin and English, the ideal situation is for the tested Mandarin and English vowels to be within the same syllable structure and surrounding sound context. In Wang's study (1997), Mandarin and English vowels were studied only in isolation. Nevertheless, English vowels are seldom pronounced in isolation in natural speech. The current

study includes multiple tokens for each tested vowel and places the vowels in similar syllable structures and between similar surrounding sounds in Mandarin and English. The details of the approximation of the syllable structures and surrounding sounds are discussed in Sections 2.3.2 and 3.2.2.

2.3 Research Languages in this Study

The acoustic properties of English and Mandarin vowels are presented in order to serve as background information for the discussion section.

2.3.1 English

General American English vowels are used for this study; these vowels include ten English monophthongs /i, ɪ, ɛ, æ, ʌ, ɝ, ɑ, ɔ, ʊ, u/ and five diphthongs /aɪ, aʊ, ɔɪ, eɪ, oʊ/ (Ladefoged, 2001, p. 27). These international phonetic symbols represent the underlying forms of English vowels used in this study.

2.3.1.1 English Accent

Sounds are highly influenced by their context. This study deals with English vowels placed within a restricted /hVd/ context to reduce variation in the same vowel in different contexts, as in studies conducted by Peterson and Barney (1952) and Yang (1996). The native speakers of English for this current study are from Texas. English-speaking subjects were sought from Texas because the Mandarin subjects in this study had lived in Texas for at least two years at the time of the recording. People from

Texas are known for their southern accent. The distinct features of a southern accent[2] can be discerned in the vowels /ɪu/, /æɪ/, /ʊɪ/, /oɪ/, as in the words "tune," "pat," "fluid," and "poet." These diphthongs are not used in this study because the emphasis of this study is not on the southern English dialect of the U.S. Rather, this study focuses on the pronunciation features of Texan English that are shared with "Standard American English" spoken in the U.S., which is defined as a pronunciation of American English relatively lacking in regional characteristics (Wolfram & Schilling-Estes, 2006, p. 406). Both southern American English and "Standard American English" have the ten monophthongs /i, ɪ, ɛ, æ, ʌ, ɝ, ɑ, ɔ, ʊ, u/ and five diphthongs /aɪ, aʊ, ɔɪ, eɪ, oʊ/, and these vowels are used in this study.

Even though this study tries to minimize the variations of vowels in the same context, it is unavoidable that speech production varies with speakers' age, gender, and speaking style (Lindblom, 1990). Two of the possible phonetic realizations of each of the English words "heed," "hid," "hayed," "head," "had," "Hudd," "herd," "hod," "hawed," "hoed," "hood," "who'd," "hide," "how'd" and "hoid" from Texans are listed blow:

[2] The information is from Dr. Gary Underwood's handout, "Accents of American English: The Southern Accent."

Table 2.1: Possible phonetic realizations of the English words used in this study.

Word	Phoneme	Phonetic Realization (I)	Phonetic Realization (II)
heed	/hid/	[hid]	[hᵊɪd]
hid	/hɪd/	[hɪd]	[hɪᵊd]
hayed	/heɪd/	[heɪd]	[hæᴵd]
head	/hɛd/	[hɛd]	[hɛᵊd]
had	/hæd/	[hæd]	[hæᵋd]
Hudd	/hʌd/	[hʌd]	[həːd]
herd	/hɜˑd/	[hɜˑd]	[hrd]
hod	/hɑd/	[hɑd]	[hɒd]
hawed	/hɔd/	[hɔd]	[hɔˈːd]
hoed	/hoʊd/	[hoʊd]	[həʊʷd]
hood	/hʊd//	[hʊd]	[hɜːd]
who'd	/hud/	[hud]	[həwd]
hide	/haɪd/	[haɪd]	[hæːⁱd]
how'd	/haʊd/	[haʊd]	[hæːᵊdɪ]
hoid[3]	/hɔɪd/	[hɔɪd]	[ə́hɔːɪd]

[3] "Hoid" is a nonsense word.

Wolfram and Schilling-Estes (2006, p. 79) state that the vowels /ɑ/ and /ɔ/ merge in words such as “caught” and “cot” in many parts of the United Sates, and that this merger is spreading quickly. The data from participants who do not differentiate “hod” and “hawed” are not included in this study. For ease of comparison between speakers of English and Mandarin, only those participants who self-reported that they pronounce /ɑ/ and /ɔ/ as in “hod” and “hawed” differently are included in this study.

Speaker and regional differences have indeed been shown to exist. For example, Appendix C contains a comparison of the acoustic distributions for English vowels from Peterson and Barney (1952) and from this current study to give a sense of the variation among English speakers from Texas and from different regions of the U.S. Peterson and Barney’s subjects are from different regions of the United States and a few of them speak English as their second language.

2.3.1.2 English Vowel Quality

The qualities of vowels are usually described by their tongue height (tongue elevation), the position of the horizontal part of the tongue (front or back), and the degree of lip-rounding. Peterson and Barney (1952) describe the acoustic properties of eleven English vowels within the /hVd/ context from 33 men, 28 women and 15 children. They found that ranges of sounds within a vowel phoneme are highly correlated to the frequencies of the first and second formants. The definition of formant is “a resonance of the vocal tract” and the formant frequencies of the vocal

tract can be estimated by examining the peaks of the spectrum (Pickett, 1999, p. 23). Formants are numbered in order of their frequencies, from lowest to highest. The size and shape of the oral-pharyngeal resonating cavities vary with different positions as the lips, tongue, jaw and pharynx articulate different sounds (Borden *et al.*, 2003; Pickett, 1999).

The frequency of F1 is related to oral and pharyngeal constrictions (Borden *et al.*, 2003; Pickett, 1999). Frequency of F1 is also related to tongue elevation. The more open the aperture of the mouth or the more constricted the pharynx, the higher the frequency of F1. The frequency of F2 is related to tongue advancement (the length of the front cavity). F2 values are raised by a front tongue constriction or are lowered by a back tongue constriction (Borden *et al*., 2003; Pickett, 1999). Lip-rounding lowers all formant frequencies because it lengthens the lip passage (Fant, 1973; Kent & Read, 2002; Pickett, 1999).

Through examining the acoustic properties of the vocal tract (*i.e*., F1 and F2 values) for each English vowel category from native and non-native speakers of English, the patterns of acoustic distribution from native speakers of English could serve as references for analyzing the realizations of vowels in the accented English of non-native speakers in this current study and assist non-native speakers to adjust their speech organs.

2.3.2 Mandarin

Mandarin is an official language in Taiwan, and Taiwanese Mandarin is based on the Beijing dialect. The Mandarin subjects in this study acquired the Southern Min or Hokkien dialect as their first language before they acquired Mandarin. After years of schooling, people in Taiwan can speak Mandarin just as well as native speakers of Mandarin, regardless of their first language. The Mandarin spoken in Taiwan deviates from the Beijing Mandarin spoken in mainland China in terms of phonemes, stress, tone, etc., as revealed in the speech of twelve newscasters from mainland China and Taiwan (C.-C. Tseng, 1999). In view of the variations of Beijing Mandarin between these two different regions, mainland China and Taiwan, subjects for this current study were sought only from Taiwan, rather than from both regions, as was done in the study conducted by Flege *et al*. (1997).

Students in Taiwan learn the Mandarin Phonetic Symbols 1 (MPS 1) published by the Minister of Education in Taiwan (see Appendix B for the MPS 1) before they start to learn Mandarin characters. The MPS 1, commonly known as “bo po mo”, is taught as early as kindergarten or the first grade in Taiwan. It is also a phonetic writing system for foreigners learning Mandarin. People educated in Taiwan are able to transcribe Mandarin characters into the MPS 1. It is also possible for them to pronounce the possible combinations of sounds in the MPS 1 if the combination is permitted in the language, *i.e.*, if it forms a syllable or syllables following a standard (C)V pattern.

There has been a lack of consensus about the Mandarin vowel inventory. The number of the vowels in Mandarin varies from study to study (Chao, 1968; Cheng, 1973; Dow, 1972; Howie, 1976; Li & Thompson, 1981; and C.-Y. Tseng, 1990). For example, Cheng (1973) claims that there are six vowel categories, /i/, /y/, /ɨ/, /ɤ/, /ɑ/, and /u/. Tseng (1990) maintains that the vowel phonemes in Mandarin are /i/, /y/, /ɛ/, /a/, /u/, /ɯ/, /ɔ/, and /ɤ/. Howie (1976) states that Mandarin has six vowels /i/, /y/, /ə/, /ɑ/, /r/, and /u/. /ɪ/ is an allophone of /i/ when in a certain context; so too /ʊ/ is an allophone of /u/; /ɛ/ and /o/ are the allophones of /ə/; /æ/ is an allophone of /ɑ/. If Mandarin has the same acoustic properties for /ɪ/, /ʊ/, /ɛ/, and /æ/ as English has, there should be no problems for Mandarin speakers in recognizing and producing English /ɪ/, /ʊ/, /ɛ/, and /æ/. However, studies do not show this to be the case (Chen *et al.*, 2001; Flege *et al*., 1997; H. Wang & van Heuven, 2003; X. Wang & Munro, 1998). Whether the acoustic properties of Mandarin /ɪ/, /ʊ/, /ɛ/, and /æ/ are the same as those in English needs to be further investigated.

The Mandarin monophthongs and Mandarin diphthongs used in this study are taken from the monophthongs and diphthongs listed in the MPS 1 as finals and double finals, respectively. These seven finals are ㄧ, ㄩ, ㄝ, ㄜ, ㄨ, ㄛ and ㄚ and are represented by /i, y, e, ə, u, o, a/, respectively. There are four double finals in the MPS 1. They are ㄞ, ㄠ, ㄟ, and ㄡ represented by /ai, au, ei, ou/, respectively. The

phonetic symbol /e/ is used to represent the Mandarin phonetic symbol ㄝ because the F1 and F2 values of Mandarin ㄝ are more similar to English /e/ than the English vowels /ɛ/ and /æ/ as pronounced by the native speakers of English in this study. The aforementioned underlying forms of Mandarin monophthongs and diphthongs are used in this study.

Mandarin is a tonal language that has four lexical tones and one neutral tone. The basic syllable structure of Mandarin is (C)V with a tone (C.-Y. Tseng, 1990). Therefore, in order to approximate the frame of the syllable structure of English test words in this study, CVC, the Mandarin subjects were asked to read a list of Mandarin vowels put in a CV context—/hV/—followed by the syllable /də/ with a neutral tone to form a syllable structure of CVCV. /də/, 的, is a Mandarin possessive and adjective marker; it is one of the most frequently spoken syllables in Mandarin.

2.3.3 L1 and L2 Definitions for this Study

The research languages in this study are Mandarin and English. As mentioned in Section 2.3.2, Mandarin is an official language in Taiwan. The Mandarin subjects in this study acquired, like three-quarters of the population of Taiwan (Huang, 1995), the Southern Min or Hokkien dialect as their first language before they acquired Mandarin. The Mandarin proficiency of educated people in Taiwan is essentially identical to that of native speakers of Mandarin in Taiwan after years of schooling. Because the research language in this study is Mandarin, the Mandarin of subjects

from Taiwan is regarded as their L1, regardless of the fact that their native language was Hokkien; and their later-learned language, English, is considered their L2.

Table 2.2: The proportion of different ethnic groups in Taiwan (Huang, 1995).

Ethnicity	Percentage	Language
Aborigines	1.7	Malayo-Polynesian
Hakka	12	Hakka
Mainland Chinese	13	Mandarin
Southern-Ming	73.3	Southern-Ming (Hokkien, Min-nan yu, or Hoklo)

Area: 36,000 square kilometers. Population: about 22,750,000[4].

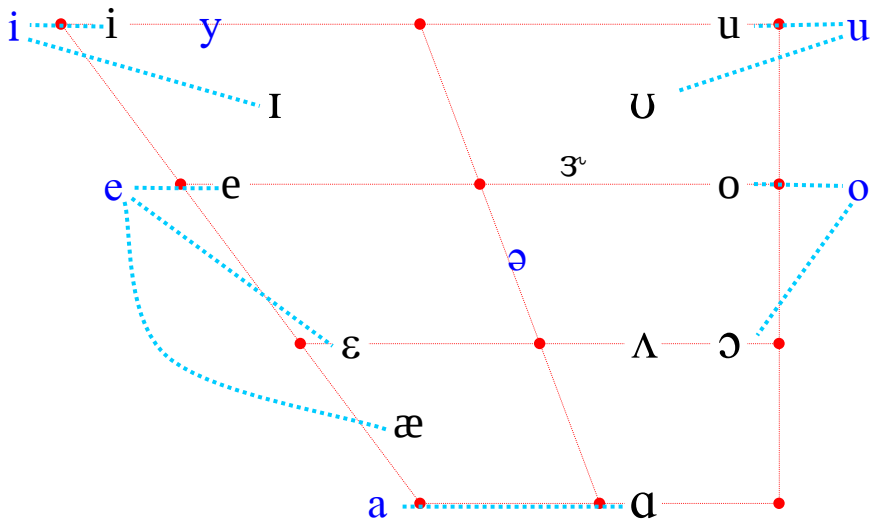
[4] Government Information Office, Taiwan. (2005). Taiwan at a Glance 2005-2006. Retrieved March 26, 2006, from http://www.gio.gov.tw/taiwan-website/5-gp/glance/index.htm.

2.4 Postulates and Hypotheses for this Study

Because the number of Mandarin vowels varies from study to study, and because the acoustic properties of Mandarin and English vowels may or may not be identical, there are two postulates that must be established before making further hypotheses. The following two postulates contribute to a number of hypotheses that this dissertation pursues.

2.4.1 Postulates

Based on the articulatory features (i.e., height, frontness vs. backness, and presence or absence of lip-rounding) that distinguish different vowels (Pullum & Ladusaw, 1996), the first postulate is that /i/, /e/, /u/, /o/ and /a/ or /ɑ/ exist in both Mandarin and English. The second postulate is that Mandarin /i/ is the closest phoneme to English /i/ and /ɪ/; Mandarin /u/ is the closest phoneme to English /u/ and /ʊ/; Mandarin /e/ is the closest phoneme to English /e/, /ɛ/ and (though this seems counterintuitive) /æ/; Mandarin /o/ is the closest phoneme to English /o/ and English /ɔ/; and Mandarin /a/ is the closest phoneme to English /ɑ/ (see Figure 2.1).



Blue: Mandarin; Black: English.

Figure 2.1: English and Mandarin vowels used in this study.[5]

[5] The IPA symbols do not reflect the real formant values of Mandarin and English vowels. The IPA symbols are arranged for ease of expressing hypotheses throughout the discussion.

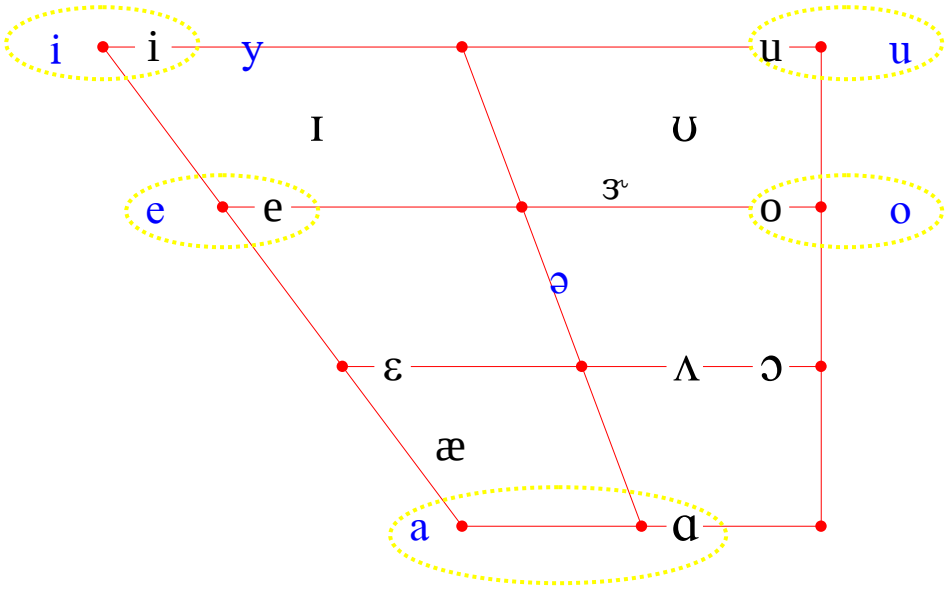
2.4.2 Hypotheses

The general background information for the hypotheses in this study is as follows. Flege (1995, 2003) states that the L1 sound system interferes with the L2 sound system in that the L1 phonology filters out important features of L2 sounds, making distinguishing between L1 and L2 versions of sounds or between similar but different L2 sounds difficult. Category assimilation occurs when L2 learners fail to perceive phonetic differences between L2 speech sounds and the closest L1 sounds before L2 learners form the non-native sound category (Best 1994; Flege, 1995, 2003). Furthermore, as stated in Flege (1995), a common view about the assimilation of L1 and L2 sounds is that when L2 sounds are "identified" as L1 sounds, they will be replaced by L1 sounds even though the L1 and L2 sounds are phonetically different.

2.4.2.1 Hypothesis 1: Vowels Existing in Mandarin and English

For the vowels existing both in Mandarin and English, Mandarin subjects identify them as Mandarin vowels because of constraints from their L1 phonology, or because the vowels existing in both Mandarin and English are indeed acoustically similar or identical. The way Mandarin subjects identify vowels existing in both Mandarin and English may be reflected in their vowel speech production. Therefore, to Mandarin speakers, the acoustic characteristics of vowels existing in both Mandarin and English are acoustically similar. For example, the acoustic properties of the

English vowels /i, e, ɑ, o, u/ are similar to those of the Mandarin vowels /i, e, a, o, u/, respectively, articulated by Mandarin speakers (see Figure 2.2).

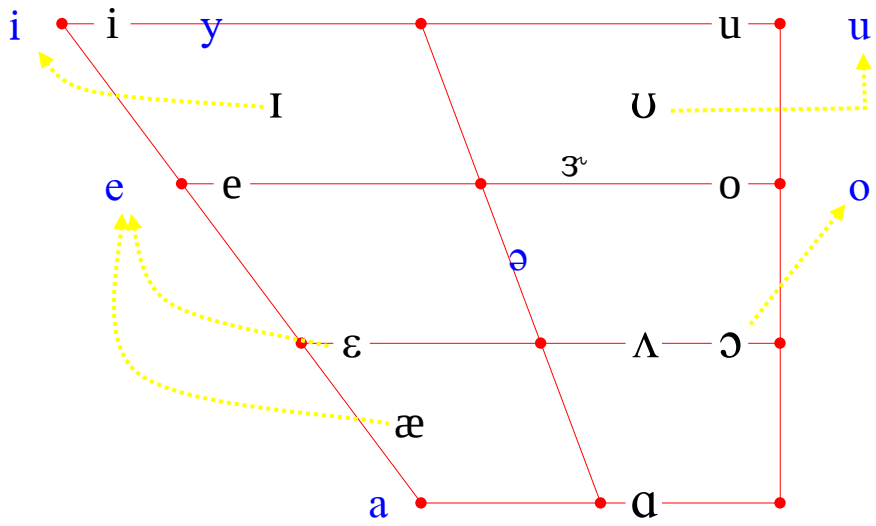


Blue: Mandarin; Black: English.

Figure 2.2: Vowels existing in both English and Mandarin used in this study.

2.4.2.2 Hypothesis 2: English Vowels without Mandarin Equivalents

For the English vowels not existing in Mandarin, Mandarin subjects identify those English vowels with their closest L1 sounds because of the difficulty of perceiving phonetic differences between L2 speech sounds and the L1 sounds closest to them (Best 1994; Flege, 1995, 2003). This kind of difficulty may result in assimilating native and non-native phonemes acoustically or perceptually. Therefore, for Mandarin speakers, English vowels which do not exist in Mandarin are replaced with their closest Mandarin equivalents. For example, the acoustic properties of English /ɪ/ are similar, but not identical, to those of Mandarin /i/, as are those of English /ɛ/ and Mandarin /e/, English /æ/ and Mandarin /e/, English /ʊ/ and Mandarin /u/, and English /ɔ/ and Mandarin /o/ (see Figure 2.3).

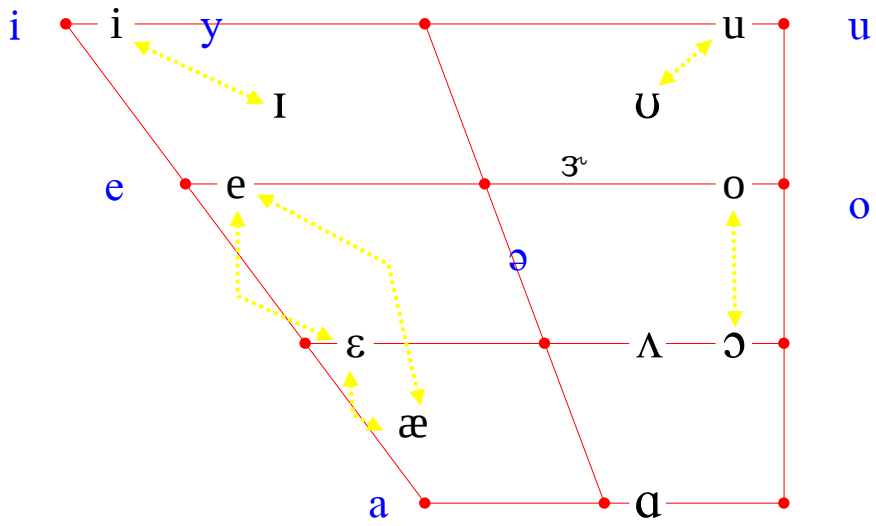


Blue: Mandarin; Black: English.

Figure 2.3: English vowels as articulated by Mandarin speakers.

2.4.2.3 Hypothesis 3: Contrasting Similar English Vowels

The L1 phonology filters out important features of L2 sounds, which makes distinguishing between certain pairs of L2 sounds difficult (Flege, 1995, 2003). Therefore, Mandarin subjects' articulation of English /ɪ/ is equivalent to that of their English /i/, despite native English speakers' ability to differentiate between them. For Mandarin speakers, the acoustic characteristics of English /i/ and /ɪ/ are equivalent. The same is true for English /e/ and English /ɛ/, English /e/ and English /æ/, English /ɛ/ and English /æ/, English /ʊ/ and English /u/, and English /ɔ/ and English /o/ (see Figure 2.4).

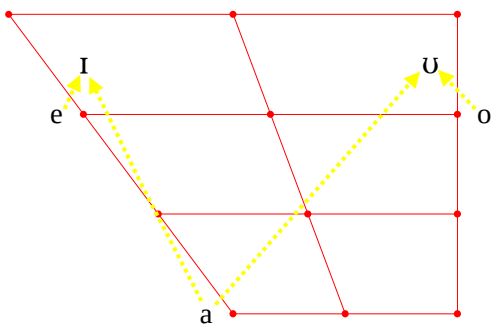


Blue: Mandarin; Black: English.

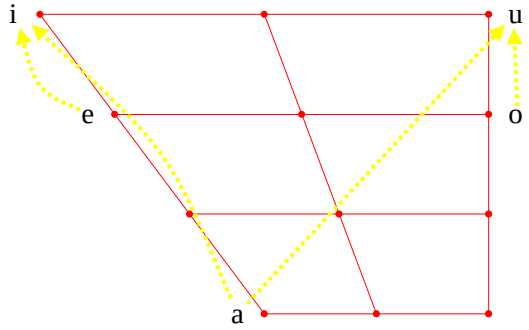
Figure 2.4: Pairs of similar English vowels that Mandarin speakers might have problems with.

2.4.2.4 Hypothesis 4: Similar Diphthongs Existing in Mandarin and English

For Mandarin speakers in this study, the acoustic characteristics of English diphthongs seem equivalent to those of Mandarin diphthongs because their L1 phonology may filter out the important features of L2 sounds that help to differentiate between those of L1 and L2 or between pairs of L2 sounds (Flege 1995, 2003). The way Mandarin subjects identify Mandarin and English diphthongs is reflected in their diphthong production. Therefore, Mandarin subjects' English diphthong production is like their Mandarin diphthong production. For example, the acoustic properties of the English diphthongs /aɪ, aʊ, eɪ, oʊ/ produced by Mandarin subjects are similar to those of Mandarin /ai, au, ei, ou/, respectively (see Figure 2.5).



English diphthongs: /aɪ/, /aʊ/, /eɪ/, and /oʊ/.



Mandarin diphthongs: /ai/, /au/, /ei/, and /ou/.

Figure 2.5: English and Mandarin diphthongs used in this study.

Chapter 3: Methodology

3.1 Subjects

Data were collected from two groups of students at UT. The first group of Mandarin subjects consisted of ten male and ten female graduate students at UT who grew up in Taiwan. These Mandarin subjects had resided in the U.S. continuously for at least two years at the time of recording. They had all received their education, from elementary school to university, in Taiwan (see Appendix D for their language background information). The second group of subjects consisted of ten male and ten female native speakers of English, all of whom were either graduate or undergraduate students at UT. The American subjects all grew up in Texas. None of the subjects had a hearing or speech disorder.

3.2 Materials

The research materials are Mandarin vowels collected from native speakers of Mandarin and English vowels from native speakers of Mandarin and native speakers of English.

3.2.1. English Vowels

To evaluate the acoustic characteristics of vowels in English, ten male and ten female Taiwanese Mandarin subjects and ten male and ten female native speakers of

American English were asked to read a series of /hVd/ syllables with one of ten English monophthongs /i, ɪ, ɛ, æ, ʌ, ɝ, ɑ, ɔ, ʊ, u/, or one of five diphthongs /aɪ, aʊ, ɔɪ, eɪ, oʊ/ in the middle. Each combination appeared on the list five times (see Appendix E). The English word lists in Appendix E were recorded both by L1-Mandarin and L1-English speakers. The symbols next to each word were to remind Mandarin subjects of the pronunciation of the English word. The Mandarin subjects had learned to pronounce those symbols early in their study of English. The intended vowels are constrained in the context of /hVd/. For example, an English vowel, /u/, is put in /hVd/ and creates a syllable, /hud/. Thus: heed, hid, head, had, hod, hawed, Hudd, herd, who'd, hood, hayed, hoed, hide, how'd and hoid. The fifteen American English monophthongs and diphthongs were chosen based on commonly used American English vowels (Ladefoged, 2001, p. 27). A list of 75 English words was ordered randomly for the Mandarin and English subjects to read (15 English words * 5 repetitions = 75 tokens). The English speakers served as a control group.

3.2.2 Mandarin Vowels

Mandarin does not have a /hVd/ syllable structure like English. The basic syllable structure of Mandarin is (C)V. To approximate the frame of the syllable structure of the English test words, CVC, the Mandarin subjects were asked to read a list of Mandarin vowels put in the CV context /hV/ followed by a second CV

combination, /də/ with a neutral tone, to form a syllable structure of CVCV. For example, /u/ is put in /hV /to form /hu/ and followed by a Mandarin character, 的, /də/, whose syllable structure is CV. /də/ is always preceded by /hV/ in all the Mandarin test syllable combinations in this study. /də/ is a Mandarin possessive and adjective marker. The syllable combinations consist of all /hV/ possibilities with all four lexical tones followed by /də/ may or may not be meaningful in Mandarin.

There are no Mandarin characters to represent the /hV/ syllables which are not meaningful in Mandarin. In these cases, the MPS 1 is used for the /hV/ syllable that has no corresponding Mandarin character. As mentioned in Chapter 2, the MPS 1 is taught as early as kindergarten or first grade in Taiwan. People educated in Taiwan are able to pronounce any possible combination of sounds shown in the MPS 1 if the combination is permitted in the language, *i.e.*, if it forms a syllable or syllables following a standard (C)V pattern.

Mandarin monophthongs /i, y, e, ə, u, o, a/ and Mandarin diphthongs /ai, au, ei, ou/ are used in this study. Each is preceded by /h/, combined with each of the four tones and followed by /də/ with a neutral tone. The Mandarin test phrases are illustrated in Table 3.1 (see Appendix F for the full list of test vowels, syllables, and MPS 1). Twenty Mandarin subjects were asked to read a list of /hVdə/ syllable combinations, containing Mandarin monophthongs and diphthongs each in each of the

four lexical tones five times (11 Mandarin vowels * 4 tones * 5 repetitions = 220 tokens).

Table 3.1: Illustration of Mandarin phrases and phonetic symbols used in this study.

	/hə/	**/hədə/**
Tone	**Mandarin Phonetic Symbols**	**Mandarin Test Phrases**
A: Tone 1	ㄏㄜ	喝 的
B: Tone 2	ㄏㄧㄜ	河 的
C: Tone 3	ㄏㄨㄜ	ㄏㄨㄜ 的
D: Tone 4	ㄏㄟㄜ	賀 的

The first element in the right-hand column of Row A shows the character used for the first syllable of /hədə/ in Tone 1. The phrase may be translated as “related to drinking.” Row B contains the characters used for /hədə/ with /hə/ in Tone 2. The phrase may be translated as “river’s.” Row C contains the MPS 1 symbols for /hə/ in Tone 3, as /hədə/ with /hə/ in Tone 3 has no meaning in Mandarin. Row D contains the characters used for /hədə/ with /hə/ in Tone 4. Although there is again a character combination in Row D, this combination has no meaningful translation.

3.3 Recording

Recording was done in a soundproofed room in the Phonetics Laboratory in the Department of Linguistics at UT. The subjects wore head-mounted microphones. Speech signals were recorded onto a laptop computer, at a 22-kHz sampling rate, using the PCquirer software package.

Both the Mandarin characters and the English words were presented randomly and listed separately on several pieces of paper. There were 220 Mandarin test phrases (including some meaningless character combinations) and 75 English test words. Ten words were listed on each page of the paper except for the last page of English test words which contained only five. The twenty Mandarin subjects read both the English and the Mandarin test words. The twenty native speakers of English read the English test words only. Before recording, all subjects were given a short warm-up session. All subjects were instructed to read the test words clearly and at a rate that they felt to be reasonably normal. In view of the size of the list, subjects were allowed to self-correct in the event of slips of the tongue or misreading.

3.4 Measurement

3.4.1 Selection of Analyzed Words

Each English and Mandarin monophthong and diphthong was read five times. Three readings of each vowel were selected for analysis, with selection starting with the ninth word of the list of 75 randomized English words that each subject read, and with the sixth test phrase of the list of 220 randomized Mandarin phrases.

3.4.2 Definition of Duration

The vowel onset was assigned at the point where the steady state of formant bars of the vowel began on the spectrogram and at the visually determined midpoint of the first identified cycle of the vowel in the waveform. The vowel offset was assigned at the point where the formant bars ended. The midpoint of the last identified cycle in the waveform before the offset of the vowel was visually determined by inspection of the waveform. If there were problems when using spectrograms in conjunction with waveforms, as some segments do not have clear ends, the offset of the vowel was determined from the spectrogram.

3.4.3 Measurements of F1 and F2 in Monophthongs

For the Mandarin and English monophthongs, once the duration of the target vowel was decided, it was divided into eight parts (Figure 3.1). The F1 and F2 of each

vowel were measured at the first (A), second (B), third (C), fourth (D), and fifth (E) points as shown. While formant values are provided directly from the output of the formant tracking by the PCquirer acoustic analysis software, wide band spectrograms for each vowel were visually examined at the same time. When spurious formant values came up, the formant values were visually determined from the spectrogram. Initial inspection of the spectrograms revealed stability around Point B and the stability was furthered validated by a repeated measures statistical analysis of a subset of the data. Values from Point B were designated as the measuring point for the remaining monophthongs of the study.

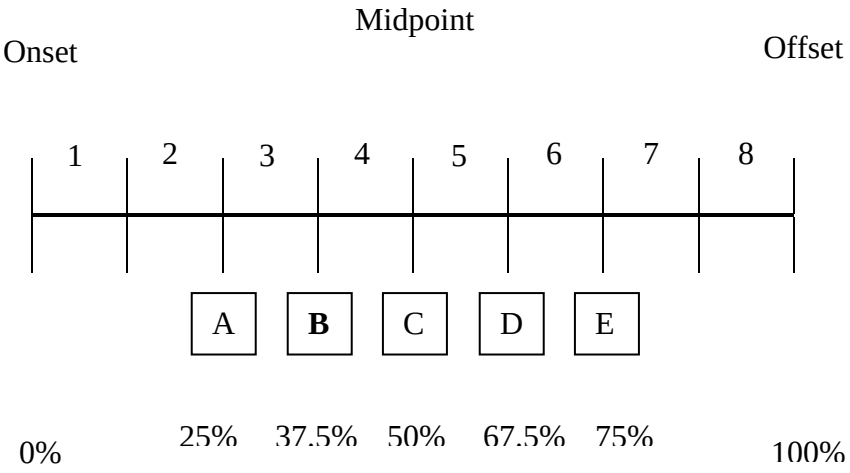


Figure 3.1: A, B, C, D and E, the measurement points for the target monophthong. It is the values from Point B that were used for the analyses.

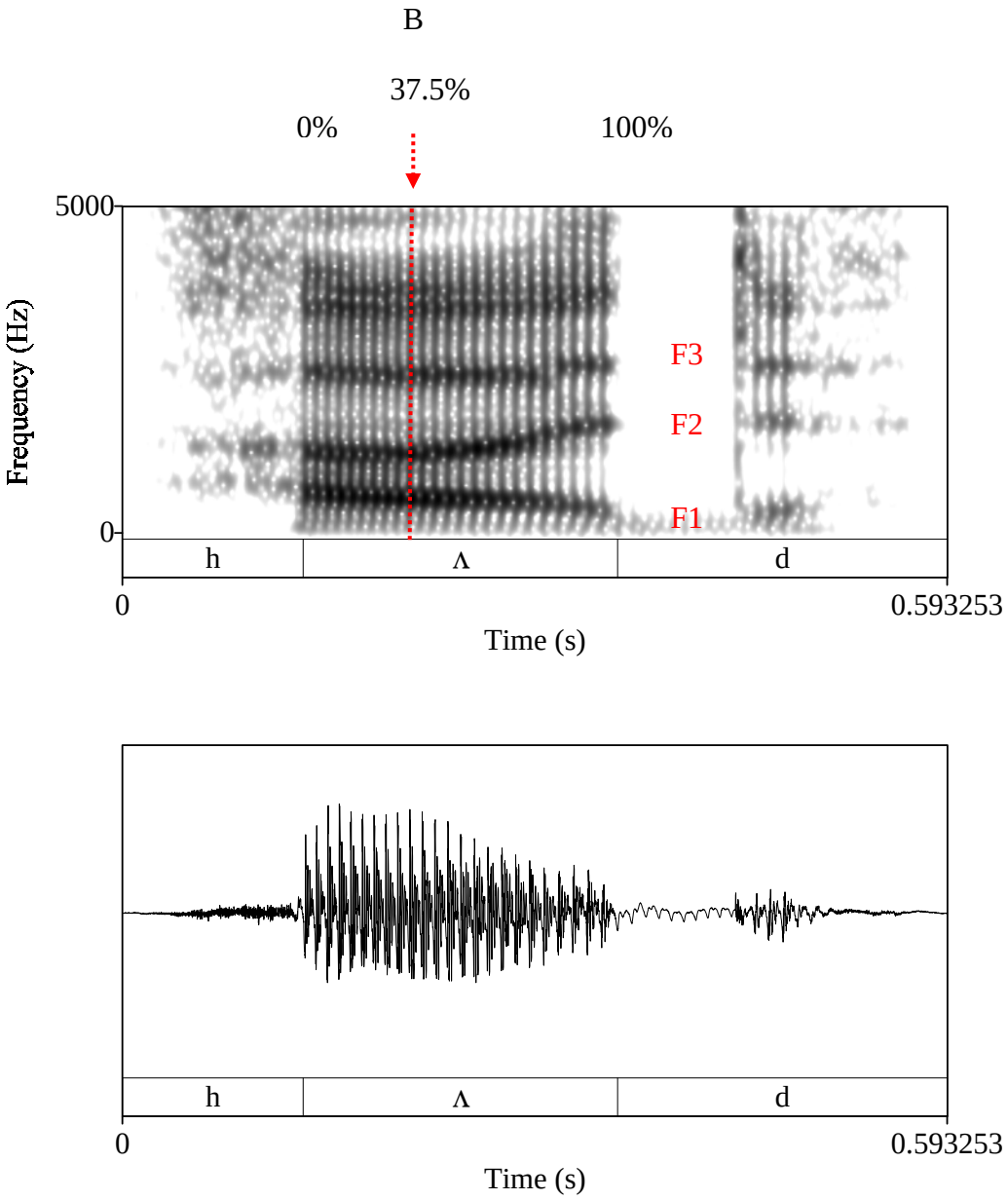


Figure 3.2: Spectrogram and waveform of an English word, “Hudd” /hʌd/. The red line indicates where to obtain F1 and F2 values for /ʌ/.

3.4.4 The Measurement Points of F1 and F2 in Diphthongs

This section discusses the method of measuring the English diphthongs /aɪ/, /aʊ/, /ɔɪ/, /eɪ/, /oʊ/ and the Mandarin diphthongs /ai/, /au/, /ei/, and /ou/.

3.4.4.1 English /aɪ/ and Mandarin /ai/

For the English diphthong /aɪ/, the measurement point of /a/ in /aɪ/ is chosen at a place where F1 and F2 are fairly steady at the beginning of the vowel duration. The measurement point of /ɪ/ in /aɪ/ is chosen at a place where F2 reaches its maximum before the formant transition is influenced by the following /d/. The same procedure for selecting measurement points was used for the Mandarin diphthong /ai/.

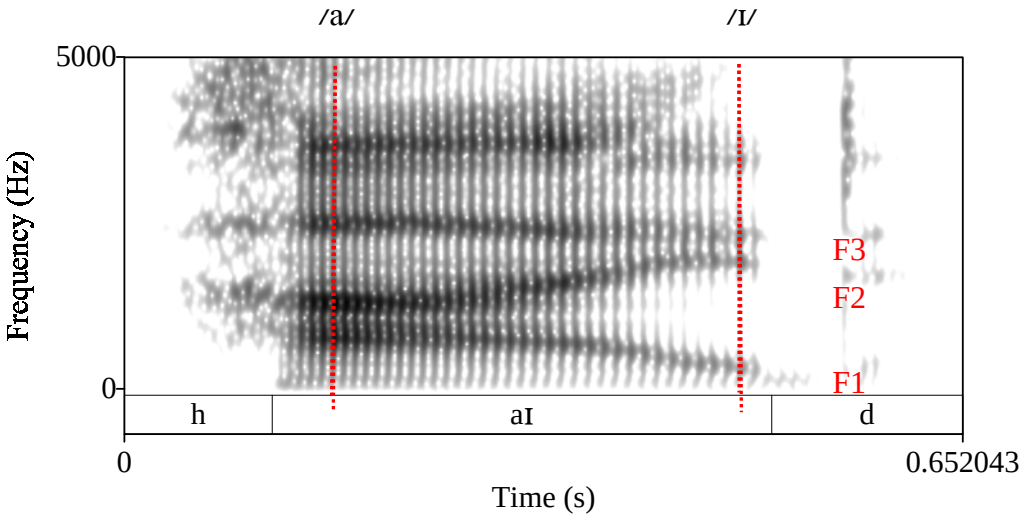


Figure 3.3: Spectrogram of an English word, “hide” /haɪd/. The red lines indicate where to obtain F1 and F2 values for /a/ (at left) and /ɪ/ (at right).

3.4.4.2 English /aʊ/ and Mandarin /au/

For the English diphthong /aʊ/, the measurement point of /a/ in /aʊ/ is chosen at a place where F1 and F2 are fairly steady at the beginning of the vowel duration. The measurement point of /ʊ/ in /aʊ/ is chosen at a visually determined last point before the formant transition is influenced by /d/. The same procedure for selecting measurement points was used for the Mandarin diphthong /au/.

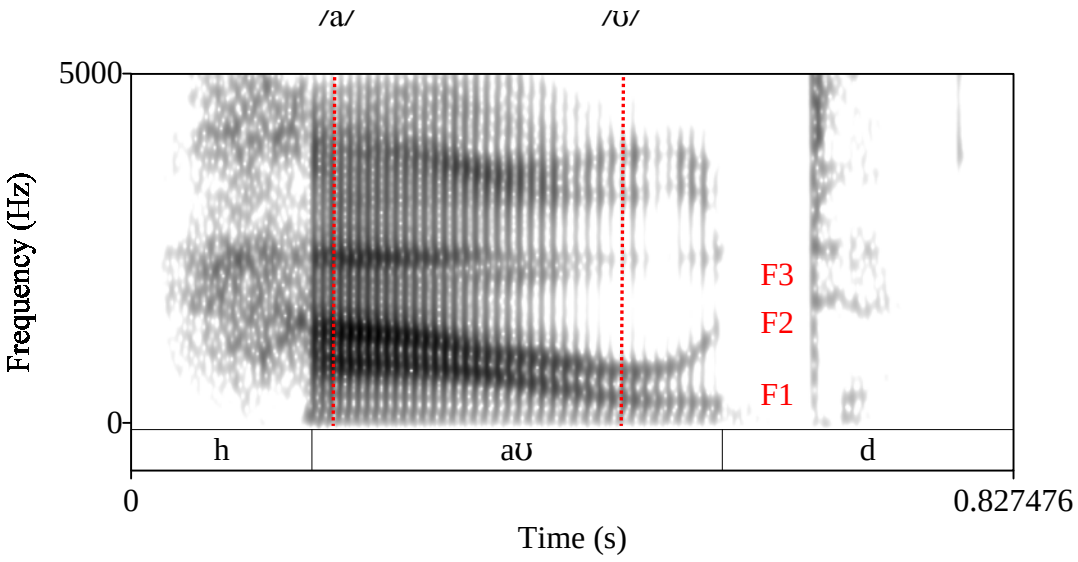


Figure 3.4: Spectrogram of an English word, “how’d” /haʊd/. The red lines indicate where to obtain F1 and F2 values for /a/ and /ʊ/.

3.4.4.3 English /ɔɪ/

For the diphthong /ɔɪ/, the measurement point of /ɔ/ in /ɔɪ/ is chosen at a place where F1 and F2 are fairly steady at the beginning of the vowel duration. The measurement point of /ɪ/ in /ɔɪ/ is chosen at a place where F2 reaches its maximum before the formant transition is influenced by /d/.

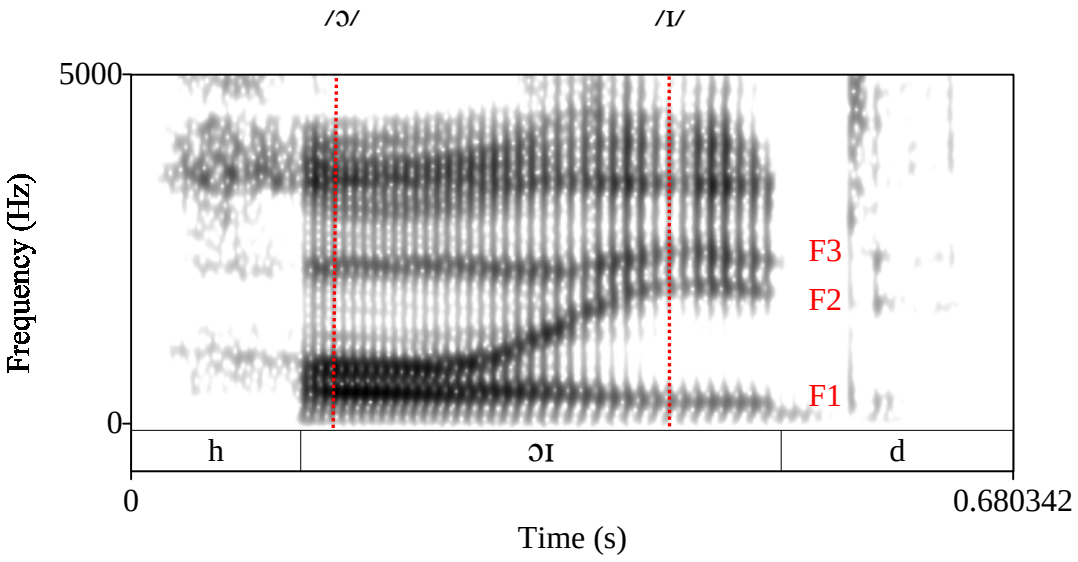


Figure 3.5: Spectrogram of a nonsense word, “hoid” /hɔɪd/. The red lines indicate the places for obtaining F1 and F2 values for /ɔ/ and /ɪ/.

3.4.4.4 English /eɪ/ and Mandarin /ei/

For the diphthong /eɪ/, the measurement point of /e/ in /eɪ/ is chosen at a place where F1 and F2 are fairly steady at the beginning of the vowel duration. The measurement point of /ɪ/ in /eɪ/ is chosen at a place where F2 reaches its maximum before the formant transition is influenced by /d/. The same method of selecting measurement points was used for the Mandarin diphthong /ei/.

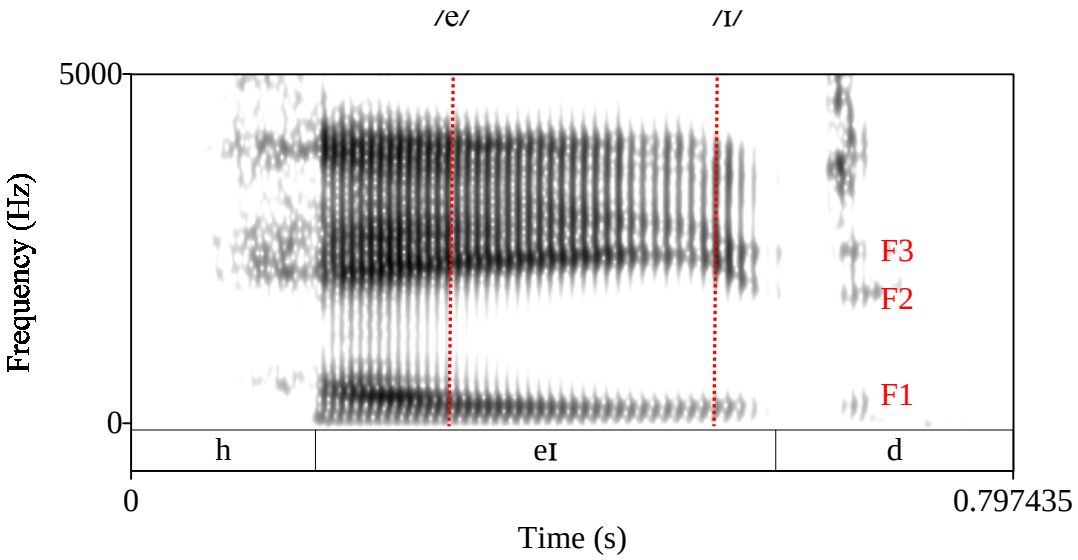


Figure 3.6: Spectrogram of an English word, “hayed” /heɪd/. The red lines indicate the places for obtaining F1 and F2 values for /e/ and /ɪ/.

3.4.4.5 English /oʊ/ and Mandarin /ou/

For the English diphthong /oʊ/, the measurement point of /o/ in /oʊ/ is chosen at a place where F1 and F2 are fairly steady at the beginning of the vowel duration. The measurement point of /ʊ/ in /oʊ/ is chosen at a visually determined last point before the formant transition is influenced by /d/. The same method of selecting measurement points was used for the Mandarin diphthong /ou/.

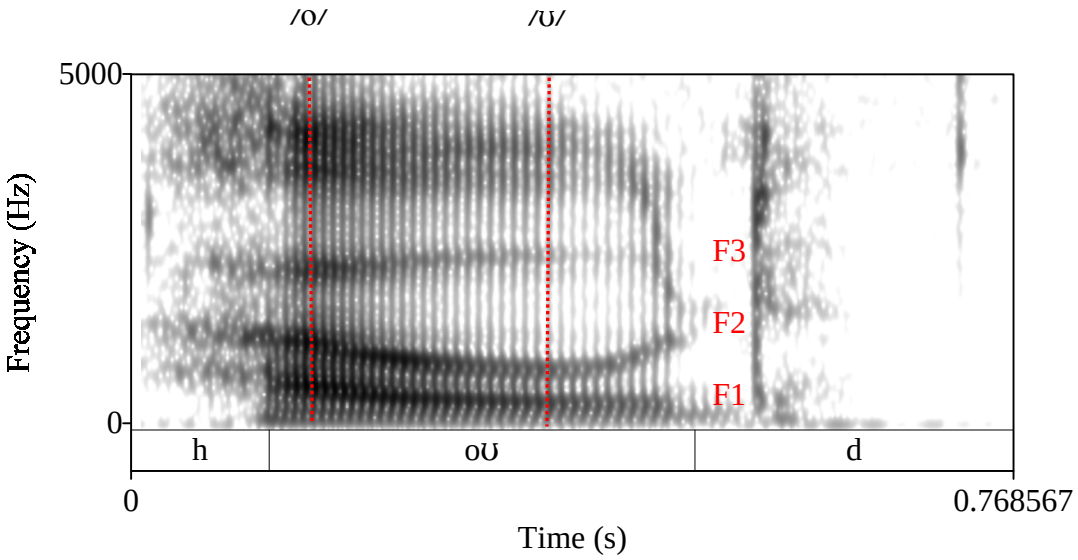


Figure 3.7: Spectrogram of an English word, “hoed” /hoʊd/. The red lines indicate the places for obtaining F1 and F2 values for /a/ and /ʊ/.

For the English vowels /i, ɪ, ɛ, æ, ʌ, ɝ, ɑ, ɔ, ʊ, u/, /e/ from /eɪ/ and /o/ from /oʊ/, there are 1,440 F1 and 1,440 F2 values, from subjects from Texas and Taiwan (12 vowels * 3 repetitions * 40 subjects * 1 measurement point = 1,440). The F1 and F2 values obtained from English /e/ and /o/ are used for comparison with other English and Mandarin monophthongs and diphthongs because English /e/ and /o/ are both cardinal vowels and elements of diphthongs. For the English diphthongs /aɪ, aʊ, ɔɪ, eɪ, oʊ/, there are 1,200 F1 and 1,200 F2 values, from subjects from Texas and Taiwan (5 diphthongs * 3 repetitions * 40 subjects * 2 measurement points = 1,200).

For the Mandarin monophthongs /i, y, e, ə, u, o, a/, there are 1,680 F1 and 1,680 F2 values from subjects from Taiwan (7 monophthongs * 3 repetitions * 4 tones * 20 subjects * 1 measurement point = 1,680). For the Mandarin diphthongs /ai, au, ei, ou/, there are 1,920 F1 and 1,920 F2 values from subjects from Taiwan (4 diphthongs * 3 repetitions * 4 tones * 20 subjects * 2 measurement points = 1,920). In rare situations, when F1 and F2 values could not be obtained through visual determination by pointing the cursor at the spectrogram and formant tracking, subjects were asked to read the word list again, and formant values for the vowel were taken only from the second reading. The Mandarin /ə/ tokens from one male and one female Mandarin subject were influenced by their speech habit of adding retroflex /r/ at the end of syllables. They were asked to read the word list again, and formant values for the

Mandarin /ə/ that had previously been influenced by /r/ were taken from the second reading only.

Chapter 4: Statistical Analysis

This chapter consists of six sections. Sections 4.1, 4.2, and 4.3 investigate the acoustic characteristics of vowels in spoken Mandarin from subjects from Taiwan, spoken English from subjects from Texas, and spoken English from subjects from Taiwan, respectively. Whether the vowels of spoken Mandarin are identical to vowels spoken in English by native speakers of Mandarin is investigated, with respect to F1 and F2 values. In Section 4.1, the first and second formant values of Mandarin vowels pronounced by ten male and ten female Mandarin subjects from Taiwan are estimated and analyzed. In Section 4.2, the first and second formant values from English vowels pronounced by ten male and ten female Texans are estimated and analyzed. In section 4.3, the first and second formant values of English vowels pronounced by ten male and ten female subjects from Taiwan, whose Mandarin vowel data are analyzed in Section 4.1, are estimated and analyzed. The statistical results suggest that within the same language, Mandarin, there are significant differences between genders in the F1 and F2 values of the same vowel. Within English from native speakers of English, the vowel-by-gender interaction is significant in F1 values and marginally significant in F2 values. Within English from Mandarin subjects, the vowel-by-gender interaction is significant in F2 values but not in F1 values. Therefore, when comparing the formant frequencies of vowels within language groups, acoustic characteristics of vowels are discussed separately by gender.

Section 4.4 concerns the acoustic characteristics of English vowels both from native speakers of American English and from Mandarin subjects. English vowel pairs (/i/ vs. /ɪ/, /u/ vs. /ʊ/, /e/ vs. /ɛ/, /e/ vs. /æ/, /ɛ/ vs. /æ/, and /o/ vs. /ɔ/) are the foci of this section. Theoretically, these vowel pairs are difficult for native speakers of Mandarin to distinguish. In order to know whether native speakers of Mandarin are able to distinguish these vowel pairs, the distribution patterns of the F1 and of the F2 values of English vowels from 20 English subjects in Section 4.2 are compared with those of English vowels pronounced by 20 Mandarin subjects in Section 4.3, whose Mandarin values are also analyzed in Section 4.1.

Section 4.5 investigates whether there is a relationship between how Mandarin subjects pronounce Mandarin vowels and how they pronounce English vowels, with respect to formant values. The focal points are on Mandarin /i/ vs. English /i/, Mandarin /i/ vs. English /ɪ/, /Mandarin /u/ vs. English /u/, Mandarin /u/ vs. English /ʊ/, Mandarin /e/ vs. English /e/, Mandarin /e/ vs. English /ɛ/, Mandarin /e/ vs. English /æ/, Mandarin /o/ vs. English /o/, and Mandarin /o/ vs. English /ɔ/.

Section 4.6 investigates whether there is a relationship between how Mandarin subjects pronounce Mandarin diphthongs and how they pronounce English diphthongs, with respect to formant values. The focal points are on Mandarin /ai/ vs. English /aɪ/,

Mandarin /au/ vs. English /aʊ/, Mandarin /ei/ vs. English /eɪ/, and Mandarin /ou/ vs. English /oʊ/.[6]

4.1 Mandarin Vowels

This section uses F1 and F2 values to define the acoustic characteristics of the spoken Mandarin monophthongs /i, y, e, ə, u, o, a/. Ten male and ten female Mandarin subjects in this study were from Taiwan. Repeated measures ANOVA was applied to determine whether F1 and F2 values varied with vowel and gender. Mauchly's Test of Sphericity was used to test the repeated measurement analysis assumption that the variance-covariance matrix has sphericity. If the sphericity assumption was violated, the Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

4.1.1 Statistical Results

Table 4.1 shows the mean F1 and F2 values for each Mandarin monophthong across subjects grouped by gender. A significant gender difference exists in both F1 values ($F_{1,18} = 92.431$, $p < 0.001$) and in F2 values ($F_{1,18} = 37.995$, $p < 0.001$). The vowel-by-gender interaction is significant in F1 values ($F_{2,37} = 4.370$, $p = 0.019$) and

[6] The comparison of English /ɔɪ/ from English and Mandarin speakers is not specifically discussed in the body of this dissertation, but is included in Appendix G.

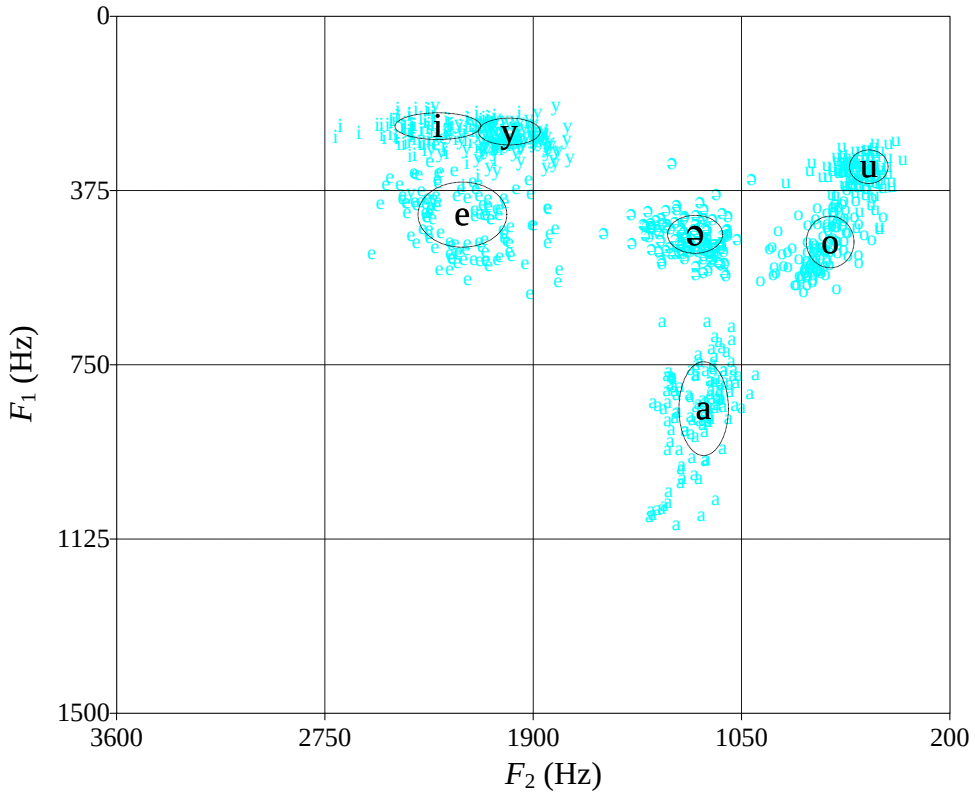
F2 values ($F_{2,41} = 14.846$, $p < 0.001$). In addition, vowels are significantly different from each other in F1 ($F_{2,37} = 407.786$, $p < 0.001$) and F2 ($F_{3,41} = 851.991$, $p < 0.001$).

From Table 4.1 and the frequency values shown in Figure 4.1, Figure 4.2 and Figure 4.3 below, it can be seen that female F1 and F2 values are significantly different from male F1 and F2 values for each Mandarin vowel. The location of the IPA symbols on the figures represents the mean for each vowel. The ellipses represent one standard deviation about the mean for each vowel.

Table 4.1: F1 and F2 mean values for each Mandarin vowel by gender.

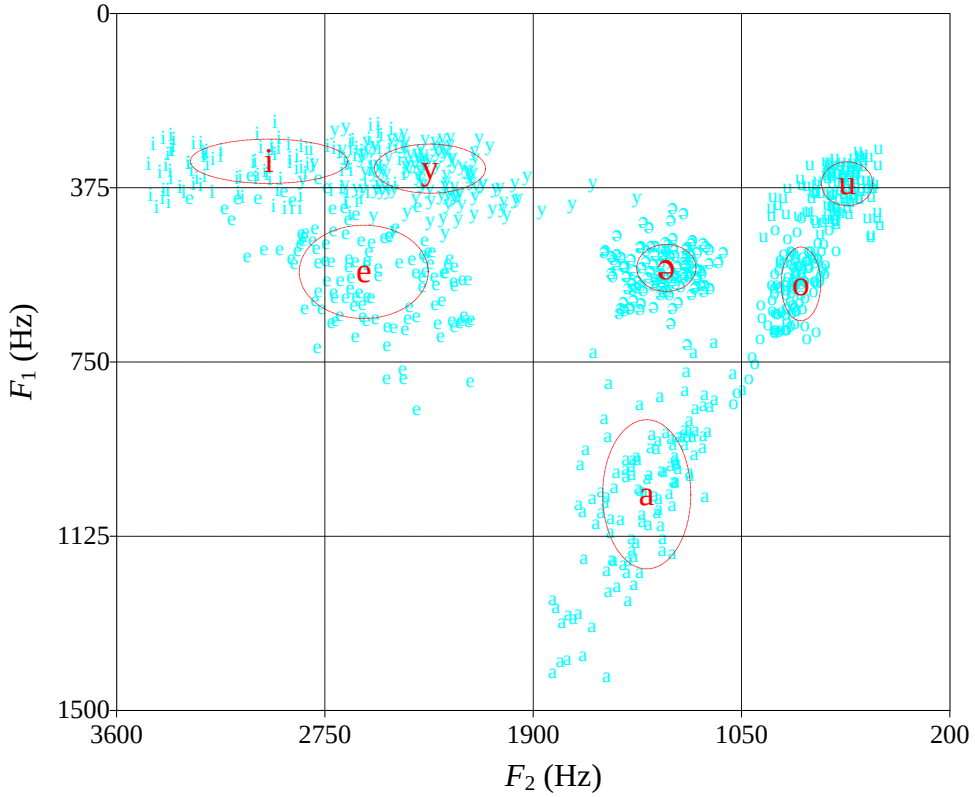
		F1			F2		
Vowel	Gender	Mean	SD[7]	*p*	Mean	SD	*p*
1. /i/	M	271	10	<0.001	2257	155	<0.001
	F	347	31		2890	297	
2. /y/	M	281	11	<0.001	1990	94	<0.001
	F	361	40		2287	179	
3. /u/	M	352	16	<0.001	642	45	0.003
	F	392	12		724	61	
4. /e/	M	448	50	<0.001	2166	157	<0.001
	F	569	56		2535	219	
5. /ə/	M	488	23	<0.001	1293	86	0.009
	F	561	19		1401	80	
6. /o/	M	503	37	0.001	787	77	0.001
	F	593	59		897	50	
7. /a/	M	839	77	0.001	1261	75	0.001
	F	1016	113		1475	145	

[7] Standard deviation (SD).



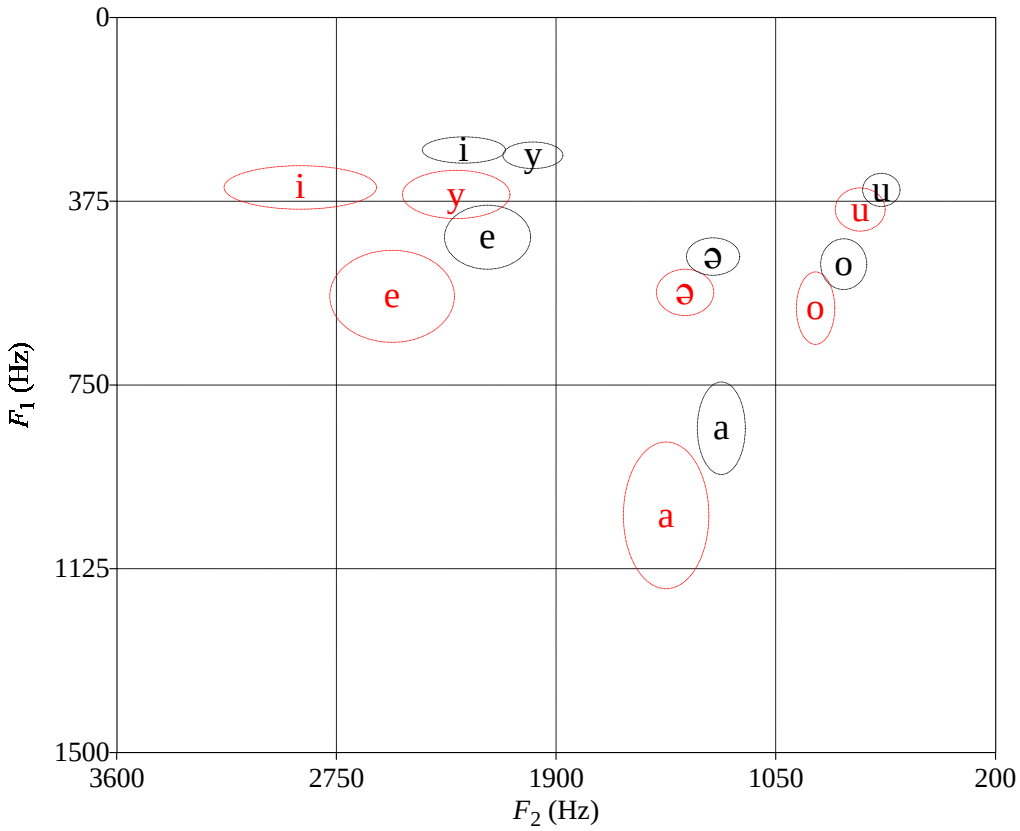
Cyan: scatter plot of Mandarin male subjects for each monophthong.
Black: mean values of Mandarin male subjects for each monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.1: F1 and F2 mean values and scatter plots of each Mandarin vowel from Mandarin male subjects.



Cyan: scatter plot of Mandarin female subjects for each monophthong.
Red: mean values of Mandarin female subjects for each monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.2: F1 and F2 mean values and scatter plots of each Mandarin vowel from female Mandarin subjects.



Black: mean values of Mandarin male subjects for each monophthong.
Red: mean values of Mandarin female subjects for each monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.3: F1 and F2 mean values of each Mandarin vowel from male and female Mandarin subjects.

4.1.1.1 F1 Values of Mandarin Vowels

As Figure 4.4 and Table 4.2 below show, in terms of F1 values, Mandarin /a/ differs significantly from all the other six Mandarin monophthongs in both male and female data. Mandarin /ə/, /e/, and /o/ in this study do not differ significantly from each other in the data from either gender. Mandarin male /u/ F1 values significantly differ from those of all the other six Mandarin monophthongs; however, those of Mandarin female /u/ do not differ significantly from those of Mandarin /y/. Both male and female Mandarin /i/ and /y/ are not significantly different in their F1 values.

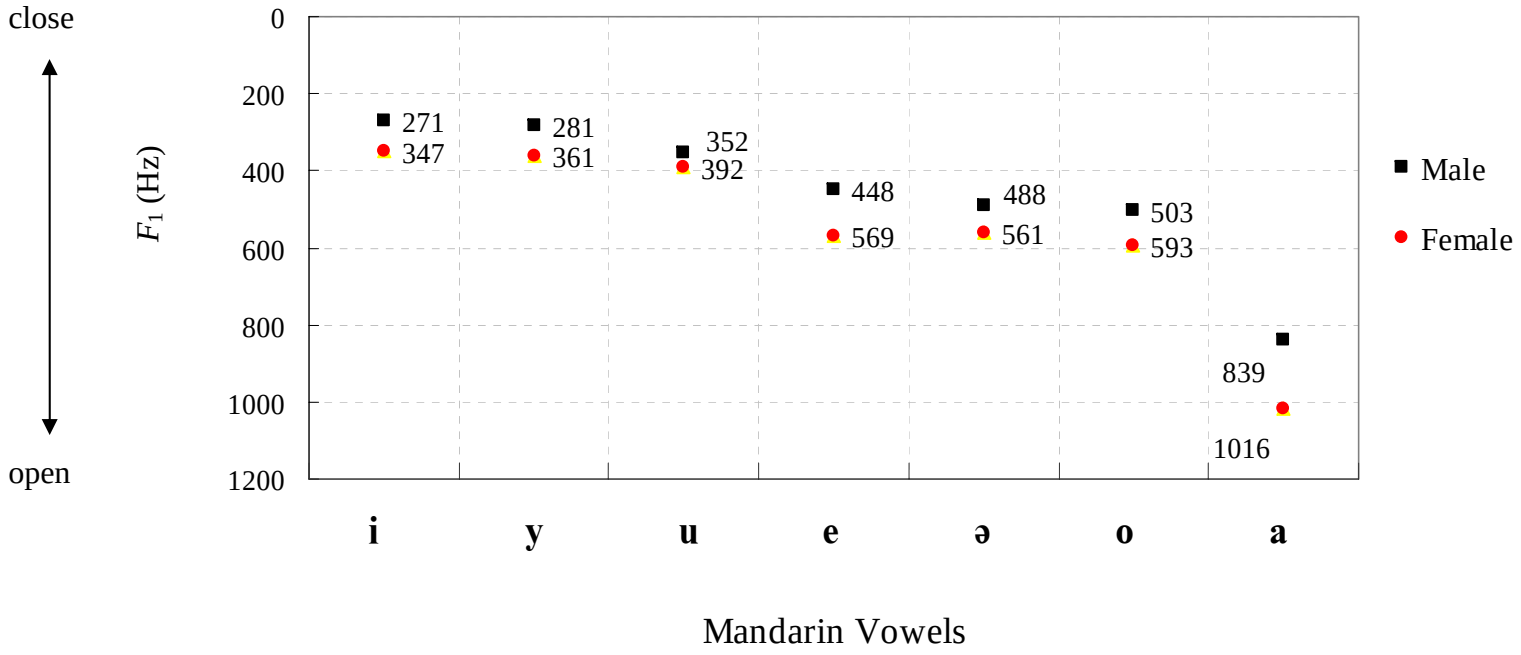


Figure 4.4: F1 mean values of each Mandarin vowel from male and female Mandarin subjects.

Table 4.2: Tests of mean differences for Mandarin F1 values from subjects from Taiwan (numbers indicate *p* values).

Vowel	/i/		/y/		/u/		/ə/		/e/		/o/		/a/	
	Gender		Gender		Gender		Gender		Gender		Gender		Gender	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F
/i/	i	i	1.000	0.280	*	*	*	*	*	*	*	*	*	*
/y/	1.000	0.280	y	y	*	0.130	*	*	*	*	*	*	*	*
/u/	*	*	*	0.130	u	u	*	*	*	*	*	*	*	*
/ə/	*	*	*	*	*	*	ə	ə	0.491	1.000	1.000	0.909	*	*
/e/	*	*	*	*	*	*	0.491	1.000	e	e	0.097	1.000	*	*
/o/	*	*	*	*	*	*	1.000	0.909	0.097	1.000	o	o	*	*
/a/	*	*	*	*	*	*	*	*	*	*	*	*	a	a

* The mean difference is significant at the 0.05 level.

4.1.1.2 F2 Values of Mandarin Vowels

As Figure 4.5 and Table 4.3 illustrate, in terms of F2 values, Mandarin /u/ and /o/ from both genders differ significantly from all the other six Mandarin monophthongs. Female Mandarin /i/, /y/, and /e/ differ significantly from the other six vowels in this study. Mandarin male /i/ does not differ from /e/ significantly. Male vowel /e/ does not differ significantly from Mandarin /i/ and /y/. Mandarin /a/ and /ə/ do not differ in F2 values for either gender.

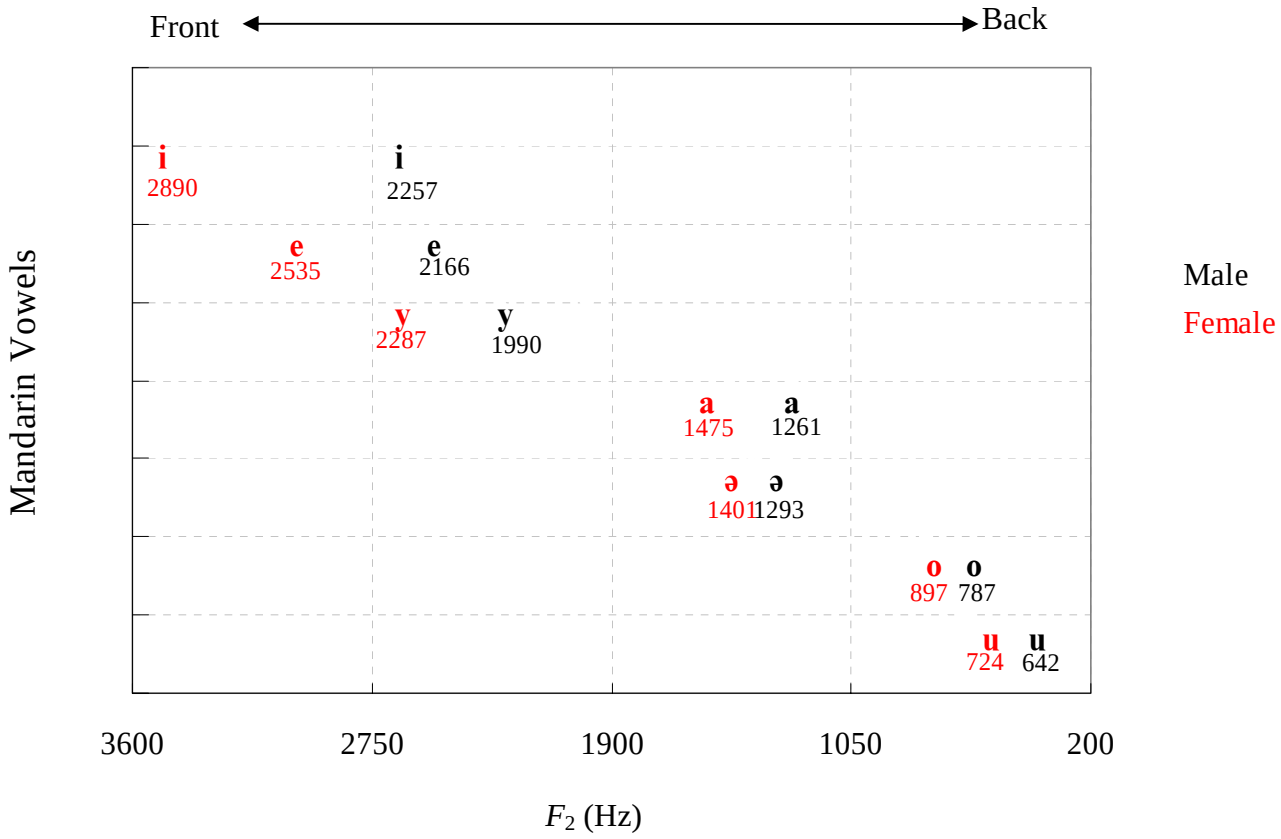


Figure 4.5: F2 mean values of each Mandarin vowel from male and female Mandarin subjects.

Table 4.3: Tests of mean differences for Mandarin F2 values from subjects from Taiwan (numbers indicate p values).

Vowel	/i/		/e/		/y/		/a/		/ə/		/o/		/u/	
	Gender		Gender		Gender		Gender		Gender		Gender		Gender	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F
/i/	i	i	0.816	*	*	*	*	*	*	*	*	*	*	*
/e/	0.816	*	e	e	0.162	*	*	*	*	*	*	*	*	*
/y/	*	*	0.162	*	y	y	*	*	*	*	*	*	*	*
/a/	*	*	*	*	*	*	a	a	1.000	0.259	*	*	*	*
/ə/	*	*	*	*	*	*	1.000	0.259	ə	ə	*	*	*	*
/o/	*	*	*	*	*	*	*	*		*	o	o	*	*
/u/	*	*	*	*	*	*	*	*	*	*	*	*	u	u

* The mean difference is significant at the 0.05 level.

4.1.2 Discussion

From Table 4.1, it is clear that F1 and F2 values differ by gender significantly for all Mandarin vowels in this study, which means that, for the same vowel, male F1 and F2 values are significantly different from female F1 and F2 values. Because male voices have lower frequencies than female ones, the gender difference is for all vowels. Furthermore, the vowel-by-gender interaction is significant in F1 and F2 values, which means the magnitude of the gender difference varies with each vowel (Figure 4.4 and Figure 4.5). In Figure 4.4 and Table 4.4, the smallest magnitude of Mandarin F1 difference between male and female subjects from Taiwan is in /u/. The value of the difference is 40 Hz. The greatest magnitude of Mandarin F1 difference between male and female subjects from Taiwan is 177 Hz, which occurs in /a/ (Figure 4.4). The magnitudes of the Mandarin F1 differences between male and female subjects for the remaining vowels, from lowest to highest /ə/, /i/, /y/, /o/, and /e/, are between 73 and 121 Hz. Because of the different magnitudes of Mandarin mean F1 value differences between male and female Mandarin subjects, the vowel-by-gender interaction is significant in F1 values.

Table 4.4: Mean gender differences in Mandarin F1 values from Taiwan.

Vowel	/u/	/ə/	/i/	/y/	/o/	/e/	/a/
Hz	40	73	76	80	90	121	177

In Figures 4.1 and 4.2, in general, Mandarin female F1 values for each Mandarin monophthong cover a wider range than Mandarin male F1 values for each Mandarin monophthong except for Mandarin /u/ and Mandarin /ə/. This phenomenon also can be observed from the standard deviations presented in Table 4.1. The female standard deviation in F1 values for each Mandarin monophthong except for Mandarin /u/ and Mandarin /ə/ is greater than the male standard deviations in this study.

F1 values are related to oral and pharyngeal constriction. F1 values are raised when constriction decreases in the front half of the oral part of the vocal tract. Greater constriction of the pharynx also results in higher F1 values (Borden *et al.*, 2003; Pickett, 1999). In general, there is a positive correlation between F1 values and the lowering of tongue and jaw (Borden *et al*., 2003; Pickett, 1999). The vowels in order of increasing values of F1 from Mandarin male and female subjects are /i/, /y/, /u/, /e/, /ə/, /o/, and /a/, and /i/, /y/, /u/, /ə/, /e/, /o/, and /a/, respectively. The only difference between the order of male and female F1 values is the position of /e/ and /ə/. Based on the results shown in Table 4.2 (*p* values), the vowels do not differ significantly from each other in F1 values in the following two groups for either gender: /i, y/ and /e, ə, o/. In other words, the constriction in the front half of the oral part of the vocal tract and in the pharynx is not significantly different within the groups /i, y/ and /e, ə, o/. The vowels within the group /i, y/ have similar degrees of tongue height; the same

is also true within the group /e, ə, o/. The greater the aperture of one's mouth, the more one's tongue and jaw are lowered naturally. Both Mandarin male and female subjects apply a characteristic relative openness of the mouth in the pronunciation of each Mandarin monophthong in this study within the same gender. For example, the openness of Mandarin /i/ is relatively smaller than that of Mandarin /a/.

In Figure 4.5, the smallest magnitude of Mandarin F2 difference between male and female subjects from Taiwan is in /u/. The difference is 82 Hz. The greatest magnitude of Mandarin F2 difference between male and female subjects from Taiwan is 633 Hz, which occurs in /i/ (Figure 4.5). The remaining vowels in order of increasing magnitude of Mandarin F2 difference between male and female subjects are /ə/, /o/, /a/, /y/, and /e/, from 108 to 369 Hz. Because the different magnitudes in Mandarin mean there are F2 value differences between male and female Mandarin subjects, the vowel-by-gender interaction is significant in F2 values.

Table 4.5: Mean gender differences in Mandarin F2 values from Taiwan.

Vowel	/u/	/ə/	/o/	/a/	/y/	/e/	/i/
Hz	82	108	109	214	297	369	633

As with F1 values, in general, Mandarin female F2 values for each Mandarin monophthong, which can be observed in Figure 4.1 and Figure 4.2, are more widely dispersed than Mandarin male F2 values for each Mandarin monophthong except for

Mandarin /ə/ and Mandarin /o/. The female standard deviation in F2 values for each Mandarin monophthong, except for Mandarin /ə/ and Mandarin /o/, is greater than the male standard deviations in this study.

There is a positive correlation between F2 values and tongue advancement; the greater the tongue advancement, the higher the F2 frequency is (Borden *et al*., 2003; Pickett, 1999). The vowels in order of increasing values of F2 from Mandarin male and female subjects are /u/, /o/, /a/, /ə/, /y/, /e/, and /i/, and /u/, /o/, /ə/, /a/, /y/, /e/, and /i/, respectively. The only difference between these male and female sequences of F2 values is in the position of /a/ and /ə/. However, based on the results in Table 4.3 (*p* values), /a/ and /ə/ do not differ from each other in F2 values for either gender. Therefore, Mandarin male and female subjects have characteristic relative degrees of tongue advancement for their Mandarin monophthongs within the same gender.

4.2 English Vowels from Subjects from Texas

This section uses F1 and F2 values to outline the acoustic characteristics of the spoken English vowels /i, ɪ, e, ɛ, æ, ʌ, ɝ, u, ʊ, o, ɔ, ɑ/. The ten male and ten female subjects are from Texas. Repeated measures ANOVA was applied to determine if F1 and F2 values varied with vowel and gender. If the sphericity assumption was violated, the Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

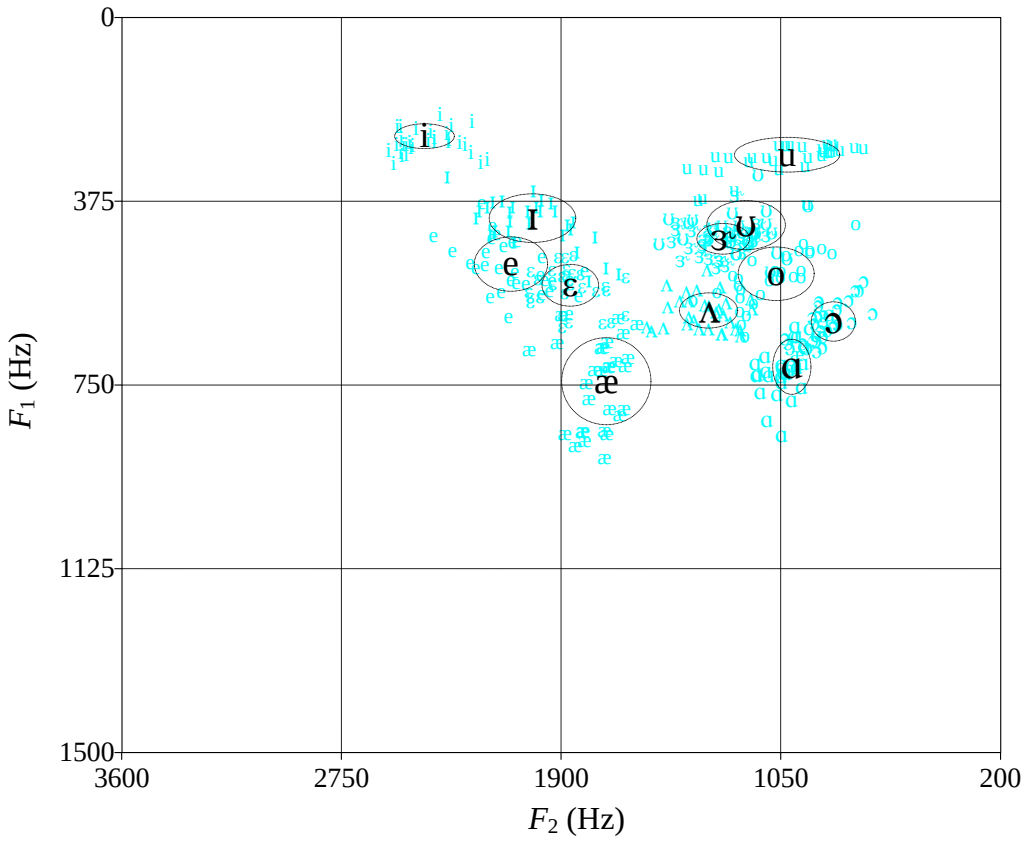
4.2.1 Statistical Results

The following tables show the mean F1 and F2 values for each English monophthong across subjects grouped by gender. A significant gender difference exists both in F1 values ($F_{1,18} = 437.277$, $p < 0.001$) and in F2 values ($F_{1,18} = 217.453$, $p < 0.001$). In addition, the vowel-by-gender interaction is significant in F1 values ($F_{3,50} = 3.676$, $p = 0.020$) and marginally significant in F2 values ($F_{2,41} = 3.084$, $p < 0.050$).

From Table 4.6 and the frequency values shown in Figure 4.6, Figure 4.7 and Figure 4.8 below, it can be seen that female F1 and F2 values are significantly different from male F1 and F2 values for each English vowel.

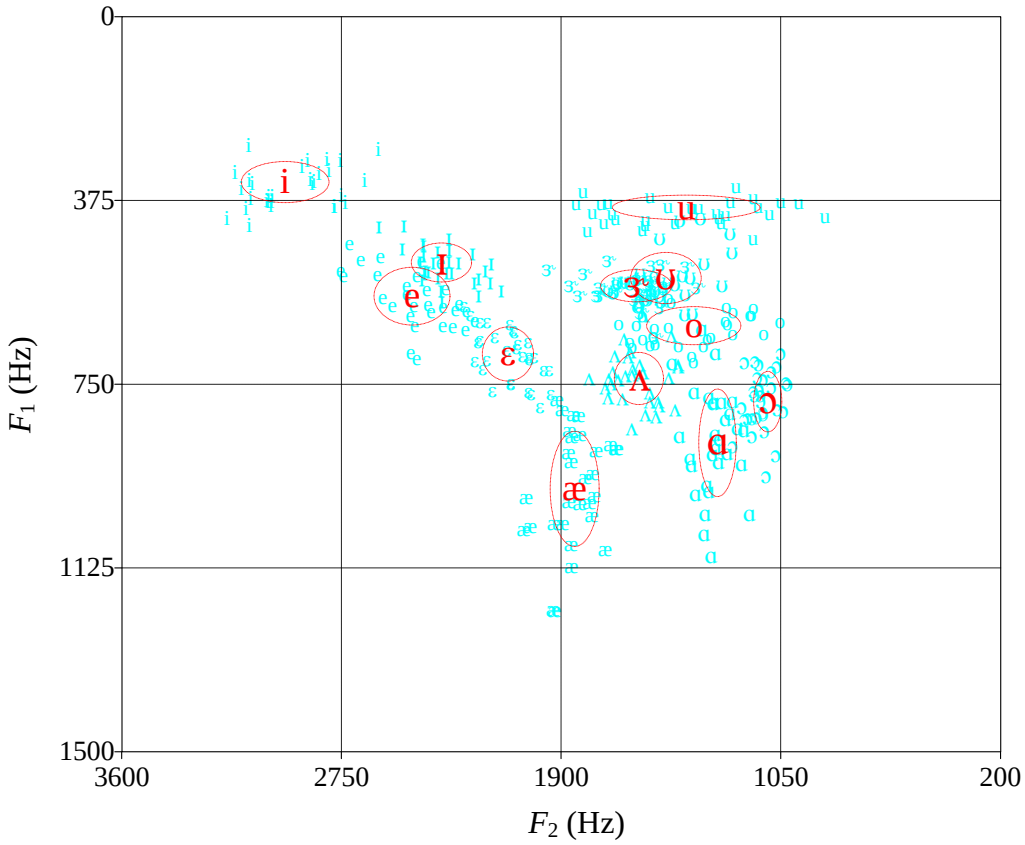
Table 4.6: F1 and F2 mean Values for each English vowel from Texan subjects by gender.

		F1			F2		
Vowel	Gender	Mean	SD	*p*	Mean	SD	*p*
1. /i/	M	276	23	<0.001	2386	106	<0.001
	F	365	35		2881	155	
2. /u/	M	311	26	<0.001	1097	185	0.002
	F	413	10		1456	260	
3. /ɪ/	M	432	45	<0.001	2002	153	<0.001
	F	518	31		2325	96	
4. /ʊ/	M	446	33	<0.001	1243	102	<0.001
	F	548	37		1528	119	
5. /ɝ/	M	472	24	<0.001	1324	77	<0.001
	F	562	23		1634	123	
6. /e/	M	520	47	0.003	2079	131	<0.001
	F	582	31		2430	106	
7. /o/	M	538	47	<0.001	1136	134	<0.001
	F	639	26		1429	156	
8. /ɛ/	M	560	37	<0.001	1868	98	<0.001
	F	693	48		2089	82	
9. /ʌ/	M	608	30	<0.001	1377	93	<0.001
	F	739	32		1624	78	
10. /ɔ/	M	629	33	<0.001	933	71	<0.001
	F	783	48		1166	38	
11. /ɑ/	M	716	47	<0.001	1081	55	<0.001
	F	862	68		1344	38	
12. /æ/	M	743	84	<0.001	1739	127	0.032
	F	950	107		1852	85	



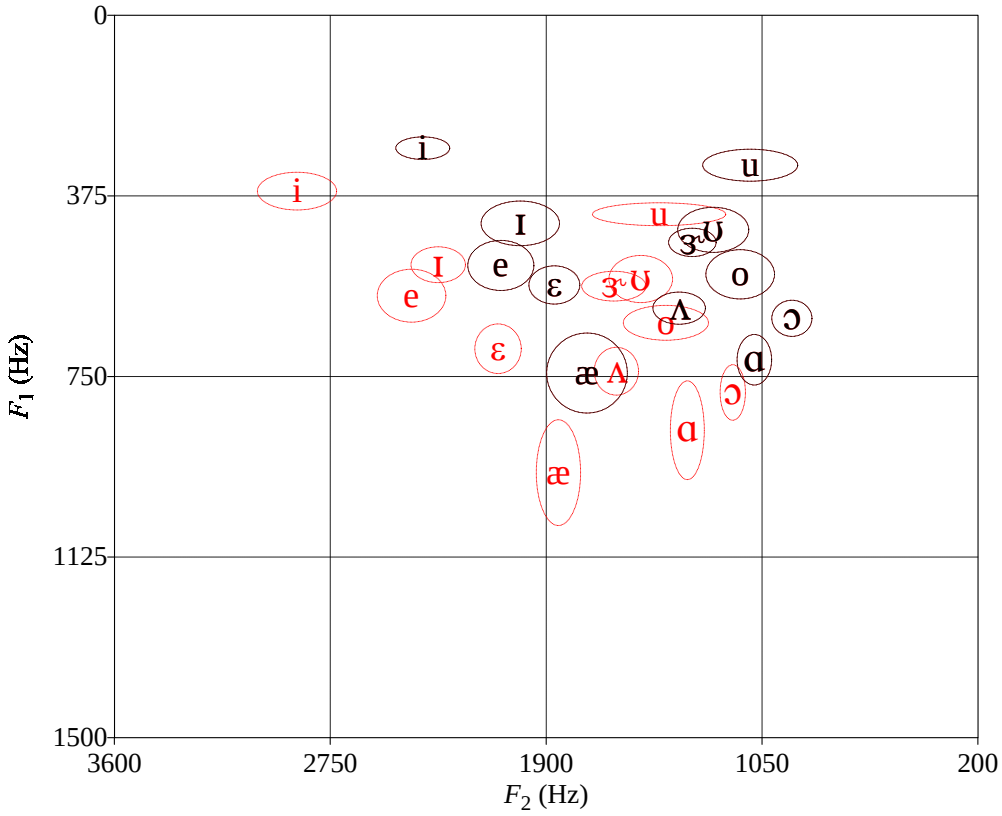
Cyan: scatter plot of English male subjects for each monophthong.
Black: mean values of English male subjects for each monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.6: F1 and F2 mean values and scatter plots of each English vowel from male subjects from Texas.



Cyan: scatter plot of English female subjects for each monophthong.
Red: mean values of English female subjects for each monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.7: F1 and F2 mean values and scatter plots of each English vowel from female subjects from Texas.



Black: mean values of English male subjects for each monophthong.
Red: mean values of English female subjects for each monophthong.
IPA symbols inside the ellipse represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.8: F1 and F2 mean values of each English vowel from male and female subjects from Texas.

4.2.1.1 F1 Values of English Vowels from Subjects from Texas

According to the F1 values shown in Figure 4.9, Table 4.7 and Table 4.8, male English vowel pairs such as /i/ vs. /u/, /ɝ/ vs. /e/, /ɛ/ vs. /ɔ/, and /æ/ vs. /ɑ/ do not differ significantly in F1 values. The female vowels /i/ and /u/ differ significantly from all the other eleven English vowels in F1 values, while the female vowel pairs /e/ vs. /o/, /o/ vs. /ɛ/, /ɔ/ vs. /ʌ/ and /æ/ vs. /ɑ/ do not differ significantly in F1 values. For male F1 values, /e/, /o/, /ɛ/ do not differ from each other significantly, and /ɪ/, /ʊ/ and /ɝ/ do not differ from each other significantly. Female F1 values do not differ from each other significantly among /ɪ/, /ʊ/, /ɝ/ and /e/.

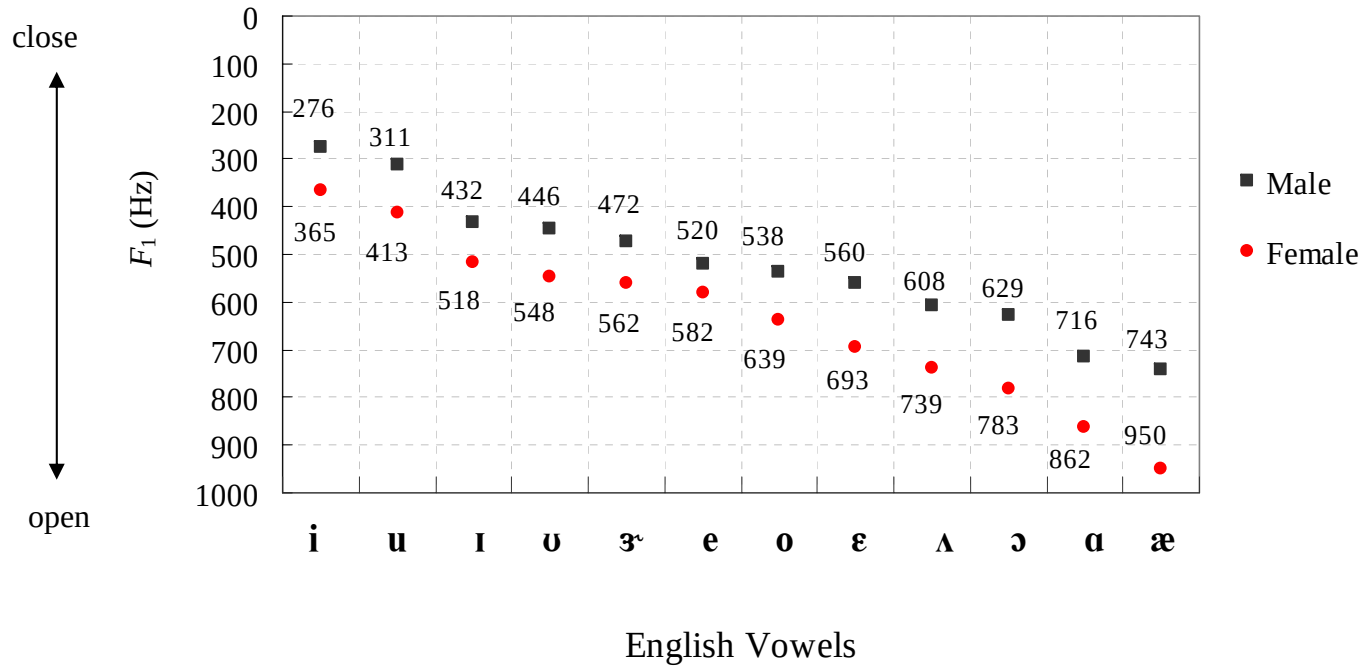


Figure 4.9: F1 mean values of English vowels from subjects from Texas.

Table 4.7: Tests of mean differences for English male F1 values from subjects from Texas (numbers indicate *p* values).

Vowels	/i/	/u/	/ɪ/	/ʊ/	/ɝ/	/e/	/o/	/ɛ/	/ɔ/	/ʌ/	/æ/	/ɑ/
/i/	i	0.104	*	*	*	*	*	*	*	*	*	*
/u/	0.104	u	*	*	*	*	*	*	*	*	*	*
/ɪ/	*	*	ɪ	1.00	0.434	*	*	*	*	*	*	*
/ʊ/	*	*	1.000	ʊ	0.872	*	*	*	*	*	*	*
/ɝ/	*	*	0.434	0.872	ɝ	0.076	*	*	*	*	*	*
/e/	*	*	*	*	0.076	e	1.000	1.000	*	*	*	*
/o/	*	*	*	*	*	1.000	o	1.000	*	*	*	*
/ɛ/	*	*	*	*	*	1.000	1.000	ɛ	0.260	*	*	*
/ɔ/	*	*	*	*	*	*	*	0.260	ɔ	1.000	0.052	*
/ʌ/	*	*	*	*	*	*	*	*	1.000	ʌ	*	*
/æ/	*	*	*	*	*	*	*	*	0.052	*	æ	1.000
/ɑ/	*	*	*	*	*	*	*	*	*	*	1.000	ɑ

* The mean difference is significant at the 0.05 level.

Table 4.8: Tests of mean differences for English female F1 values from subjects from Texas (numbers indicate *p* values).

Vowels	/i/	/u/	/ɪ/	/ʊ/	/ɝ/	/e/	/o/	/ɛ/	/ɔ/	/ʌ/	/æ/	/ɑ/
/i/	i	*	*	*	*	*	*	*	*	*	*	*
/u/	*	u	*	*	*	*	*	*	*	*	*	*
/ɪ/	*	*	ɪ	0.280	0.184	0.073	*	*	*	*	*	*
/ʊ/	*	*	0.280	ʊ	1.000	1.000	*	*	*	*	*	*
/ɝ/	*	*	0.184	1.000	ɝ	1.000	*	*	*	*	*	*
/e/	*	*	0.073	1.000	1.000	e	0.109	*	*	*	*	*
/o/	*	*	*	*	*	0.109	o	0.408	*	*	*	*
/ɛ/	*	*	*	*	*	*	0.408	ɛ	*	*	*	*
/ɔ/	*	*	*	*	*	*	*	*	1.000	ʌ	*	*
/ʌ/	*	*	*	*	*	*	*	*	ɔ	1.000	*	*
/æ/	*	*	*	*	*	*	*	*	*	*	æ	0.146
/ɑ/	*	*	*	*	*	*	*	*	*	*	0.146	ɑ

* The mean difference is significant at the 0.05 level.

4.2.1.2 F2 Values of English Vowels from Subjects from Texas

Based on the F2 values shown in Figure 4.10, and Table 4.9 and Table 4.10, male /i/ differs significantly from other male vowels in F2 values. Female /i/, /ɛ/, /æ/, and /ɔ/ differ significantly from other female vowels in F2 values. Male /e/ and /ɪ/ do not differ significantly from each other; neither do male /ɛ/ vs. /æ/, nor /ʌ/ vs. /ɝ/. The female vowels /e/ and /ɪ/ do not differ significantly in F2 values. The vowels within the following female vowel groups do not differ from each other in F2 values: /ɝ, ʌ, ʊ, u/, /ʌ, ʊ, u, o/, and /u, o, ɑ/. The vowels within the following male vowel groups do not differ significantly from each other in F2 values: /ɝ, ʊ, o, u/ and /o, u, ɑ/.

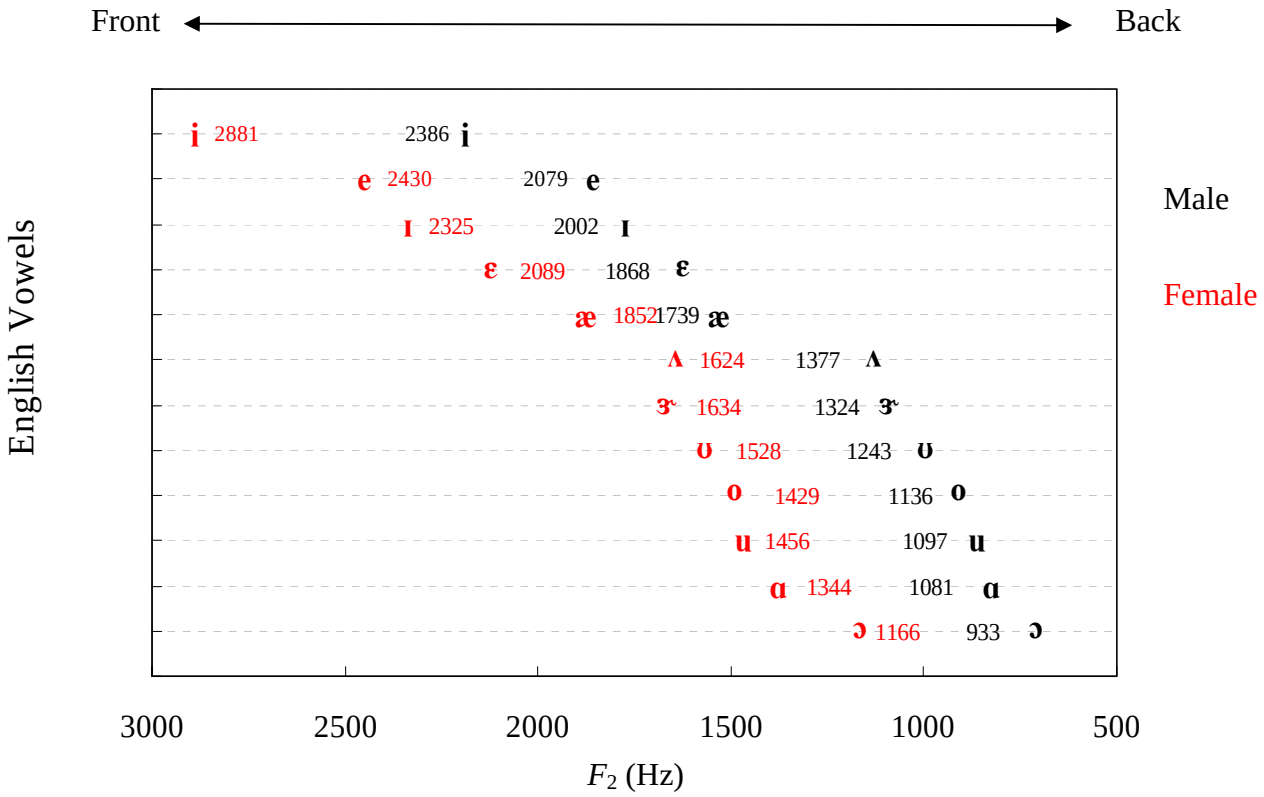


Figure 4.10: F2 mean values of English vowels from subjects from Texas.

Table 4.9: Tests of mean differences for English male F2 values from subjects from Texas (numbers indicate *p* values).

Vowels	/i/	/e/	/ɪ/	/ɛ/	/æ/	/ʌ/	/ɝ/	/ʊ/	/o/	/u/	/ɑ/	/ɔ/
/i/	i	*	*	*	*	*	*	*	*	*	*	*
/e/	*	e	1.000	*	*	*	*	*	*	*	*	*
/ɪ/	*	1.000	ɪ	*	*	*	*	*	*	*	*	*
/ɛ/	*	*	*	ɛ	0.434	*	*	*	*	*	*	*
/æ/	*	*	*	0.434	æ	*	*	*	*	*	*	*
/ʌ/	*	*	*	*	*	ʌ	1.000	*	*	0.118	*	*
/ɝ/	*	*	*	*	*	1.000	ɝ	0.958	0.073	0.330	*	*
/ʊ/	*	*	*	*	*	*	0.958	ʊ	0.813	1.000	*	*
/o/	*	*	*	*	*	*	0.073	0.813	o	1.000	1.000	*
/u/	*	*	*	*	*	0.118	0.330	1.000	1.000	u	1.000	1.000
/ɑ/	*	*	*	*	*	*	*	*	1.00	1.000	ɑ	*
/ɔ/	*	*	*	*	*	*	*	*	*	1.000	*	ɔ

* The mean difference is significant at the 0.05 level.

Table 4.10: Tests of mean differences for English female F2 values from subjects from Texas (numbers indicate *p* values).

Vowels	/i/	/e/	/ɪ/	/ɛ/	/æ/	/ɝ/	/ʌ/	/ʊ/	/u/	/o/	/ɑ/	/ɔ/
/i/	i	*	*	*	*	*	*	*	*	*	*	*
/e/	*	e	0.336	*	*	*	*	*	*	*	*	*
/ɪ/	*	0.336	ɪ	*	*	*	*	*	*	*	*	*
/ɛ/	*	*	*	ɛ	*	*	*	*	*	*	*	*
/æ	*	*	*	*	æ	*	*	*	*	*	*	*
/ɝ/	*	*	*	*	*	ɝ	1.000	0.171	1.000	*	*	*
/ʌ/	*	*	*	*	*	1.000	ʌ	0.166	1.000	0.126	*	*
/ʊ/	*	*	*	*	*	0.171	0.166	ʊ	1.000	1.000	*	*
/u/	*	*	*	*	*	1.000	1.000	1.000	u	1.000	1.000	*
/o/	*	*	*	*	*	*	0.126	1.000	1.000	o	1.000	*
/ɑ/	*	*	*	*	*	*	*	*	1.000	1.000	ɑ	*
/ɔ/	*		*	*	*	*	*	*	*	*	*	ɔ

* The mean difference is significant at the 0.05 level.

4.2.2 Discussion

From Table 4.5, it is clear that F1 and F2 values differ by gender significantly for all English vowels in this study, which means that, for the same vowel, male F1 and F2 values from subjects from Texas are significantly different from the values of their female counterparts. Because males have lower frequencies than females, the gender difference applies to all vowels. Furthermore, the vowel-by-gender interaction is significant in F1 and marginally significant in F2 values, which means that the magnitude of the difference between males and females within the same vowel varies significantly in F1 values and marginally significantly in F2 values (Figure 4.9 and Figure 4.10). In Figure 4.9, the smallest magnitude of F1 difference in English vowels between male and female subjects from Texas is in /e/. The value of the difference is 82 Hz. The greatest magnitude of F1 difference between male and female subjects from Texas is 207 Hz, which occurs in /æ/ (Figure 4.9). The remaining vowels, in order of increasing magnitude of F1 differences between male and female subjects, are /ɪ/, /i/, /ɝ/, /o/, /u/, /ʊ/, /ʌ/, /ɛ/, /ɑ/, and /ɔ/, and their range of differences is from 86 to 154 Hz. Because of the different magnitudes of English mean, there are F1 value differences between male and female English subjects, the vowel-by-gender interaction is significant in F1 values.

Table 4.11: Mean gender differences in English F1 values from Texas.

Vowels	/e/	/ɪ/	/i/	/ɝ/	/o/	/u/	/ʊ/	/ʌ/	/ɛ/	/ɑ/	/ɔ/	/æ/
Hz	82	86	89	90	101	102	102	131	133	146	154	207

Based on the English F1 values from male and female subjects from Texas in Table 4.6, the English vowels ordered by relative degree of tongue elevation are: /æ/, /ɑ/, /ɔ/, /ʌ/, /ɛ/, /o/, /e/, /ɝ/, /ʊ/, /ɪ/, /u/, and /i/. Based on the results in Table 4.6 (*p* values), the degree of tongue elevation does not differ significantly within the pairs /i/ vs. /u/, /ɝ/ vs. /e/, /ɛ/ vs. /ɔ/, or /æ/ vs. /ɑ/ for male subjects. The degree of tongue height differs significantly between /ɪ/, /ʊ/ and /ɝ/. According to Table 4.8 (*p* values), tongue height distinguishes /i/ from /u/ significantly but does not differ significantly between vowel pairs such as /e/ and /o/, /o/ and /ɛ/, /ɔ/ and /ʌ/, and /æ/ and /ɑ/ for female subjects. The degree of tongue height does not differ between the vowels /ɪ/, /ʊ/, /ɝ/, and /e/, according to Table 4.8 (*p* values).

The vowel-by-gender interaction is marginally significantly in F2 values (Figure 4.10). In Figure 4.10, the smallest magnitude of F2 difference in English vowels between male and female subjects from Texas occurs in /æ/. The value of the difference is 113 Hz. The greatest magnitude of F2 difference between male and female subjects from Texas is 495 Hz, which occurs in /i/ (Figure 4.10). The

remaining English vowels ordered by increasing magnitude of F2 differences between male and female subjects are /ɛ/, /ɔ/, /ʌ/, /ɑ/, /ʊ/, /o/, /ɜ˞/, /ɪ/, /e/, and /u/, and the range of the differences is from 221 to 359 Hz. Because the different magnitudes of English mean that there are F2 value differences between male and female English subjects, the vowel-by-gender interaction is marginally significant in F2 values.

Table 4.12: Mean gender differences in English F2 values from Texas.

Vowels	/æ/	/ɛ/	/ɔ/	/ʌ/	/ɑ/	/ʊ/	/o/	/ɜ˞/	/ɪ/	/e/	/u/	/i/
Hz	113	221	233	247	263	285	293	310	323	351	359	495

Based on the English F2 values from male and female subjects from Texas in Table 4.6, ordering vowels by increased relative degree of fronting of the tongue for English vowels yields /ɔ, ɑ, u, o, ʊ, ɜ˞, ʌ, æ, ɛ, ɪ, e, i/ for male subjects, and /ɔ, ɑ, o, u, ʊ, ʌ, ɜ˞, æ, ɛ, ɪ, e, i/ for female subjects. Although the relative positions of /u/ and /o/ and of /ɜ˞/ and /ʌ/ are different for the male and female F2 values, the male and female F2 values within the pairs /u/ and /o/, and the male and female F2 values within the pairs /ɜ˞/ and /ʌ/, are not significantly different (Table 4.9 and Table 4.10). Therefore, the relative degree of tongue advancement for each of the English vowels is the same in both male and female subjects. However, there is a slight difference between genders as to which vowels share similar degrees of tongue advancement. Based on the F2 values shown in Figure 4.10 and Tables 4.9 and 4.10, the tongue advancement

of male /i/ differs significantly from that of the other male vowels. Male subjects from Texas do not differ significantly in tongue advancement within the pairs /e/ and /ɪ/, /ɛ/ and /æ/, and /ʌ/ and /ɝ/. Tongue advancement for female /i/, /ɛ/, /æ/, and /ɔ/ differs significantly from that for other female vowels. The female vowels /e/ and /ɪ/ do not differ significantly in tongue advancement. The vowels within the following female vowel groups do not differ significantly from each other in tongue advancement: /ɝ, ʌ, ʊ, u/, /ʌ, ʊ, u, o/, and /u, o, ɑ/ (Table 4.10). Nor do the vowels within the following male vowel groups differ significantly from each other in tongue advancement: /ɝ, ʊ, o, u/ and /o, u, ɑ/ (Table 4.9).

4.3 English Vowels from Subjects from Taiwan

This section uses F1 and F2 values to outline the acoustic characteristics of the spoken English vowels /i, ɪ, e, ɛ, æ, ʌ, ɝ, u, ʊ, o, ɔ, ɑ/ from ten male and ten female subjects from Taiwan. Repeated measures ANOVA was applied to determine whether F1 and F2 values varied with vowel and gender. If the sphericity assumption was violated, the Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

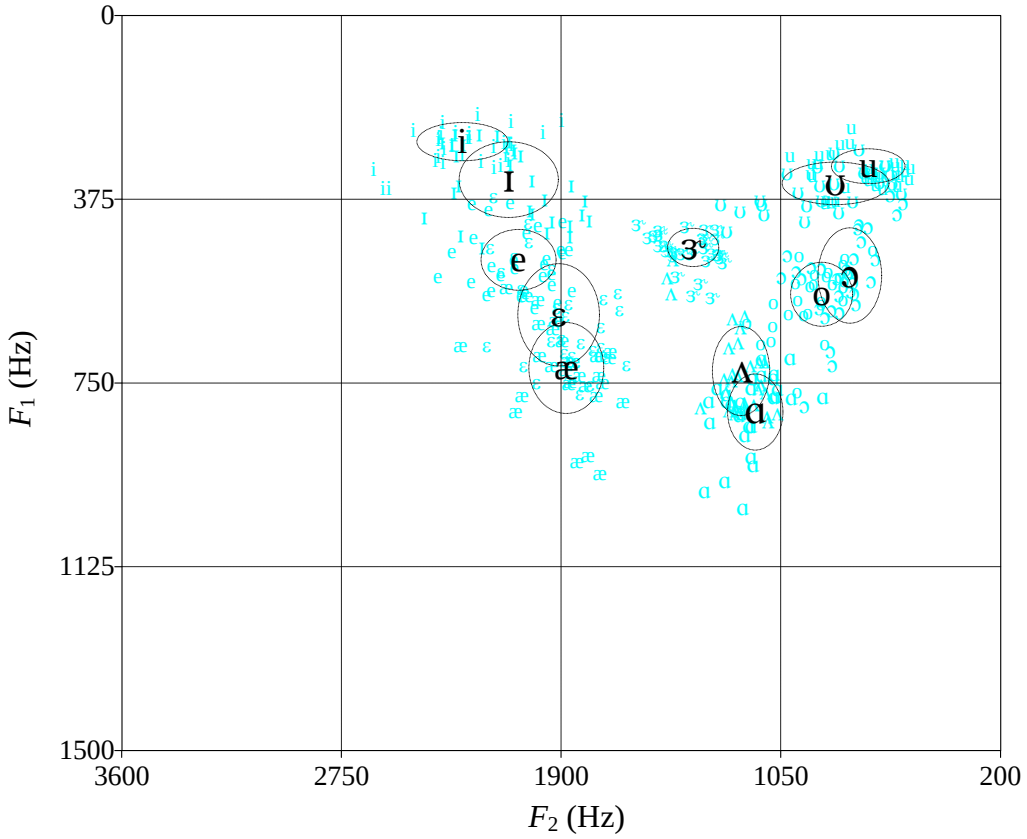
The following tables show the mean F1 and F2 values for each English monophthong across subjects, and are grouped by gender. A significant gender difference exists both in F1 values ($F_{1,18} = 35.527$, $p < 0.001$), and in F2 values ($F_{1,18} = 49.811$, $p < 0.001$). In addition, the vowel-by-gender interaction is significant in F2 values ($F_{5,88} = 8.666$, $p < 0.001$), but not significant in F1 values ($F_{5,92} = 1.471$, $p = 0.206$).

4.3.1 Statistical Results

Table 4.11 and the frequency values shown in Figure 4.11, Figure 4.12 and Figure 4.13 below, indicate that most female F1 and F2 values are significantly different from the male F1 and F2 values for each English vowel.

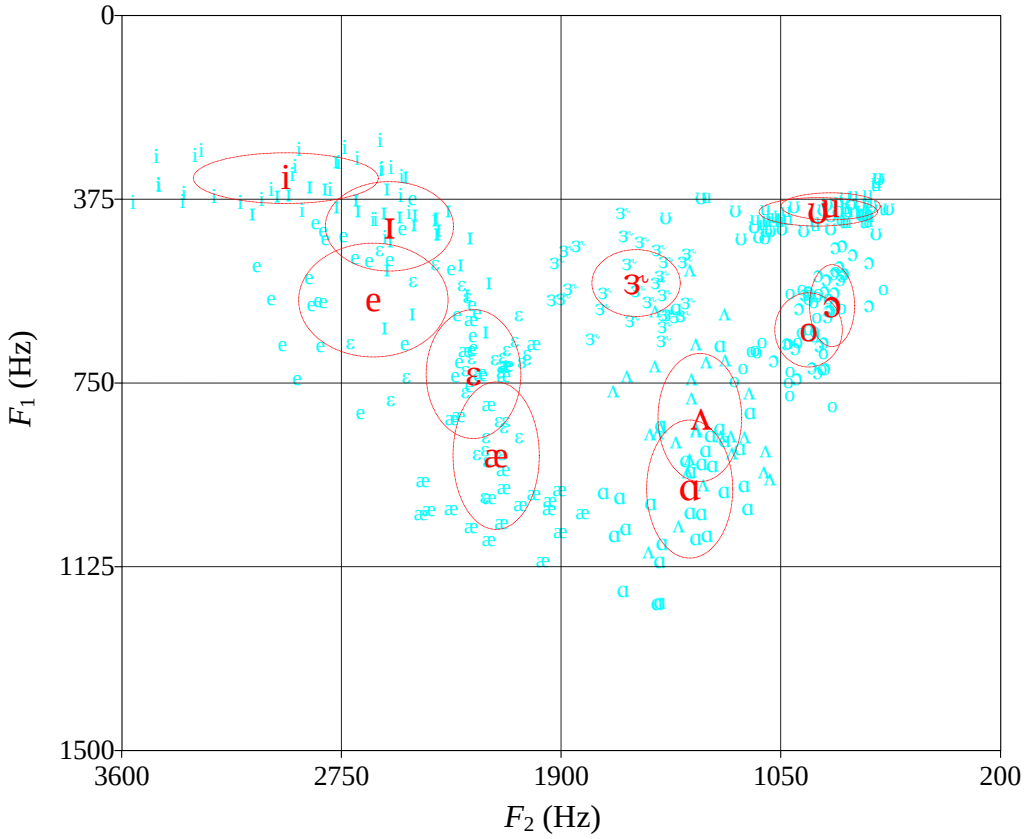
Table 4.13: F1 and F2 mean values for each English vowel from subjects from Taiwan by gender.

		F1			F2		
Vowel	Gender	Mean	SD	*p*	Mean	SD	*p*
1. /i/	M	290	34	0.001	2251	163	<0.001
	F	360	43		2879	309	
2. /u/	M	337	32	<0.001	809	124	0.062
	F	413	25		942	173	
3. /ɪ/	M	362	73	0.011	2086	174	<0.001
	F	452	68		2511	198	
4. /ʊ/	M	370	38	0.001	925	179	0.491
	F	424	21		986	209	
5. /ɝ/	M	492	33	0.007	1431	85	0.002
	F	560	61		1634	151	
6. /e/	M	515	48	0.023	2051	129	<0.001
	F	592	85		2568	262	
7. /ɔ/	M	545	89	0.106	874	110	0.121
	F	603	58		937	56	
8. /o/	M	581	54	0.010	975	103	0.325
	F	649	51		1020	99	
9. /ɛ/	M	620	57	0.016	1909	125	0.001
	F	733	121		2211	165	
10. /ʌ/	M	727	84	0.061	1261	99	0.016
	F	816	112		1407	143	
11. /æ/	M	722	83	0.005	1882	126	0.001
	F	889	143		2131	146	
12. /ɑ/	M	805	70	<0.001	1210	91	<0.001
	F	952	60		1444	118	



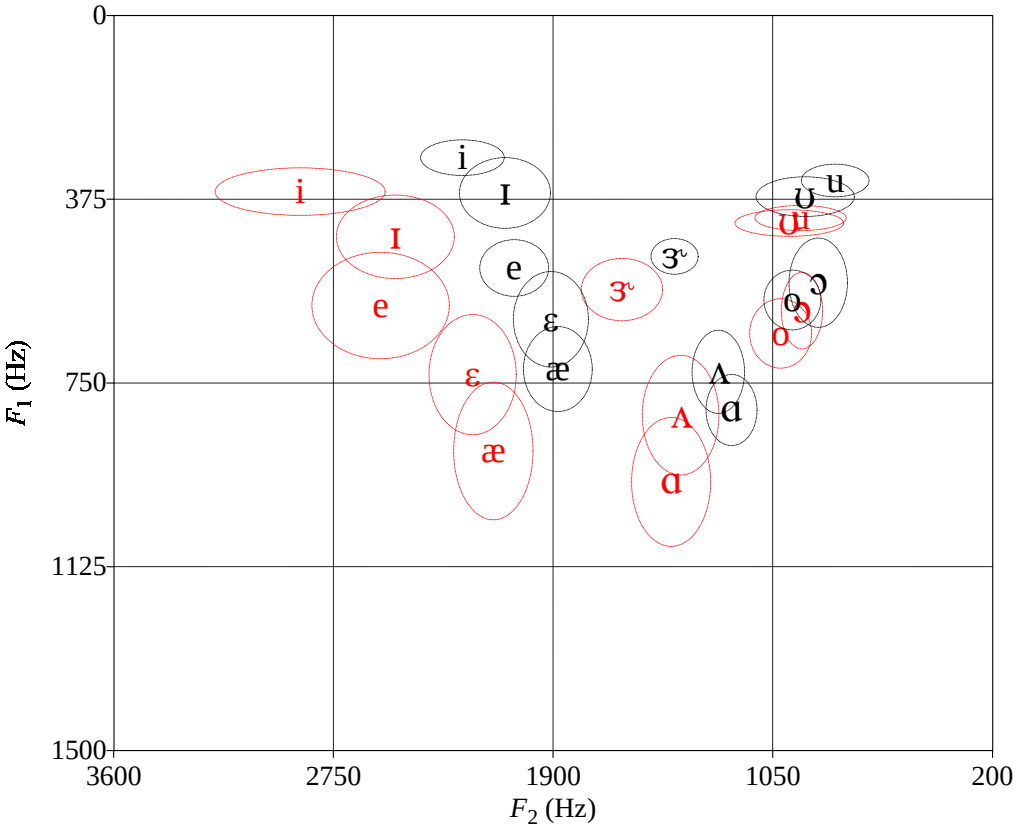
Cyan: scatter plot of male subjects from Taiwan for each English monophthong.
Black: mean values of male subjects from Taiwan for each English monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.11: F1 and F2 mean values and scatter plots of each English vowel from Mandarin male subjects.



Cyan: scatter plot of female subjects from Taiwan for each English monophthong.
Red: mean values of female subjects from Taiwan for each English monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.12: F1 and F2 mean values and scatter plots of each English vowel from Mandarin female subjects.



Black: mean values of Mandarin male subjects for each English monophthong.
Red: mean values of Mandarin female subjects for each English monophthong.
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.13: F1 and F2 mean values of each English vowel from Mandarin male and female subjects.

4.3.1.1 F1 Values of English Vowels from Subjects from Taiwan

Although the vowel-by-gender interaction is not significant in the F1 values, the pairwise comparisons using Bonferroni's adjustment for multiple comparisons are still presented in order to be consistent with the analyses in other sections of this dissertation. The F1 values in Figure 4.14 and in Tables 4.14 and 4.15 illustrate that the vowels in the following vowel groups do not differ significantly with respect to male and female F1 values: /u, ɪ, ʊ/, /ɝ, e, ɔ/, /e, ɔ, o, ɛ/, /ɛ, ʌ, æ/ and /ʌ, æ, ɑ/. The male vowels /i/, /u/, /ɪ/ do not differ from each other significantly with respect to F1 values; the female /i/, /u/, and /ʊ/ do not differ from each other significantly with respect to F1 values.

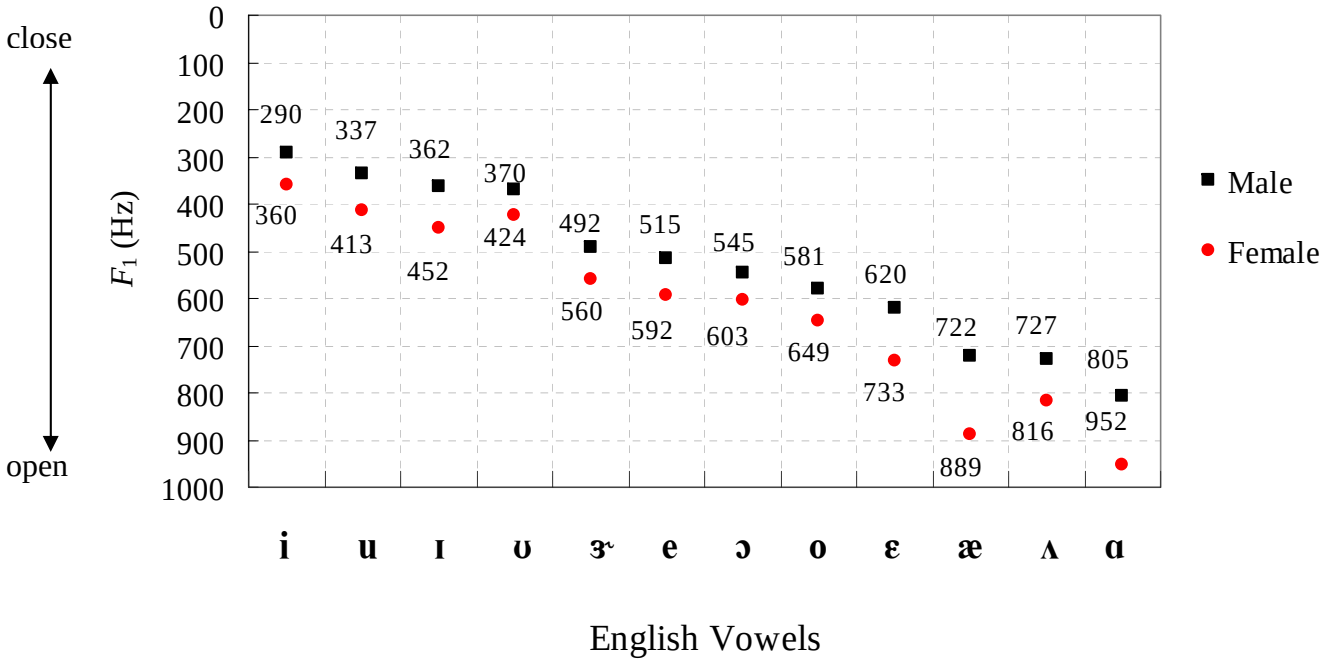


Figure 4.14: F1 mean values of English vowels from subjects from Taiwan.

Table 4.14: Tests of mean differences for English male F1 values from subjects from Taiwan (numbers indicate *p* values).

Vowels	/i/	/u/	/ɪ/	/ʊ/	/ɝ/	/e/	/ɔ/	/o/	/ɛ/	/ʌ/	/æ/	/ɑ/
/i/	i	0.254	0.260	*	*	*	*	*	*	*	*	*
/u/	0.254	u	1.000	0.846	*	*	*	*	*	*	*	*
/ɪ/	0.260	1.000	ɪ	1.000	*	*	*	*	*	*	*	*
/ʊ/	*	0.846	1.000	ʊ	*	*	*	*	*	*	*	*
/ɝ/	*	*	*	*	ɝ	1.000	1.000	*	0.084	*	*	*
/e/	*	*	*	*	1.000	e	1.000	0.520	1.000	*	*	*
/ɔ/	*	*	*	*	1.000	1.000	ɔ	1.000	1.000	*	*	*
/o/	*	*	*	*	*	0.520	1.000	o	1.000	*	0.180	*
/ɛ/	*	*	*	*	0.084	1.000	1.000	1.000	ɛ	1.000	1.000	*
/ʌ/	*	*	*	*	*	*	*	*	1.000	ʌ	1.000	1.000
/æ/	*	*	*	*	*	*	*	0.180	1.000	1.000	æ	0.289
/ɑ/	*	*	*	*	*	*	*	*	*	1.000	0.289	ɑ

* The mean difference is significant at the 0.05 level.

Table 4.15: Tests of mean differences for English Female F1 values from subjects from Taiwan (numbers indicate *p* values).

Vowels	/i/	/u/	/ʊ/	/ɪ/	/ɝ/	/e/	/ɔ/	/o/	/ɛ/	/ʌ/	/æ/	/ɑ/
/i/	i	0.086	0.060	*	*	*	*	*	*	*	*	*
/u/	0.086	u	1.000	1.000	*	*	*	*	*	*	*	*
/ʊ/	0.060	1.000	ʊ	1.000	*	*	*	*	*	*	*	*
/ɪ/	*	1.000	1.000	ɪ	*	*	*	*	*	*	*	*
/ɝ/	*	*	*	*	ɝ	1.000	1.000	*	*	*	*	*
/e/	*	*	*	*	1.000	e	1.000	1.000	0.192	*	*	*
/ɔ/	*	*	*	*	1.000	1.000	ɔ	1.000	0.101	*	*	*
/o/	*	*	*	*	*	1.000	1.000	o	1.000	*	*	*
/ɛ/	*	*	*	*	*	0.192	0.101	1.000	ɛ	1.000	0.070	*
/ʌ/	*	*	*	*	*	*	*	*	1.000	ʌ	1.000	0.082
/æ/	*	*	*	*	*	*	*	*	0.070	1.000	æ	1.000
/ɑ/	*	*	*	*	*	*	*	*	*	0.082	1.000	ɑ

* The mean difference is significant at the 0.05 level.

4.3.1.2 F2 Values of English Vowels from Subjects from Taiwan

According to the F2 values in Figure 4.15 and in Tables 4.16 and 4.17, male and female vowels in the following vowel groups do not differ significantly in their F2 values: /ʌ, ɑ/ and /ʊ, o, u, ɔ /. The vowels in the following male vowel groups also do not differ in their F2 values significantly: /i, ɪ/, /ɪ, e, æ/, /e, ɛ, æ/, /ɝ, ʌ/ and /ɑ, ʊ/. The female vowels /ɪ/ and /e/ do not differ significantly in F2 value; neither do female /ɛ/ and /æ/. Female /i/ and /ɝ/ differ significantly from other English vowels in terms of F2 values.

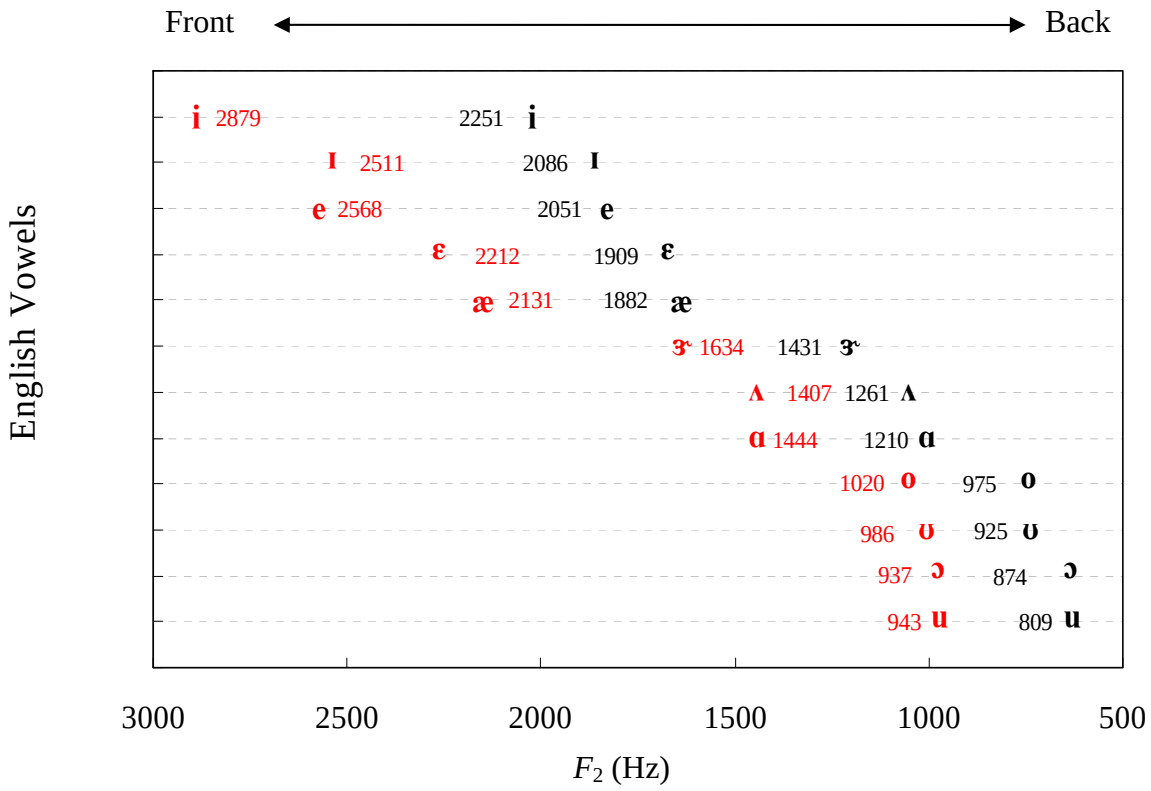


Figure 4.15: F2 mean values of English vowels from subjects from Taiwan.

Table 4.16: Tests of mean differences for English male F2 values from subjects from Taiwan (numbers indicate *p* values).

Vowels	/i/	/ɪ/	/e/	/æ/	/ɛ/	/ɝ/	/ʌ/	/ɑ/	/ʊ/	/o/	/ɔ/	/u/
/i/	i	1.000		*	*	*	*	*	*	*	*	*
/ɪ/	1.000	ɪ	1.000	0.361	*	*	*	*	*	*	*	*
/e/	*	1.000	e	0.807	1.000	*	*	*	*	*	*	*
/æ/	*	0.361	0.807	æ	1.000	*	*	*	*	*	*	*
/ɛ/	*	*	1.000	1.000	ɛ	*	*	*	*	*	*	*
/ɝ/	*	*	*	*	*	ɝ	0.099	*	*	*	*	*
/ʌ/	*	*	*	*	*	0.099	ʌ	1.000	*	*	*	*
/ɑ/	*	*	*	*	*	*	1.000	ɑ	0.102	*	*	*
/ʊ/	*	*	*	*	*	*	*	0.102	ʊ	1.000	1.000	0.578
/o/	*	*	*	*	*	*	*	*	1.000	o	0.264	0.484
/ɔ/	*	*	*	*	*	*	*	*	1.000	0.264	ɔ	1.000
/u/	*	*	*	*	*	*	*	*	0.578	0.484	1.000	u

* The mean difference is significant at the 0.05 level.

Table 4.17: Tests of mean differences for English female F2 values from subjects from Taiwan (numbers indicate *p* values).

Vowels	/i/	/ɪ/	/e/	/ɛ/	/æ/	/ɝ/	/ʌ/	/ɑ/	/ʊ/	/o/	/u/	/ɔ/
/i/	i	*	*	*	*	*	*	*	*	*	*	*
/ɪ/	*	ɪ	1.000	*	*	*	*	*	*	*	*	*
/e/	*	1.000	e	*	*	*	*	*	*	*	*	*
/ɛ/	*	*	*	ɛ	1.000	*	*	*	*	*	*	*
/æ/	*	*	*	1.000	æ	*	*	*	*	*	*	*
/ɝ/	*	*	*	*	*	ɝ	*	*	*	*	*	*
/ʌ/	*	*	*	*	*	*	ʌ	1.000	*	*	*	*
/ɑ/	*	*	*	*	*	*	1.000	ɑ	*	*	*	*
/ʊ/	*	*	*	*	*	*	*	*	ʊ	1.000	1.000	1.000
/o/	*	*	*	*	*	*	*	*	1.000	o	1.000	0.918
/u/	*	*	*	*	*	*	*	*	1.000	1.000	u	1.000
/ɔ/	*	*	*	*	*	*	*	*	1.000	0.918	1.000	ɔ

* The mean difference is significant at the 0.05 level.

4.3.2 Discussion

From Table 4.13, it is clear that F1 and F2 values in this study differ significantly with respect to gender for English vowels except for /ɔ/ and /ʌ/ in F1 values and /u/, /ʊ/, /ɔ/ and /ʌ/ in F2 values. This means that in general, for the same vowel, either male F1 or male F2 values from subjects from Taiwan are significantly different from their female counterparts. The vowel-by-gender interaction is significant in F2 but not in F1 values, which means that the magnitude of the gender difference within the same vowel varies with vowels significantly in F2 values (Figure 4.15) but not in F1 values (Figure 4.14). Thus, the magnitude of the gender difference varies consistently in F1 values, with males exhibiting lower frequencies than females.

Table 4.18: Mean gender differences in English F1 values from subjects from Taiwan.

Vowels	/ʊ/	/ɔ/	/o/	/ɝ/	/i/	/u/	/e/	/ʌ/	/ɪ/	/ɛ/	/ɑ/	/æ/
Hz	54	58	68	68	70	76	77	89	90	113	147	167

The reason why male and female subjects from Taiwan do not differ significantly in F1 values as result of vowel-and-gender interaction is that the F1 values of the vowels have large standard deviations, which means there is more variation in the data. This makes it difficult to discern vowel differences.

In Table 4.18, the smallest magnitude of F1 difference in English vowels between male and female subjects from Taiwan is found in /ʊ/. The value of the difference is 54 Hz. The greatest magnitude of F1 difference between male and

female subjects from Taiwan is 167 Hz, which occurs in /æ/ (Table 4.18). Ordering the remaining vowels by magnitude of F1 differences between male and female subjects yields: /ɔ/, /o/, /ɜ˞/, /i/, /u/, /e/, /ʌ/, /ɪ/, /ɛ/, and /ɑ/. This range of mean difference is from 58 to 147 Hz.

Based on English F1 values from male subjects from Taiwan in Table 4.11, ordering the values by the relative degree to which tongue and jaw are raised yields: /ɑ/, /æ/, /ʌ/, /ɛ/, /o/, /ɔ/, /e/, /ɜ˞/, /ʊ/, /ɪ/, /u/, and /i/. Vowels from female subjects from Taiwan are in the same order except that /ʊ/ and /ɪ/ are reversed. Based on the results in Tables 4.14 and 4.15 (*p* values), the vowels in the following vowel groups do not differ significantly in aperture of the mouth for male and female subjects: /u, ɪ, ʊ/, /ɜ˞, e, o/, /e, ɔ, o, ɛ/, /ɛ, ʌ, æ/ and /ʌ, æ, ɑ/. Male vowels /i/, /u/, /ɪ/ do not differ significantly from each other in tongue height (Table 4.14). Female /i/, /u/, and /ʊ/ do not differ significantly from each other in tongue height (Table 4.15).

The vowel-by-gender interaction is significant with respect to F2 values (Figure 4.15). In Figure 4.15, the smallest magnitude of F2 difference between male and female subjects from Taiwan is shown to occur with the English vowel /o/. The value of the difference is 45 Hz. The greatest magnitude of F2 difference between male and female subjects from Taiwan is 628 Hz, which occurs with /i/. Ordering the remaining vowels by magnitude of F2 differences between male and female subjects

yields: /ʊ/, /ɔ/, /u/, /ʌ/, /ɝ/, /ɑ/, /æ/, /ɛ/, /ɪ/, and /e/. The range of the mean differences is from 61 to 517 Hz.

Table 4.19: Mean differences in English F2 between male and female subjects from Taiwan.

Vowels	/o/	/ʊ/	/ɔ/	/u/	/ʌ/	/ɝ/	/ɑ/	/æ/	/ɛ/	/ɪ/	/e/	/i/
Hz	45	61	63	133	146	203	234	249	302	425	517	628

Based on the English F2 values from male and female subjects from Taiwan in Table 4.13, the relative degree of tongue advancement for English vowels ascends in the order /u, ɔ, ʊ, o, ɑ, ʌ, ɝ, æ, ɛ, e, ɪ, i/ for the male subjects, and in the order /ɔ, u, ʊ, o, ʌ, ɑ, ɝ, æ, ɛ, ɪ, e, i/ for the female subjects.

According to the F2 values in Figure 4.15, Table 4.14 (*p* values) and Table 4.15 (*p* values), the male and female vowels in the following vowel groups do not differ significantly from each other in tongue advancement: /ʌ, ɑ/, and /ʊ, o, u, o/. The vowels in the following male vowel groups also do not differ significantly from each other in tongue advancement: /i, ɪ/, /ɪ, e, æ/, /e, æ, ɛ/, /ɝ, ʌ/ and /ɑ, ʊ/. The female vowels /ɪ/ and /e/ do not differ significantly in tongue advancement, neither do female /ɛ/ and /æ/. Female /i/ and /ɝ/ differ significantly from all the other English vowels in tongue advancement.

4.4 English Vowels from Subjects from Texas and Taiwan

Section 4.4 is concerned with the acoustic characteristics of English vowels both from native speakers of English from Texas and from Mandarin speakers from Taiwan. Repeated measures ANOVA was used to analyze data to determine if F1 and F2 values varied with vowel, gender, and language group. If the sphericity assumption was violated, Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

In this study, each English vowel was compared with all of the other English vowels. However, the analysis focuses on the following six English vowel pairs which are most theoretically important: /i/ vs. /ɪ/, /u/ vs. /ʊ/, /ɛ/ vs. /æ/, /e/ vs. /ɛ/, /e/ vs. /æ/, and /o/ vs. /ɔ/. The F1 and F2 values of the aforementioned English vowel pairs from the 20 English subjects in Section 4.2 are compared with those of English vowel pairs pronounced by the 20 Mandarin subjects in Section 4.3, whose Mandarin values are also analyzed in Section 4.1.

4.4.1 Statistical Results

The vowel-by-language group interaction is significant with respect to F1 values ($F_{5,173} = 15.708$, $p < 0.001$) and F2 values ($F_{5,176} = 27.103$, $p < 0.001$). In addition, the three-way interaction among language group, gender, and vowel is significant in F1 values ($F_{10,173} = 2.194$, $p = 0.022$) and F2 values ($F_{10,176} = 6.396$, $p <$

0.001). Figures 4.16 to 4.19 are the scatter plots for the above-mentioned vowel pairs from the two subject groups from Texas and Taiwan. Ellipses have been drawn one standard deviation about the mean of the F1 and F2 values for each vowel.

4.4.1.1 English /i/ and /ɪ/

In Tables 4.20, 4.21 and 4.23, for English male and female subjects from Texas and female subjects from Taiwan, English /i/ and English /ɪ/ differ significantly with respect to F1 and F2 values. However, for male subjects from Taiwan, English /i/ differs significantly from English /ɪ/ with respect to F1 values but not F2 values (Table 4.22).

4.4.1.2 English /u/ and /ʊ/

For male and female subjects from Texas, the English vowels /u/ and /ʊ/ differ significantly in F1 values but not in F2 values (Tables 4.24 and 4.25). For male and female subjects from Taiwan, English /u/ and /ʊ/ do not differ significantly with respect to F1 values or F2 values (Tables 4.26 and 4.27).

4.4.1.3 English /ɛ/ and /æ/

For male and female subjects from Texas, and female subjects from Taiwan, English vowels /ɛ/ and /æ/ differ significantly in F1 values (Tables 4.28, 4.29, and 4.31). For female subjects from Texas, English /ɛ/ and English /æ/ differ significantly

in F2 values (Table 4.29). For male subjects from Texas and female subjects from Taiwan, English /ɛ/ and English /æ/ do not differ significantly in F2 values (Tables 4.28 and 4.31). For male subjects from Taiwan, English /ɛ/ and English /æ/ do not differ significantly in F1 and F2 values (Table 4.30).

4.4.1.4 English /e/ and /ɛ/

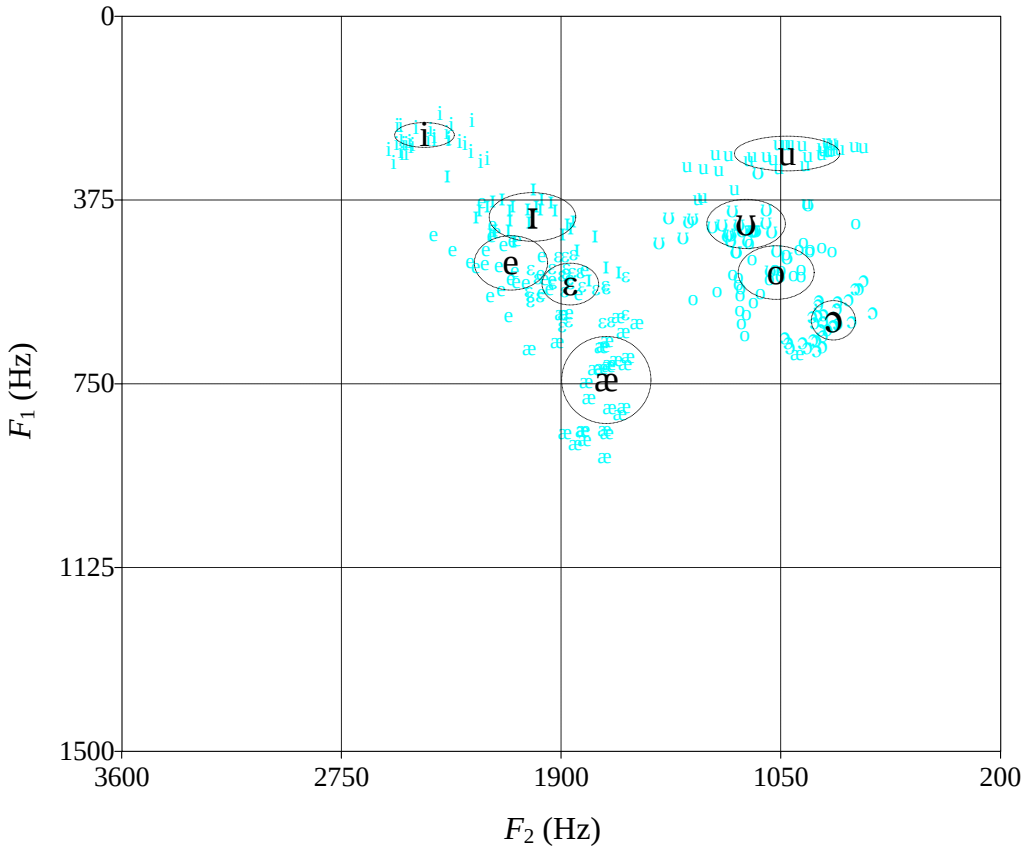
For the English vowel pair /e/ and /ɛ/, male and female subjects from Texas differ significantly in F2 values but not in F1 values (Tables 4.32 and 4.33). For English /e/ and /ɛ/, male subjects from Taiwan do not differ significantly in F1 and F2 values (Table 4.34), but female subjects from Taiwan differ in F1 and F2 values (Table 4.35).

4.4.1.5 English /e/ and /æ/

For the English vowel pair /e/ and /æ/, male and female subjects from Texas and female subjects from Taiwan differ significantly in F1 and F2 values (Tables 4.36, 4.37, and 4.39); male subjects from Taiwan differ significantly in F1 values but not in F2 values (Table 4.33).

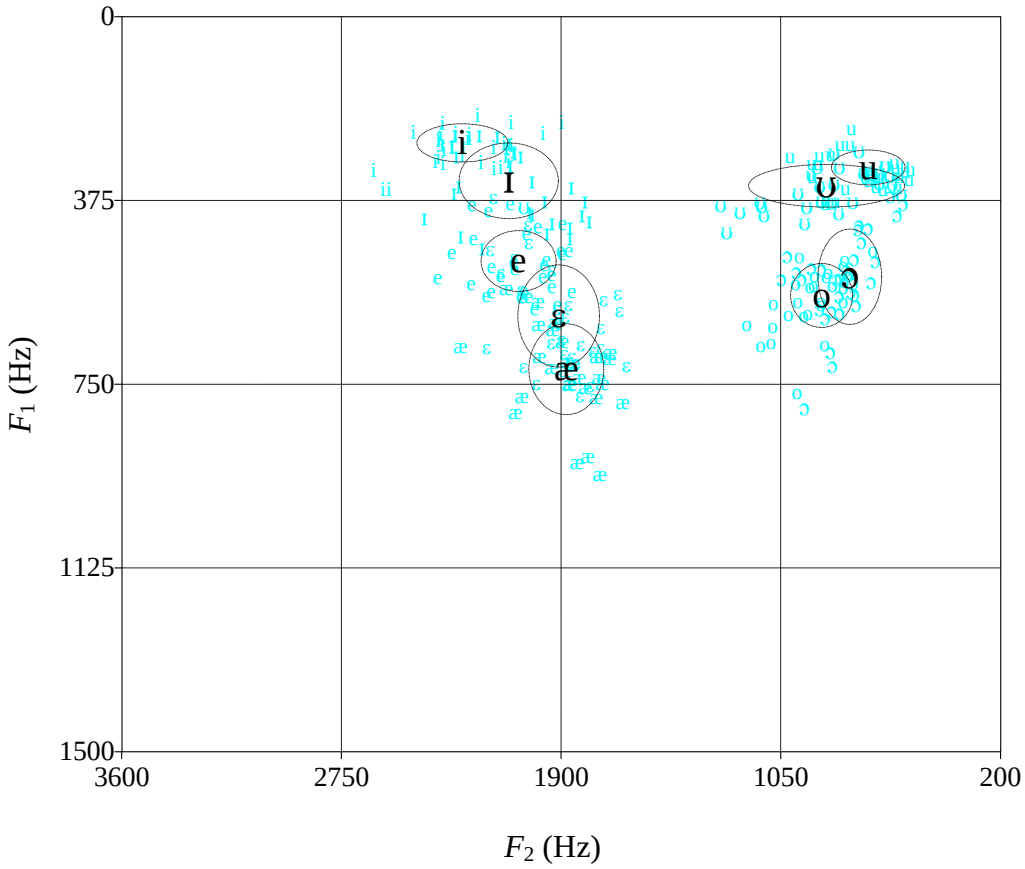
4.4.1.6 English /o/ and /ɔ/

For the English vowel pair /o/ and /ɔ/, male and female subjects from Texas differ significantly in F1 and F2 values (Tables 4.40 and 4.41). However, for male and female subjects from Taiwan English /o/ and /ɔ/ do not differ significantly in F1 or F2 values (Tables 4.42 and 4.43).



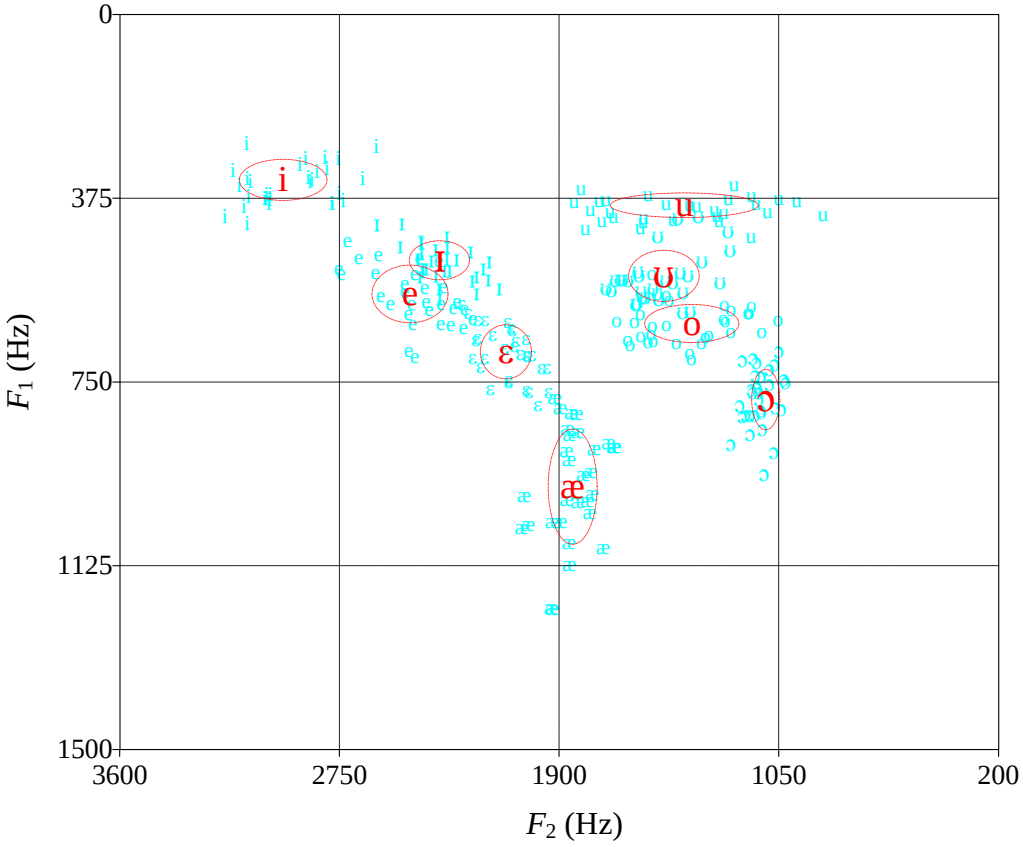
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.16: Nine English vowels from male subjects from Texas.



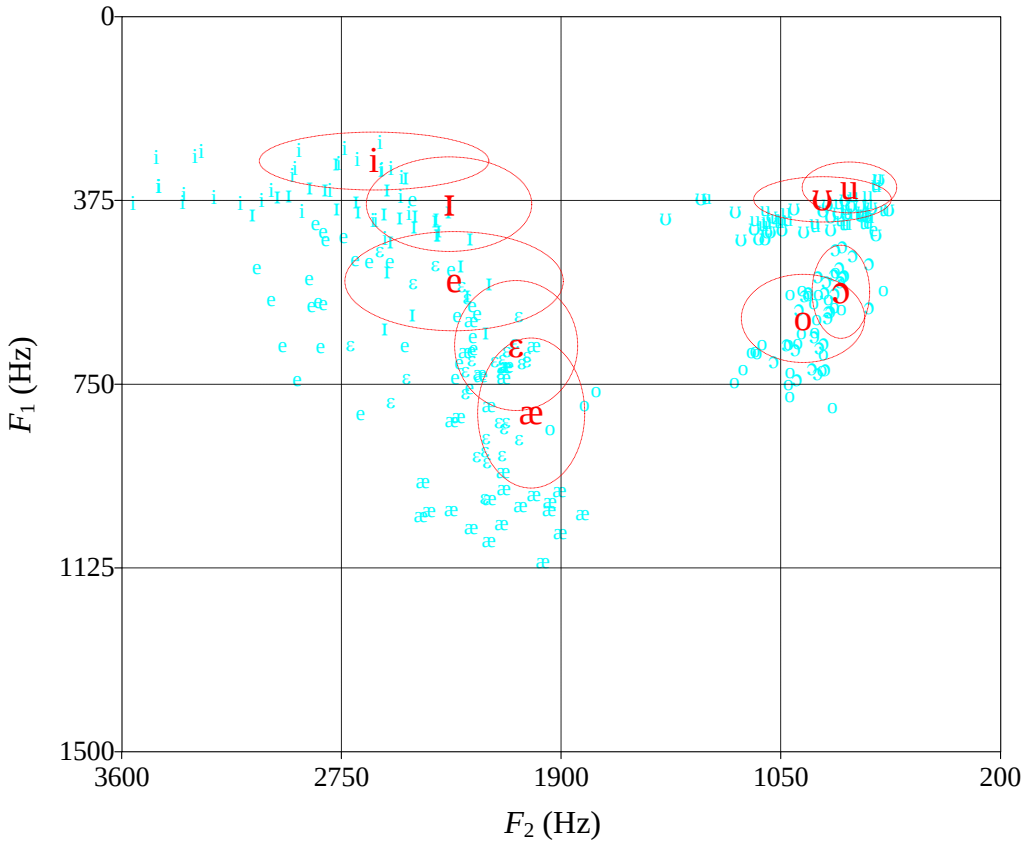
IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.17: Nine English vowels from male subjects from Taiwan.



IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.18: Nine English vowels from female subjects from Texas.



IPA symbols inside the ellipses represent the mean value.
Ellipses represent one standard deviation about the mean.

Figure 4.19: Nine English vowels from female subjects from Taiwan.

Table 4.20: English /i/ vs. English /ɪ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/i/	276	9.287	<0.001	2386	106	<0.001
/ɪ/	432	12.158		2002	260	

Table 4.21: English /i/ vs. English /ɪ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/i/	365	35	<0.001	2881	155	<0.001
/ɪ/	518	31		2325	153	

Table 4.22: English /i/ vs. English /ɪ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/i/	290	34	0.037	2251	163	0.611
/ɪ/	362	73		2086	174	

Table 4.23: English /i/ vs. English /ɪ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/i/	360	43	0.002	2879	309	<0.001
/ɪ/	452	68		2511	174	

Table 4.24: English /u/ vs. English /ʊ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/u/	311	26	<0.001	1097	185	0.316
/ʊ/	446	33		1243	102	

Table 4.25: English /u/ vs. English /ʊ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/u/	413	10	<0.001	1456	260	1.000
/ʊ/	547	37		1528	119	

Table 4.26: English /u/ vs. English /ʊ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/u/	337	32	0.479	809	124	1.000
/ʊ/	370	38		925	179	

Table 4.27: English /u/ vs. English /ʊ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/u/	413	25	1.000	942	173	1.000
/ʊ/	424	21		986	209	

Table 4.28: English /ɛ/ vs. English /æ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/ɛ/	560	37	0.002	1868	82	0.366
/æ/	743	84		1739	127	

Table 4.29: English /ɛ/ vs. English /æ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/ɛ/	693	48	<0.001	2089	82	<0.001
/æ/	950	107		1852	85	

Table 4.30: English /ɛ/ vs. English /æ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/ɛ/	620	57	0.745	1909	125	1.000
/æ/	722	83		1882	126	

Table 4.31: English /ɛ/ vs. English /æ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/ɛ/	733	121	0.015	2211	165	1.000
/æ/	889	143		2131	146	

Table 4.32: English /e/ vs. English /ɛ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	520	47	1.000	2079	131	0.004
/ɛ/	560	37		1868	82	

Table 4.33: English /e/ vs. English /ɛ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	582	31	0.098	2430	106	<0.001
/ɛ/	693	48		2089	82	

Table 4.34: English /e/ vs. English /ɛ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	515	48	0.158	2051	129	0.265
/ɛ/	620	57		1909	125	

Table 4.35: English /e/ vs. English /ɛ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	592	85	0.006	2510	333	<0.001
/ɛ/	733	121		2211	165	

Table 4.36: English /e/ vs. English /æ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	520	47	<0.001	2079	131	<0.001
/æ/	743	84		1739	127	

Table 4.37: English /e/ vs. English /æ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	582	31	<0.001	2430	106	<0.001
/æ/	950	107		1852	85	

Table 4.38: English /e/ vs. English /æ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	515	48	0.001	2051	129	0.166
/æ/	722	83		1882	126	

Table 4.39: English /e/ vs. English /æ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/e/	592	85	<0.001	2510	333	<0.001
/æ/	889	143		2131	146	

Table 4.40: English /o/ vs. English /ɔ/ from Texas males.

English vowels	Texas Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/o/	538	47	0.002	1136	134	<0.001
/ɔ/	629	33		933	71	

Table 4.41: English /o/ vs. English /ɔ/ from Texas females.

English vowels	Texas Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/o/	639	26	<0.001	1429	156	<0.001
/ɔ/	783	48		1166	38	

Table 4.42: English /o/ vs. English /ɔ/ from Taiwan males.

English vowels	Taiwan Males					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/o/	581	54	1.000	975	103	0.701
/ɔ/	545	89		874	110	

Table 4.43: English /o/ vs. English /ɔ/ from Taiwan females.

English vowels	Taiwan Females					
	F1			F2		
	mean	SD	*p*	mean	SD	*p*
/o/	668	66	1000	1106	277	1.000
/ɔ/	603	58		937	56	

4.4.2 Discussion

Six English vowel pairs (/i/ vs. /ɪ/, /u/ vs. /ʊ/, /ɛ/ vs. /æ/, /e/ vs. /ɛ/, /e/ vs. /æ/, and /o/ vs. /ɔ/) from subjects from Texas and Taiwan are discussed in this section. The vowel-by-language group interaction is significant in F1 values ($F_{5,173} = 15.708$, $p < 0.001$) and F2 values ($F_{5,176} = 27.103$, $p < 0.001$), which means that within the same vowel, F1 and F2 values differ significantly by language group. In addition, the three-way interaction among language group, gender, and vowel is significant in F1 values ($F_{10,173} = 2.194$, $p = 0.022$) and F2 values ($F_{10,176} = 6.396$, $p < 0.001$), which means that within the same language group and the same vowel, F1 and F2 values differ significantly by gender.

Figures 4.16 to 4.19 are the scatter plots for the above-mentioned vowel pairs from two subject groups, Texans and Taiwanese. One standard deviation about the mean of the F1 and F2 values is also plotted on top of the scatter plot for each selected vowel. Comparing the male data in the scatter plots (Figures 4.16 and 4.17) in general, the standard deviations for the selected vowels are greater in the male data from Taiwan than in the data from Texas. The same observation can also be made of the female data in Figures 4.18 and 4.19. Furthermore, there is more overlap between selected vowel pairs in the male and female data from Taiwan than in the data from Texas. The following sections contain more detailed discussion for each selected pair of vowels.

4.4.2.1 English /i/ and /ɪ/

In general, there is a negative correlation between F1 values and tongue elevation, and there is a positive correlation between F2 values and tongue advancement (Borden *et al*., 2003; Pickett, 1999). English /i/ is a close-front unrounded vowel. The lips are not rounded for English /i/ and /ɪ/. The position of the tongue is very close to the roof of the mouth compared with other vowels; in other words, the aperture of the mouth is very small. Moreover, the position of the tongue is forward. The constriction occurs at the front of the palate. English /ɪ/ is a near-close near-front unrounded vowel. The tongue position is a little lower and further back than that of English /i/. The English male and female subjects from Texas and female subjects from Taiwan differ significantly for English /i/ and English /ɪ/ with respect to F1 and F2 values (Table 4.20, Table 4.21, and Table 4.23, respectively), which means that in male and female subjects from Texas and female subjects from Taiwan tongue height and tongue advancement differ significantly for English /i/ and /ɪ/. However, male subjects from Taiwan differ significantly in tongue elevation but not in tongue advancement between English /i/ and English /ɪ/.

4.4.2.2 English /u/ and /ʊ/

English /u/ is a close-back rounded vowel. The vertical position of the tongue is close to the roof of the mouth and the horizontal position is towards to the soft palate. English /ʊ/ is a near-close near-back rounded vowel. The tongue position is a little lower and further forward than that of English /u/. The lips are rounded for English /u/ and /ʊ/. Based on Table 4.24 and Table 4.25 (*p* values), for the English vowel pair /u/ and /ʊ/, male and female subjects from Texas differ significantly in the aperture of the mouth but not in tongue advancement. It can be inferred that the main difference between English /u/ and English /ʊ/ is in the aperture of the mouth. Male and female subjects from Taiwan do not differ significantly in the aperture of the mouth or the backing of the tongue for English /u/ and /ʊ/ (Tables 4.26 and 4.27).

4.4.2.3 English /ɛ/ and /æ/

English /ɛ/ is an open-mid front-unrounded vowel. Tongue elevation of English /ɛ/ is intermediate between that of an open vowel and that of a mid vowel. The horizontal tongue position is relatively for forward in the mouth. English /æ/ is a near-open front-unrounded vowel. The aperture of the mouth is less open than that of an open vowel such as /ɑ/. The lips are unrounded for English /ɛ/ and English /æ/.

The horizontal tongue position is forward in the mouth. For the English vowel pair /ɛ/ and /æ/, male and female subjects from Texas and female subjects from Taiwan differ significantly in the vertical position of the tongue (the aperture of the mouth) (Tables 4.28, 4.29, and 4.31). Female subjects from Texas differ significantly in tongue advancement between English /ɛ/ and /æ/ (Tables 4.29). Male subjects from Texas and female subjects from Taiwan do not differ significantly in tongue advancement between English /ɛ/ and /æ/ (Tables 4.28 and 4.31). Male subjects from Texas do not differ significantly in tongue advancement for English /ɛ/ and English /æ/ (Table 4.28). Male subjects from Taiwan do not differ significantly in tongue elevation or tongue advancement for English /ɛ/ and English /æ/ (Table 4.30).

4.4.2.4 English /e/ and /ɛ/

English /e/ is a close-mid front-unrounded vowel. The vertical tongue position is between that of a close vowel such as /i/ and that of a mid vowel such as /ə/. The amount of front tongue constriction is less than in /i/. For the English vowel pair /e/ and /ɛ/, male and female subjects from Texas differ significantly in front tongue constriction but not in the aperture of the mouth (Tables 4.32 and 4.33). Male subjects from Taiwan do not differ significantly in aperture of the mouth or front tongue constriction for English /e/ and English /ɛ/ (Table 4.34). Female subjects from Taiwan

differ significantly in the aperture of the mouth and front tongue constriction for this pair of English vowels (Table 4.35).

4.4.2.5 English /e/ and /æ/

Male and female subjects from Texas and female subjects from Taiwan differ significantly in the aperture of the mouth and front tongue constriction for English /e/ and English /æ/ (Table 4.36, Table 4.37, and Table 4.39). Male subjects from Taiwan differ significantly in the aperture of the mouth for English /e/ and English /æ/ but not in front tongue constriction (Table 4.38).

4.4.2.6 English /o/ and /ɔ/

English /o/ is a close-mid back-rounded vowel. The aperture of the mouth is between that of a close vowel and that of a mid vowel. For the horizontal tongue position, English /o/ typically has less back tongue constriction and also less lip-rounding than English /u/ (Pickett, 1999). English /ɔ/ is an open-mid back-rounded vowel. The aperture of the mouth is between that of an open vowel and that of a mid vowel. The horizontal tongue position of English /o/ and /ɔ/ is as far back as possible in the mouth. With regard to the vowel pair /o/ and /ɔ/, male and female subjects from Texas differ significantly in the aperture of the mouth and back tongue constriction (Tables 4.40 and 4.41). However, male and female subjects from Taiwan do not differ

significantly in the aperture of the mouth and back tongue constriction for these English vowels (Tables 4.42 and 4.43).

4.5 Comparing Mandarin Vowels and English Vowels from Mandarin Subjects

This section investigates whether there is any correspondence between how Mandarin subjects pronounce Mandarin vowels and how they pronounce the Mandarin vowels' English equivalents. Repeated measures ANOVA was applied to determine if F1 and F2 values varied with vowel and gender. If the sphericity assumption was violated, the Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

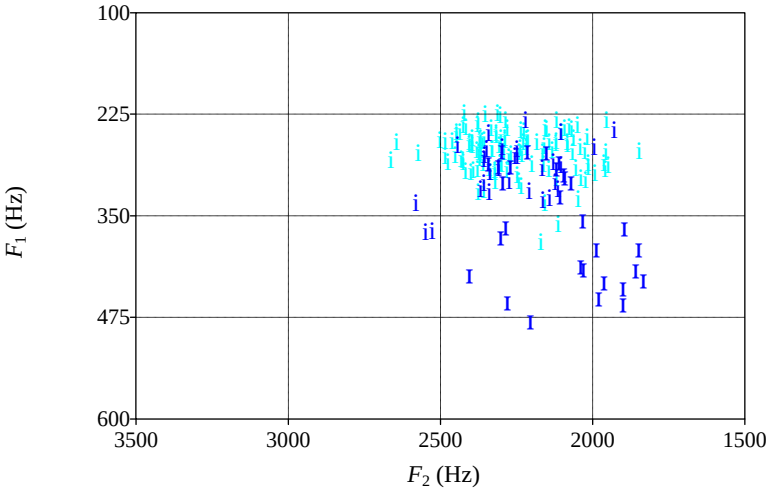
In this study, each Mandarin vowel was compared to each English vowel, as well as to all the other Mandarin vowels. The F1 and F2 values of Mandarin /i/ vs. English /i/, Mandarin /i/ vs. English /ɪ/, /Mandarin /u/ vs. English /u/, Mandarin /u/ vs. English /ʊ/, Mandarin /e/ vs. English /e/, Mandarin /e/ vs. English /ɛ/, Mandarin /e/ vs. English /æ/ and Mandarin /o/ vs. English /o/, and Mandarin /o/ vs. English /ɔ/, and Mandarin /a/ vs. English /ɑ/ are analyzed.

4.5.1 Statistical Results

A significant gender difference exists for both F1 values ($F_{1,18} = 57.965$, $p < 0.001$) and F2 values ($F_{1,18} = 49.270$, $p < 0.001$). In addition, the vowel-by-gender interaction is significant in the F2 values ($F_{5,90} = 9.843$, $p < 0.001$), but not in the F1 values ($F_{5,97} = 2.008$, $p = 0.078$).

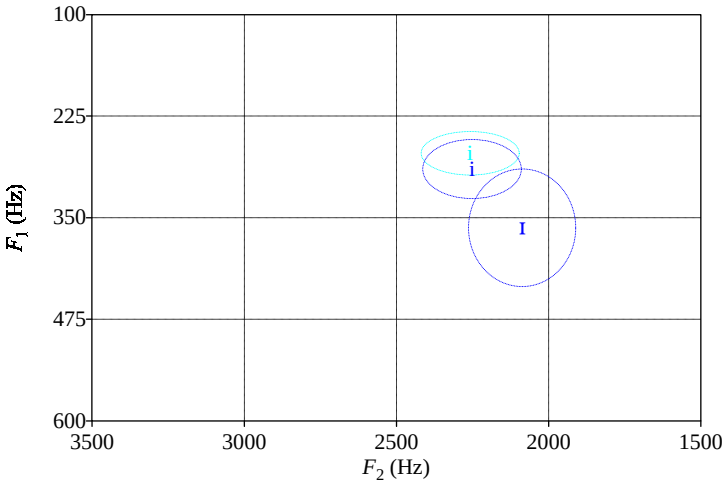
4.5.1.1 Mandarin /i/ vs. English /i/ and /ɪ/ from Subjects from Taiwan

Mandarin male and female subjects do not differ significantly in their F1 and F2 values for Mandarin /i/ and English /i/ (Figures 4.20 to 4.23 and Tables 4.44 and 4.46). Mandarin female subjects differ significantly in F1 and F2 values for Mandarin /i/ and English /ɪ/ (Figures 4.22 and 4.23 and Table 4.47). Mandarin male subjects do not differ significantly in F1 and F2 values for Mandarin /i/ and English /ɪ/ (Figures 4.20 and 4.21 and Table 4.45).



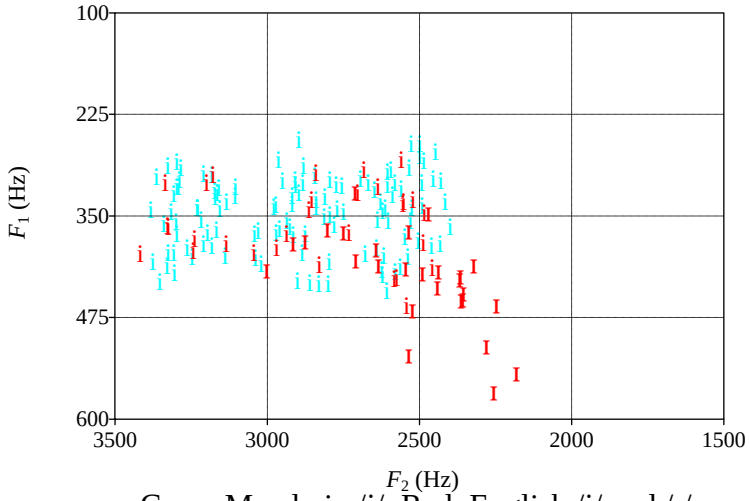
Cyan: Mandarin /i/; Blue: English /i/ and /ɪ/.

Figure 4.20: Scatter plot for Mandarin /i/ vs. English /i/ and /ɪ/ from male subjects from Taiwan.



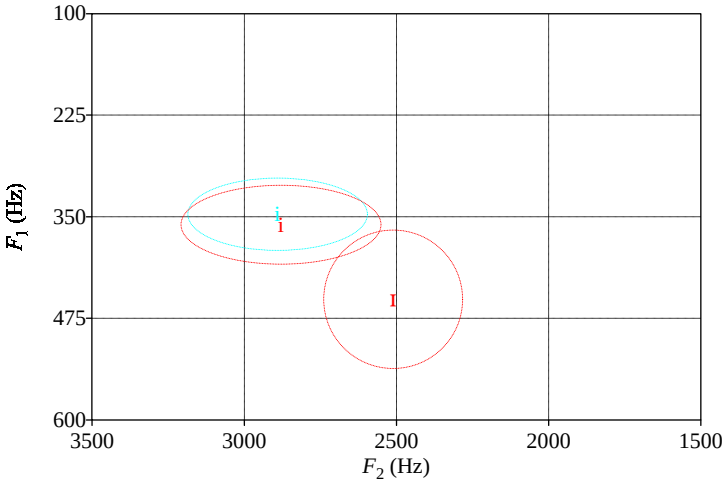
Cyan: Mandarin /i/; Blue: English /i/ and /ɪ/.
Ellipses represent one standard deviation about the mean.

Figure 4.21: Mean and standard deviation for Mandarin /i/ vs. English /i/ and /ɪ/ from male subjects from Taiwan.



Cyan: Mandarin /i/; Red: English /i/ and /ɪ/.

Figure 4.22: Scatter plot for Mandarin /i/ vs. English /i/ and /ɪ/ for female subjects from Taiwan.



Cyan: Mandarin /i/; Red: English /i/ and /ɪ/.
Ellipses represent one standard deviation about the mean.

Figure 4.23: Mean and standard deviation for Mandarin /i/ vs. English /i/ and /ɪ/ for female subjects from Taiwan.

Table 4.44: Mandarin /i/ vs. English /i/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/i/	271	10	1.000	2257	155	1.000
English	/i/	290	34		2251	163	

Table 4.45: Mandarin /i/ vs. English /ɪ/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/i/	271	10	0.114	2257	155	1.000
English	/ɪ/	362	73		2086	174	

Table 4.46: Mandarin /i/ vs. English /i/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/i/	347	31	1.000	2890	297	1.000
English	/i/	360	43		2879	309	

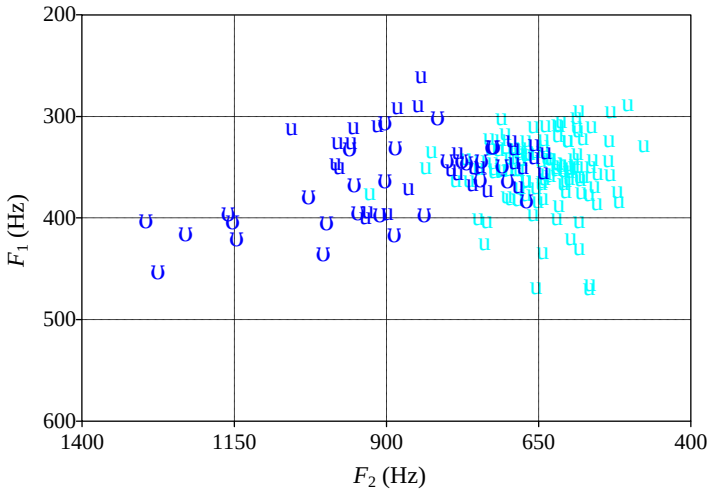
Table 4.47: Mandarin /i/ vs. English /ɪ/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/i/	347	31	0.032	2890	297	0.007
English	/ɪ/	452	68		2511	198	

4.5.1.2 Mandarin /u/ vs. English /u/ and /ʊ/ from Subjects from Taiwan

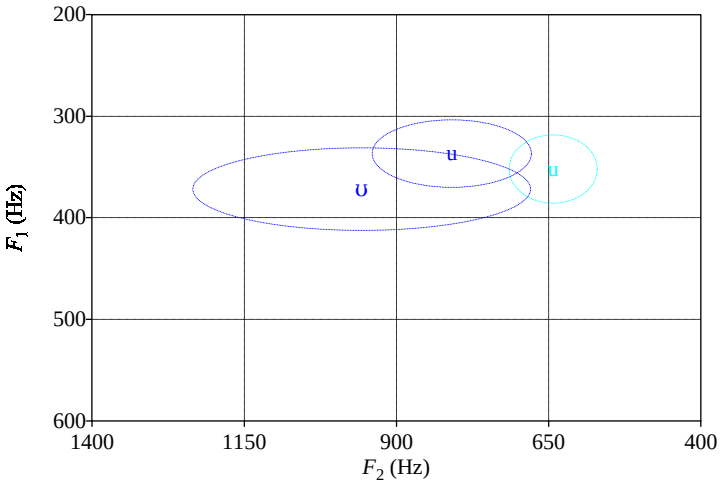
Mandarin male subjects do not differ significantly in their F1 and F2 values for Mandarin /u/ and English /u/ (Figures 4.24 and 4.25 and Table 4.48). However, female Mandarin /u/ and English /u/ differ significantly in F2 values but not in F1 values (Figures 4.26 and 4.27 and Table 4.50).

Female Mandarin /u/ and English /ʊ/ do not differ significantly in F1 and F2 values (Figures 4.26 and 4.27 and Table 4.51). Male Mandarin /u/ and English /ʊ/ differ significantly in F2 values but not in F1 values (Figures 4.24, and 4.25, and Table 4.49).



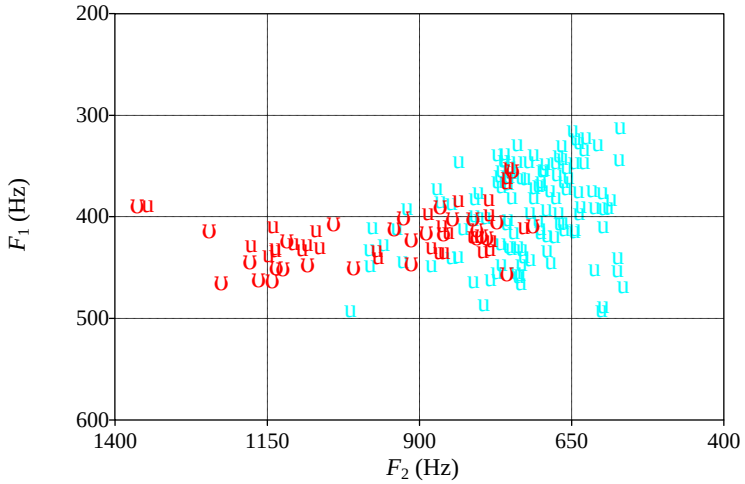
Cyan: Mandarin /u/; Blue: English /u/ and /ʊ/.

Figure 4.24: Scatter plot for Mandarin /u/ vs. English /u/ and /ʊ/ for male subjects from Taiwan.



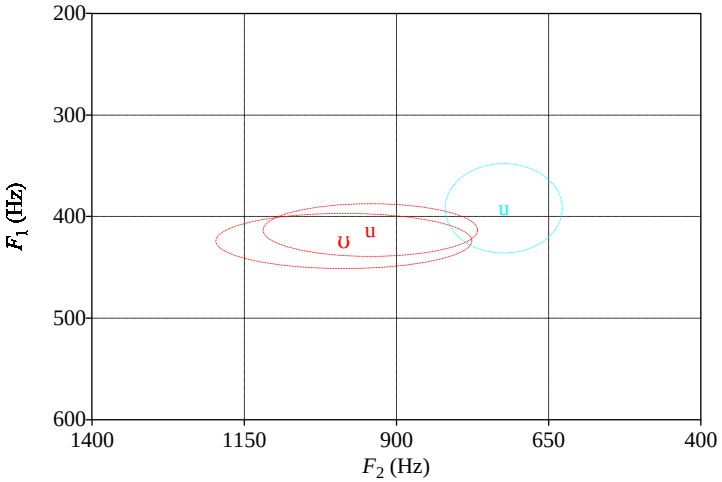
Cyan: Mandarin /u/; Blue: English /u/ and /ʊ/
Ellipses represent one standard deviation about the mean.

Figure 4.25: Mean and standard deviation for Mandarin /u/ vs. English /u/ and /ʊ/ for male subjects from Taiwan.



Cyan: Mandarin /u/; Red: English /u/ and /ʊ/

Figure 4.26: Scatter plot for Mandarin /u/ vs. English /u/ and /ʊ/ for female subjects from Taiwan.



Cyan: Mandarin /u/; Red: English /u/ and /ʊ/.
Ellipses represent one standard deviation about the mean.

Figure 4.27: Mean and standard deviation for Mandarin /u/ vs. English /u/ and /ʊ/ for female subjects from Taiwan.

Table 4.48: Mandarin /u/ vs. English /u/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/u/	352	16	1.000	642	45	0.278
English	/u/	337	32		809	124	

Table 4.49: Mandarin /u/ vs. English /ʊ/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/u/	352	16	1.000	642	45	0.037
English	/ʊ/	370	38		925	179	

Table 4.50: Mandarin /u/ vs. English /u/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/u/	392	12	1.000	724	61	0.021
English	/u/	413	25		942	173	

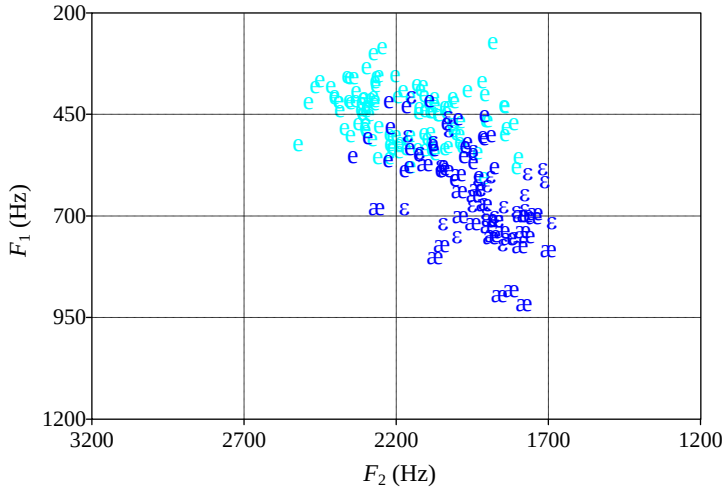
Table 4.51: Mandarin /u/ vs. English /ʊ/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/u/	392	12	1.000	724	61	0.075
English	/ʊ/	424	21		986	209	

4.5.1.3 Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ from Subjects from Taiwan

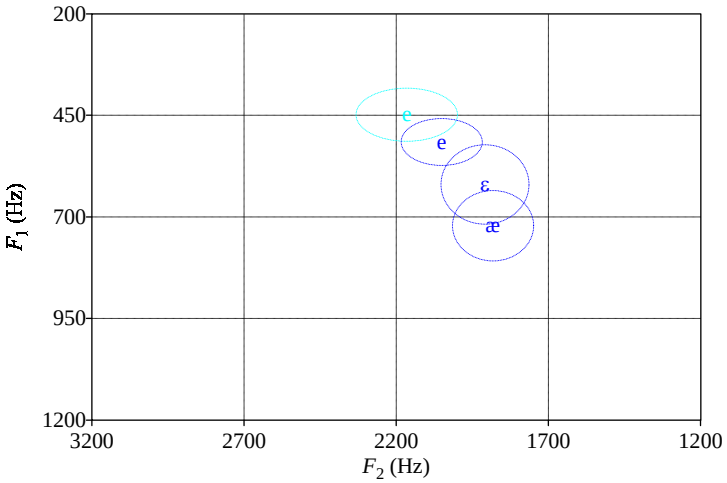
Mandarin /e/ and English /e/ do not differ in F1 and F2 values from either male or female subjects (Figures 4.28 to 4.31, Tables 4.52 and 4.55). Comparisons of male Mandarin /e/ vs. English /ɛ/ (Figures 4.28 and 4.29 and Table 4.53) and of Mandarin /e/ vs. English /æ/ (Figures 4.28 and 4.29 and Table 4.54) reveal significant differences in F1 values but not in F2 values.

Comparisons of female Mandarin /e/ vs. English /ɛ/ (Figures 4.30 and 4.31 and Table 4.56) and of female Mandarin /e/ vs. English /æ/ (Figures 4.30 and 4.31 and Table 4.57) reveal significant differences in both F1 and F2 values.



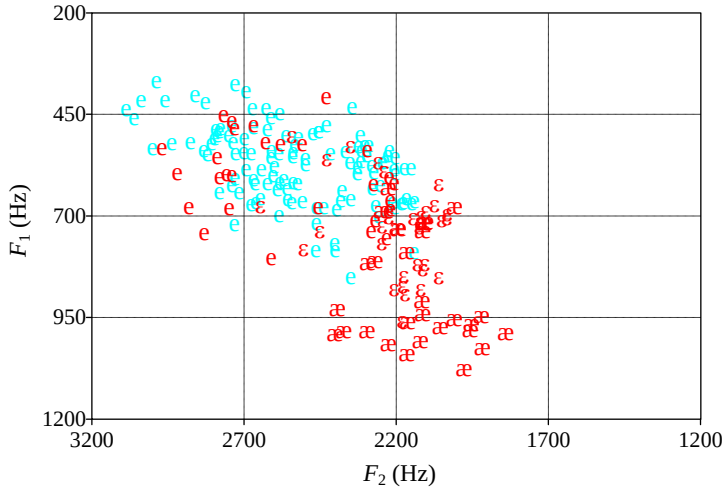
Cyan: Mandarin /e/; Blue: English e/, /ɛ/, and /æ/.

Figure 4.28: Scatter plot for Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ for male subjects from Taiwan.



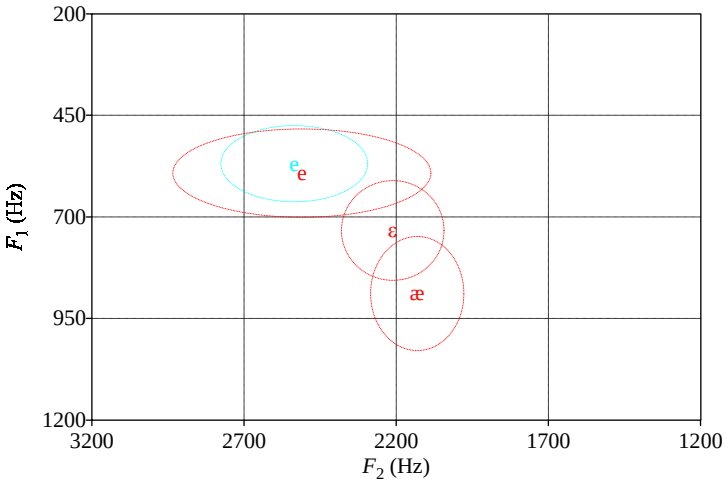
Cyan: Mandarin /e/; Blue: English e/, /ɛ/, and /æ/.
Ellipses represent one standard deviation about the mean.

Figure 4.29: Mean and standard deviation for Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ for male subjects from Taiwan.



Cyan: Mandarin /e/; Red: English e/, /ɛ/, and /æ/.

Figure 4.30: Scatter plot for Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ for female subjects from Taiwan.



Cyan: Mandarin /e/; Red: English e/, /ɛ/, and /æ/.
Ellipses represent one standard deviation about the mean.

Figure 4.31: Mean and standard deviation for Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ for female subjects from Taiwan.

Table 4.52: Mandarin /e/ vs. English /e/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	448	50	1.000	2166	157	1.000
English	/e/	515	48		2051	129	

Table 4.53: Mandarin /e/ vs. English /ɛ/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	448	50	0.004	2166	157	0.063
English	/ɛ/	620	57		1909	125	

Table 4.54: Mandarin /e/ vs. English /æ/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	448	50	0.001	2166	157	0.067
English	/æ/	722	83		1882	126	

Table 4.55: Mandarin /e/ vs. English /e/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	569	56	1.000	2535	219	1.000
English	/e/	592	85		2568	262	

Table 4.56: Mandarin /e/ vs. English /ɛ/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	569	56	0.007	2535	219	0.005
English	/ɛ/	733	121		2211	165	

Table 4.57: Mandarin /e/ vs. English /æ/ from female subjects from Taiwan.

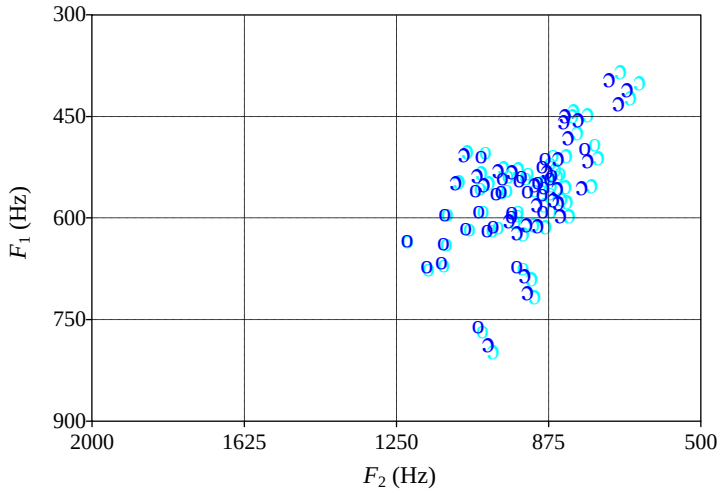
		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	569	56	<0.001	2535	219	0.001
English	/æ/	889	143		2131	146	

4.5.1.4 Mandarin /o/ vs. English /o/ and /ɔ/ from Subjects from Taiwan

Mandarin female subjects do not differ significantly in their F1 and F2 values for Mandarin /o/ and English /o/ (Figures 4.34 and 4.35 and Table 4.60), nor for Mandarin /o/ and English /ɔ/ (Figures 4.34 and 4.35 and Table 4.61). Mandarin male subjects differ significantly in F2 values for Mandarin /o/ and English /o/ (Figures 4.32 and 4.33 and Table 4.58) but not in F1 values. Mandarin male subjects differ significantly in F2 values, but not in F1 values, for Mandarin /o/ and English /ɔ/ (Table 4.59).

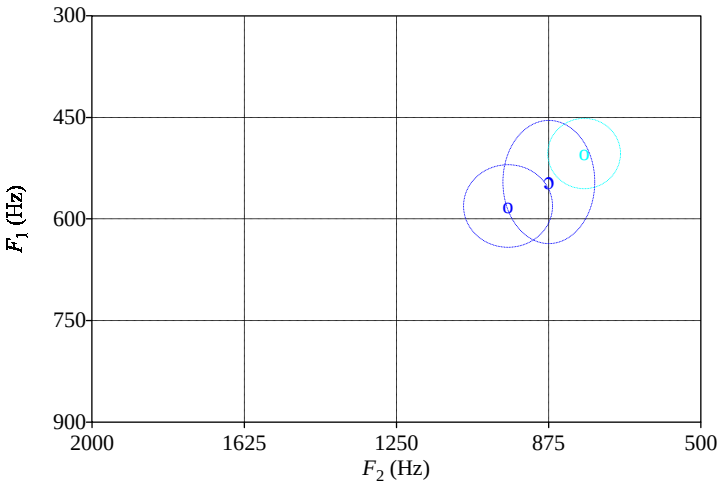
4.5.1.5 Mandarin /a/ vs. English /ɑ/ from Subjects from Taiwan

Mandarin male and female subjects do not differ significantly in F1 and F2 values for Mandarin /a/ and English /ɑ/ (Figures 4.36 and 4.39 and Tables 4.62 and 4.63).



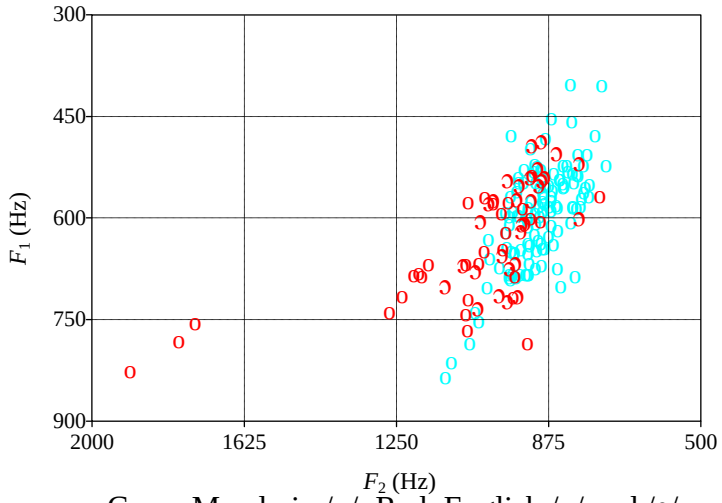
Cyan: Mandarin /o/; Blue: English /o/ and /ɔ/.

Figure 4.32: Scatter plot for Mandarin /o/ vs. English /o/ and /ɔ/ from male subjects from Taiwan.



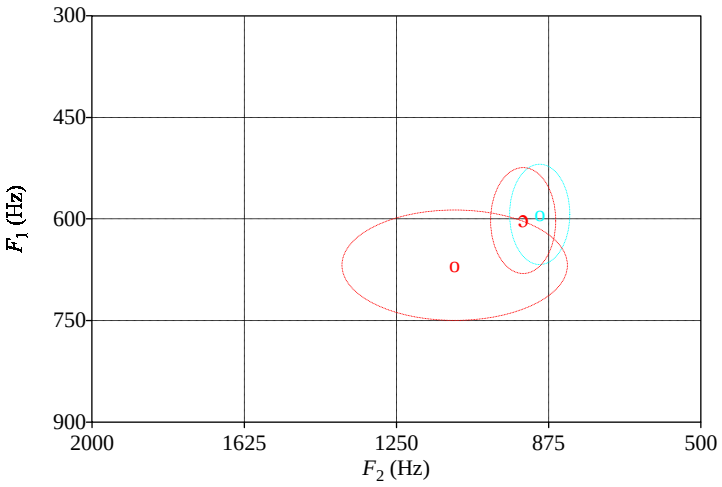
Cyan: Mandarin /o/; Blue: English /o/ and /ɔ/.
Ellipses represent one standard deviation about the mean.

Figure 4.33: Mean and standard deviation for Mandarin /o/ vs. English /o/ and /ɔ/ from male subjects from Taiwan.



Cyan: Mandarin /o/; Red: English /o/ and /ɔ/.

Figure 4.34: Scatter plot for Mandarin /o/ vs. English /o/ and /ɔ/ from female subjects from Taiwan.



Cyan: Mandarin /o/; Red: English /o/ and /ɔ/.
Ellipses represent one standard deviation about the mean.

Figure 4.35: Mean and standard deviation for Mandarin /o/ vs. English /o/ and /ɔ/ from female subjects from Taiwan.

Table 4.58: Mandarin /o/ vs. English /o/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	503	37	0.130	787	77	0.002
English	/o/	581	54		975	103	

Table 4.59: Mandarin /o/ vs. English /ɔ/ from male subjects from Taiwan.

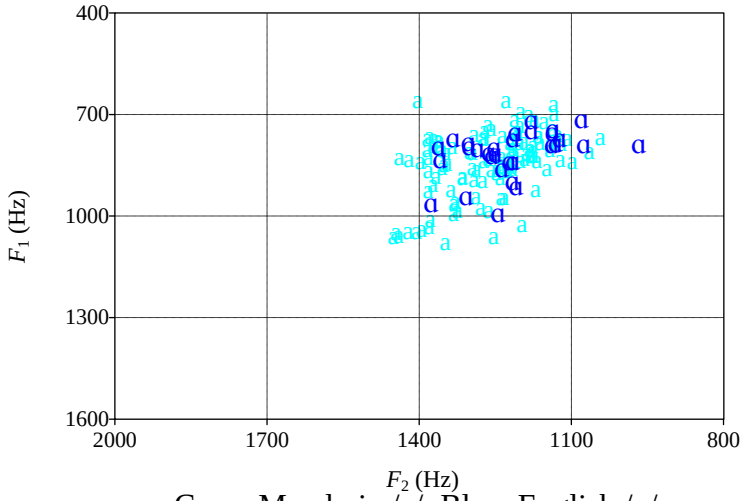
		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	503	37	1.000	787	77	0.023
English	/ɔ/	545	89		874	110	

Table 4.60: Mandarin /o/ vs. English /o/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	593	59	1.000	897	50	0.160
English	/o/	649	51		1020	99	

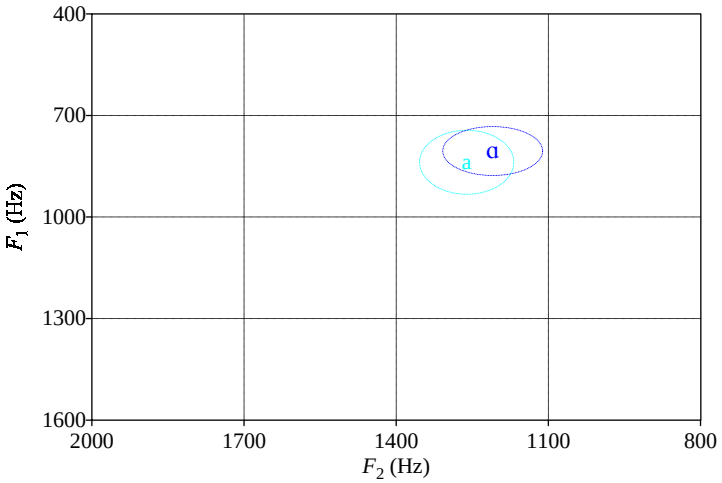
Table 4.61: Mandarin /o/ vs. English /ɔ/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	593	59	1.000	897	50	1.000
English	/ɔ/	603	58		937	56	



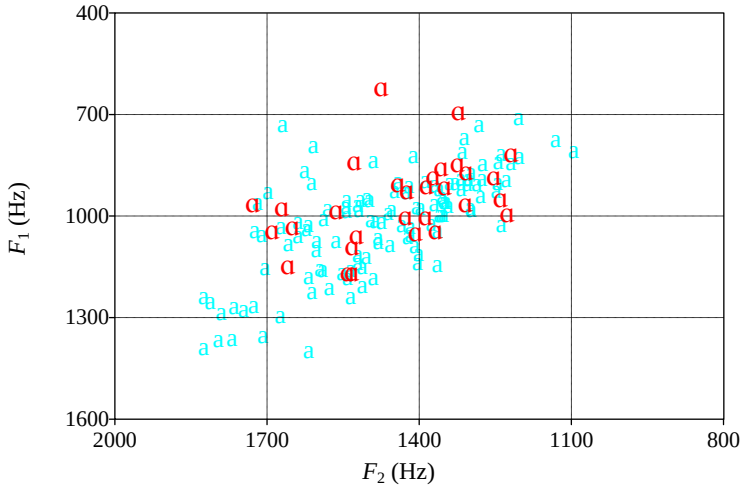
Cyan: Mandarin /a/; Blue: English /ɑ/.

Figure 4.36: Scatter plot for Mandarin /a/ vs. English /ɑ/ from male subjects from Taiwan.



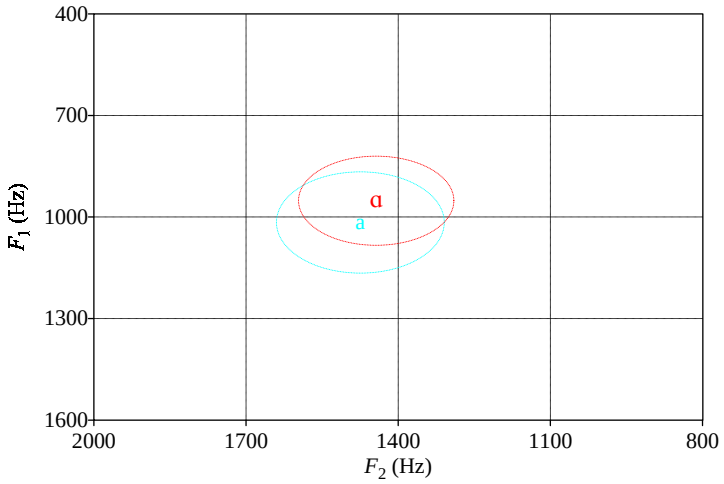
Cyan: Mandarin /a/; Blue: English /ɑ/.
Ellipses represent one standard deviation about the mean.

Figure 4.37: Mean and standard deviation for Mandarin /a/ vs. English /ɑ/ from male subjects from Taiwan.



Cyan: Mandarin /a/; Red: English /ɑ/.

Figure 4.38: Scatter plot for Mandarin /a/ vs. English /ɑ/ from female subjects from Taiwan.



Cyan: Mandarin /a/; Red: English /ɑ/.
Ellipses represent one standard deviation about the mean.

Figure 4.39: Mean and standard deviation for Mandarin /a/ vs. English /ɑ/ from female subjects from Taiwan.

Table 4.62: Mandarin /a/ vs. English /ɑ/ from male subjects from Taiwan.

		Male subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	839	77	1.000	1261	75	1.000
English	/ɑ/	805	70		1210	91	

Table 4.63: Mandarin /a/ vs. English /ɑ/ from female subjects from Taiwan.

		Female subjects from Taiwan					
		F1			F2		
		mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	1016	113	1.000	1475	118	1.000
English	/ɑ/	952	60		1444	145	

4.5.2 Discussion

4.5.2.1 Mandarin /i/ vs. English /i/ and /ɪ/ from Subjects from Taiwan

Mandarin male and female subjects do not differ significantly in their tongue height and tongue advancement for Mandarin /i/ and English /i/ (Figures 4.20 to 4.23 and Tables 4.44 and 4.46). Mandarin female subjects differ significantly in tongue height and tongue advancement for Mandarin /i/ and English /ɪ/ (Figures 4.22 and 4.23 and Table 4.47), while Mandarin male subjects do not differ significantly in tongue height and tongue advancement (Figures 4.20 and 4.21 and Table 4.45).

4.5.2.2 Mandarin /u/ vs. English /u/ and /ʊ/ from Subjects from Taiwan

Mandarin male subjects do not differ significantly in tongue height and tongue advancement for Mandarin /u/ and English /u/ (Figures 4.24 and 4.25 and Table 4.48). However, female Mandarin /u/ and English /u/ differ significantly in back tongue constriction (proximity to the soft palate) but not in tongue height (Figures 4.26 and 4.27 and Table 4.50).

Female Mandarin /u/ and English /ʊ/ do not differ significantly either in back tongue constriction or in tongue height (Figures 4.26 and 4.27 and Table 4.50). Male Mandarin /u/ and English /ʊ/ differ significantly in back tongue constriction (Figures 4.24 and 4.25 and Table 4.49) but not in tongue height.

4.5.2.3 Mandarin /e/ vs. English /e/, /ɛ/, and /æ/ from Subjects from Taiwan

Mandarin /e/ and English /e/ do not differ significantly in respect of their front tongue constriction (proximity to the middle of the palate) or in tongue height, in the speech of either males or females (Figures 4.28 to 4.31, Tables 4.52 and 4.55). Comparisons of male Mandarin /e/ with English /ɛ/ (Figures 4.28 and 4.29 and Table 4.53), and with English /æ/ (Figures 4.28 and 4.29 and Table 4.54) reveal significant differences in tongue height but not in tongue advancement.

Comparisons of female Mandarin /e/ with English /ɛ/ (Figures 4.30 and 4.31 and Table 4.56), and with English /æ/ (Figures 4.30 and 4.31 and Table 4.57) show significant differences in both tongue height and tongue advancement.

4.5.2.4 Mandarin /o/ vs. English /o/ and /ɔ/ from Subjects from Taiwan

Mandarin female subjects do not differ significantly in tongue elevation and tongue advancement for Mandarin /o/ and English /o/ (Figures 4.34 and 4.35 and Table 4.60), nor for Mandarin /o/ and English /ɔ/ (Figures 4.34 and 4.35 and Table 4.61). Mandarin male subjects differ significantly in tongue advancement, but not in tongue elevation, for Mandarin /o/ and English /o/ (Figures 4.32 and 4.33 and Table 4.58); this is also true for Mandarin /o/ and English /ɔ/ (Table 4.59).

4.5.2.5 Mandarin /a/ vs. English /ɑ/ from Subjects from Taiwan

Neither male nor female Mandarin subjects differ significantly in tongue height and tongue advancement between Mandarin /a/ and English /ɑ/ (Figures 4.36 and 4.37 and Tables 4.62 and 4.63).

4.6 English and Mandarin Diphthongs

This section investigates whether there is a relationship between how Mandarin subjects pronounce Mandarin diphthongs and how they pronounce the Mandarin diphthongs' English equivalents. Repeated measures ANOVA was applied to determine if F1 and F2 values varied with vowel and gender. If the sphericity assumption was violated, the Greenhouse-Geisser adjusted values are reported instead. Mean values for F1 and F2 were further compared by pairwise comparisons using Bonferroni's adjustment for multiple comparisons.

In this section, each vowel in a diphthong was compared with all the other vowels in both Mandarin and English diphthongs. For example, /a/ in English /aɪ/ was compared with all the vowels in the Mandarin diphthongs (/ai, au, ei, ou/) as well as with the /ɪ/ in English /aɪ/ and the vowels in the English diphthongs (/aʊ, eɪ, oʊ/). The F1 and F2 values of Mandarin double finals (diphthongs) (Mandarin /ai/ vs. English /aɪ/, /Mandarin /au/ vs. English /aʊ/, Mandarin /ei/ vs. English /eɪ/, and Mandarin /ou/ vs. English /oʊ/) are analyzed.

4.6.1 Statistical Results

A significant gender difference exists for both F1 values ($F_{1,18} = 70.711$, $p < 0.001$) and F2 values ($F_{1,18} = 56.297$, $p < 0.001$). In addition, the vowel-by-gender

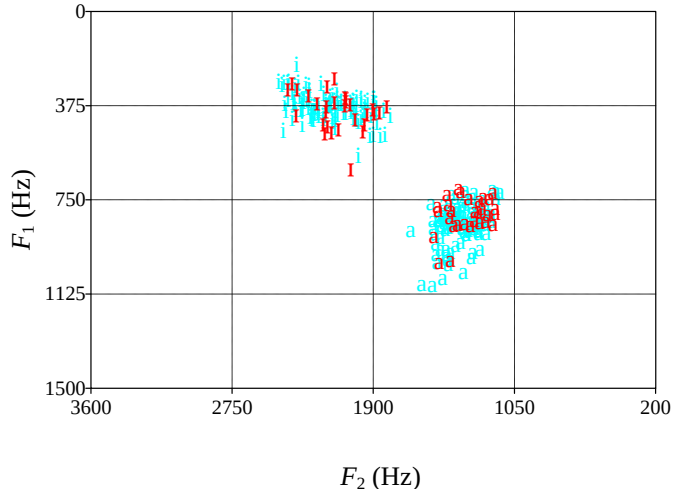
interaction is significant in F1 values ($F_{3,58} = 7.141$, $p < 0.001$) and in F2 values ($F_{4,73} = 10.323$, $p < 0.001$).

Table 4.64: Mandarin diphthongs from Mandarin speakers.

Vowels			F1			F2		
		Gender	Mean	SD	*p*	Mean	SD	*p*
/ai/	/a/	M	845	73	<0.001	1368	78	<0.001
		F	1049	95		1689	162	
	/i/	M	380	34	0.006	2159	164	<0.001
		F	426	33		2671	261	
/au/	/a/	M	785	62	0.001	1171	91	0.007
		F	935	102		1327	134	
	/u/	M	503	45	0.310	854	98	0.064
		F	535	84		944	106	
/ei/	/e/	M	481	39	0.002	2130	144	<0.001
		F	554	48		2577	232	
	/i/	M	328	37	0.014	2260	166	<0.001
		F	368	29		2853	248	
/ou/	/o/	M	545	44	<0.001	879	86	0.001
		F	637	41		1007	53	
	/u/	M	393	35	0.283	714	81	0.035
		F	410	33		793	73	

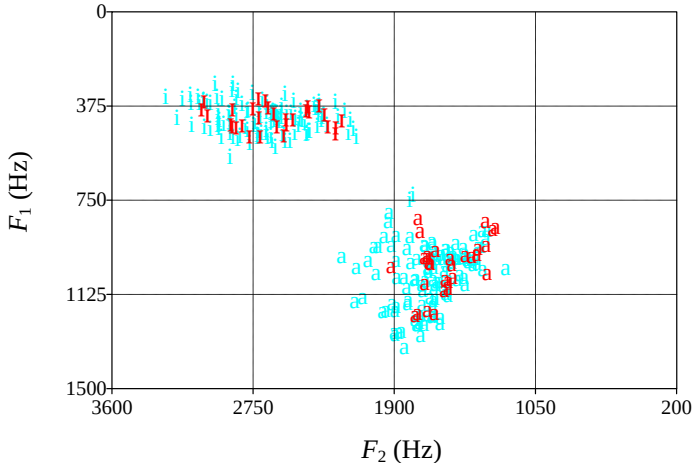
Table 4.65: English diphthongs from Mandarin speakers.

Vowels			F1			F2		
		Gender	Mean	SD	*p*	Mean	SD	*p*
/aɪ/	/a/	M	808	72	<0.001	1304	112	<0.001
		F	1020	101		1569	127	
	/ɪ/	M	373	59	0.202	2126	161	<0.001
		F	403	39		2667	263	
/aʊ/	/a/	M	786	54	<0.001	1229	104	0.004
		F	984	128		1473	209	
	/ʊ/	M	457	76	0.888	874	104	0.562
		F	461	47		903	114	
/eɪ/	/e/	M	515	48	0.023	2051	129	0.001
		F	592	85		2568	262	
	/ɪ/	M	297	48	0.142	2249	158	0.001
		F	324	28		2878	258	
/oʊ/	/o/	M	581	54	0.010	975	103	0.325
		F	649	51		1020	99	
	/ʊ/	M	342	47	0.182	1101	203	0.332
		F	365	23		1222	328	



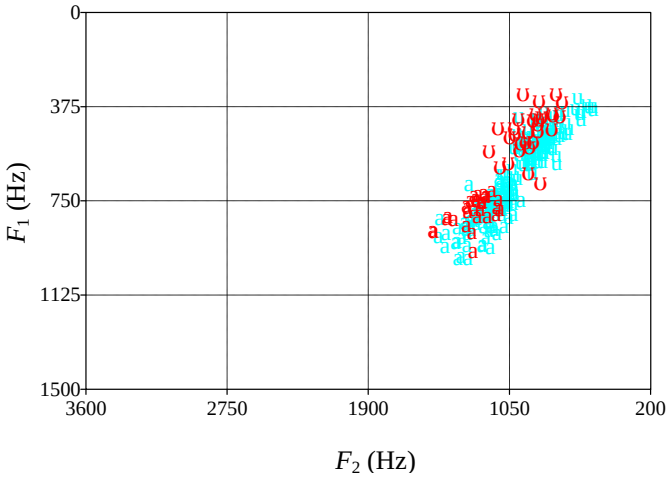
Cyan: Mandarin /ai/; Red: English /aɪ/.

Figure 4.40: Mandarin /ai/ and English /aɪ/ from male subjects from Taiwan.



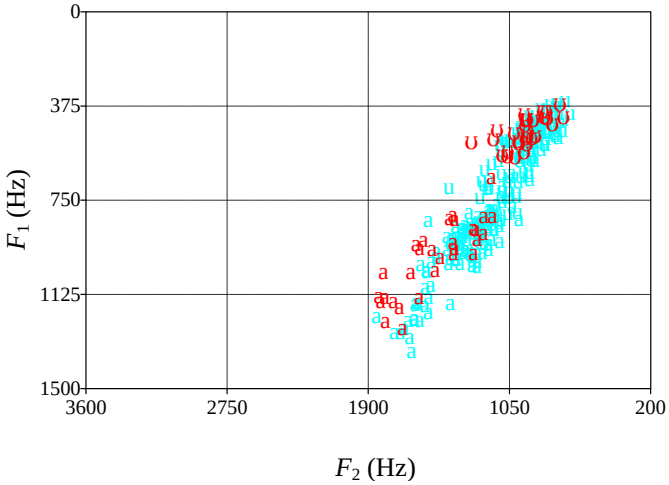
Cyan: Mandarin /ai/; Red: English /aɪ/.

Figure 4.41: Mandarin /ai/ and English /aɪ/ from female subjects from Taiwan.



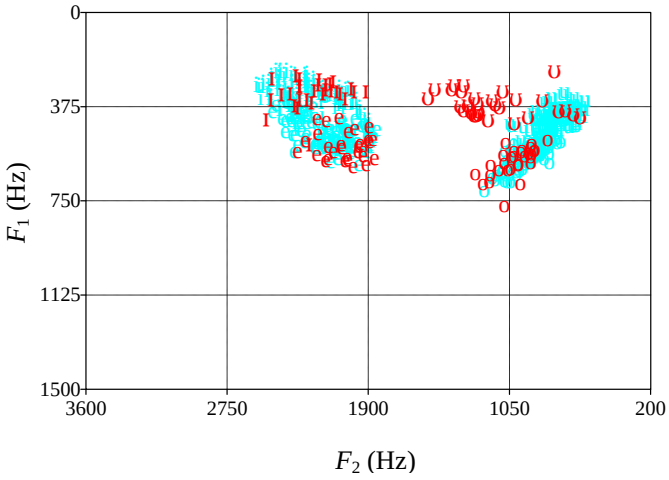
Cyan: Mandarin /au/; Red: English /aʊ/.

Figure 4.42: Mandarin /au/ and English /aʊ/ from male subjects from Taiwan.



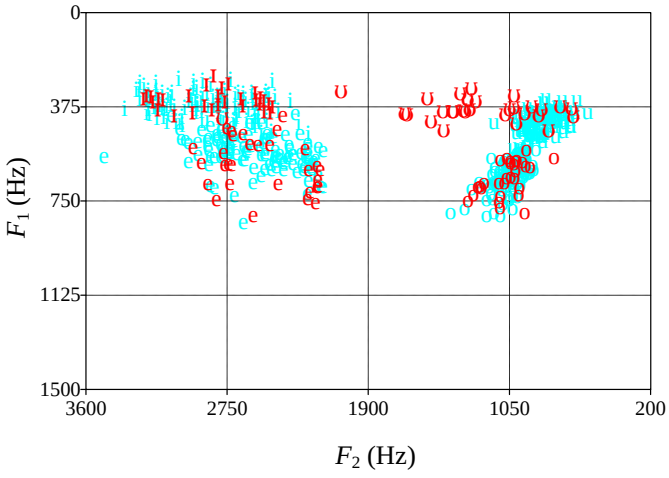
Cyan: Mandarin /au/; Red: English /aʊ/.

Figure 4.43: Mandarin /au/ and English /aʊ/ from female subjects from Taiwan.



Cyan: Mandarin /ei/ and /ou/; Red: English /eɪ/ and /oʊ/.

Figure 4.44: Mandarin and English /ei/ and /ou/ from male subjects from Taiwan.



Cyan: Mandarin /ei/ and /ou/; Red: English /eɪ/ and /oʊ/.

Figure 4.45: Mandarin and English /eɪ/ and /oʊ/ from female subjects from Taiwan.

Table 4.66: Mandarin /ai/ and English /aɪ/ from male subjects from Taiwan.

		Male								Male					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	845	73	1.000	1368	78	1.000	Mandarin	/i/	380	34	1.000	2159	164	1.000
English	/a/	808	72		1304	112		English	/ɪ/	373	59		2126	161	

Table 4.67: Mandarin /ai/ and English /aɪ/ from female subjects from Taiwan.

		Female								Female					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	1049	95	1.000	1689	162	1.000	Mandarin	/i/	426	33	1.000	2671	261	1.000
English	/a/	1020	101		1569	127		English	/ɪ/	403	39		2667	263	

Table 4.68: Mandarin /au/ and English /aʊ/ from male subjects from Taiwan.

		Male								Male					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	785	62	1.000	1171	91	1.000	Mandarin	/u/	503	45	1.000	854	98	1.000
English	/a/	786	54		1229	104		English	/ʊ/	457	76		874	104	

Table 4.69: Mandarin /au/ and English /aʊ/ from female subjects from Taiwan.

		Female								Female					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/a/	935	102	0.483	1327	134	1.000	Mandarin	/u/	535	84	1.000	944	106	1.000
English	/a/	984	128		1473	209		English	/ʊ/	461	47		903	114	

Table 4.70: Mandarin /ei/ and English /eɪ/ from male subjects from Taiwan.

		Male								Male					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	481	39	1.000	2130	144	1.000	Mandarin	/i/	328	37	1.000	2260	166	1.000
English	/e/	515	48		2051	129		English	/ɪ/	297	48		2249	158	

Table 4.71: Mandarin /ei/ and English /eɪ/ from female subjects from Taiwan.

		Female								Female					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/e/	554	48	1.000	2577	232	1.000	Mandarin	/i/	368	29	1.000	2853	248	1.000
English	/e/	592	85		2568	262		English	/ɪ/	324	28		2878	258	

Table 4.72: Mandarin /ou/ and English /oʊ/ from male subjects from Taiwan.

		Male								Male					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	545	44	1.000	879	86	0.162	Mandarin	/u/	393	35	0.66	714	81	0.023
English	/o/	581	54		975	103		English	/ʊ/	342	47		1101	203	

Table 4.73: Mandarin /ou/ and English /oʊ/ from female subjects from Taiwan.

		Female								Female					
		F1			F2					F1			F2		
		mean	SD	*p*	mean	SD	*p*			mean	SD	*p*	mean	SD	*p*
Mandarin	/o/	637	41	1.000	1007	53	1.000	Mandarin	/u/	410	33	0.205	793	73	0.007
English	/o/	649	51		1020	99		English	/ʊ/	365	23		1222	328	

4.6.2 Discussion

Tables 4.66 to 4.73 show that the vowels taken from Mandarin and English diphthongs, such as Mandarin /a/ from /ai/ and English /a/ from /aɪ/, do not differ significantly in F1 and F2 values when produced by subjects of the same gender, except for the F2 values of Mandarin /u/ from /ou/ and of English /ʊ/ from /oʊ/. This suggests that the articulatory features of Mandarin diphthongs and English diphthongs from Mandarin subjects, as attested at the measurement points, are the same except for the tongue advancement of Mandarin /u/ in /ou/ and of English /ʊ/ in /oʊ/.

Chapter 5: Overall Discussion and Conclusion

5.1 Overall Discussion

The purpose of this section is to summarize the findings and then discuss whether the results from Chapter 4 are in accordance with the hypotheses in this study. The cross-sectional discussions include the following themes:

A. The shape of the vowel space of subjects from Taiwan and Texas
B. The degree of correspondence between L1 and L2 for vowels existing in both Mandarin and English, with respect to formant values (Hypothesis 1 and Hypothesis 4)
C. For the L2 English vowels that do not exist in L1 Mandarin:
    1. Assimilation of non-native phonemes to native phonemes (Hypothesis 2)
    2. The degree of contrast with their Mandarin equivalents (Hypothesis 3)

5.1.1 Vowel Space

This chapter starts to examine the acoustic characteristics of native speakers' Mandarin and English vowels. Figures 4.1 and 4.2 indicate that the Mandarin vowel phonemes tend to be kept distinct from one or another as do the English vowel phonemes in Figures 4.6 and 4.7 except for English /ɝ/ and /ʊ/. The vowel /ɝ/ may be

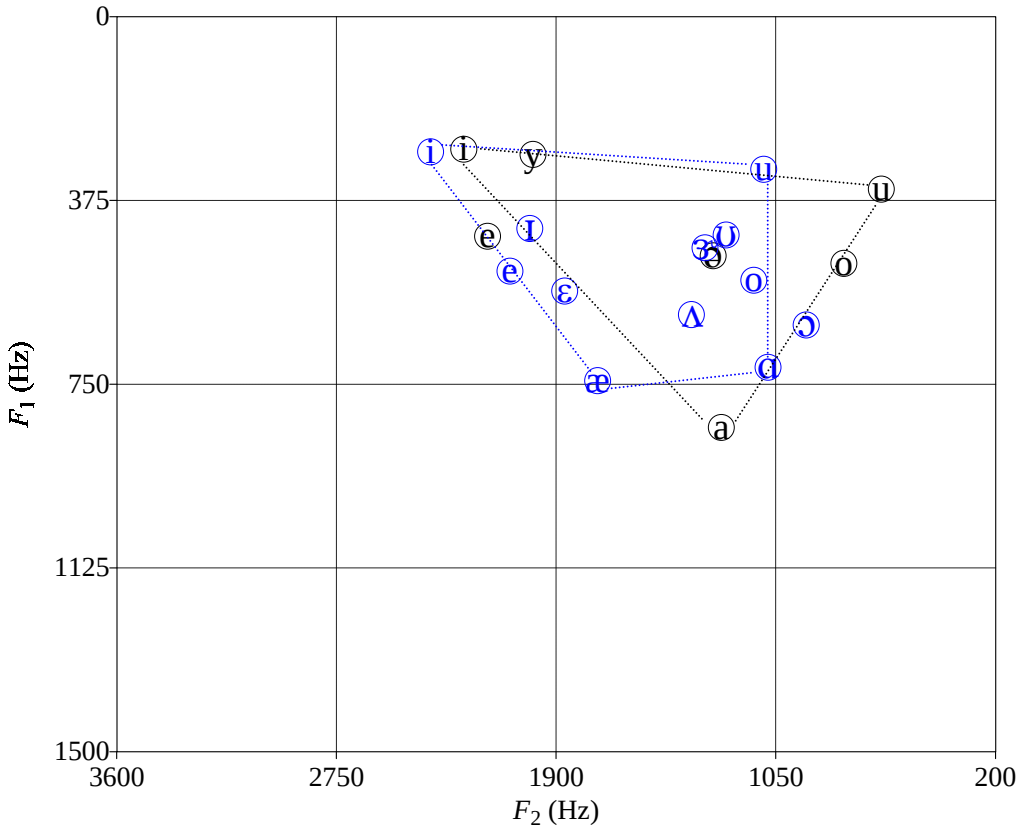
distinguished from other vowels by the third formant (Peterson & Barney, 1952). Vowels tend to disperse in the vowel system of a language in order to preserve auditory contrast (Liljencrants & Lindblom, 1972; Lindblom, 1990). Compared to the scatter plots for native speakers of English, the data for some English vowels from non-native speakers of English are more widely dispersed and overlapping of phonemes occurs (Figures 4.6, 4.7, 4.11, and 4.12). The English vowels from non-native speakers of English in the following vowel groups on the scatter plot overlap one standard deviation about the mean: /i, ɪ/, /ɛ, æ/, /u, ʊ/, /o, ɔ/, and /ʌ, ɑ/ (Figures 4.11 and 4.12).

5.1.1.1 Vowel Space of Native Speakers of Mandarin and English

The vowel space of Mandarin and English from native speakers in this study is estimated and plotted in Figure 5.1 and Figure 5.2 for male and female subjects, respectively. The shape of the Mandarin vowel space is triangular, whereas the shape of the English vowel space is quadrilateral in this study. The distances between the Mandarin close vowels /i/ and /u/, close-front /i/ and open-front /a/, and Mandarin close-back /u/ and open-front /a/ in the vowel space are greater than that between English close vowels /i/ and /u/, close-front /i/ and open-back /ɑ/, and English close-back /u/ and open-back /ɑ/ from native speakers in this study (Figures 5.1, and 5.2). Taking anthropometric differences into account, the distances between the above-mentioned corner vowels in Mandarin are not smaller than in English.

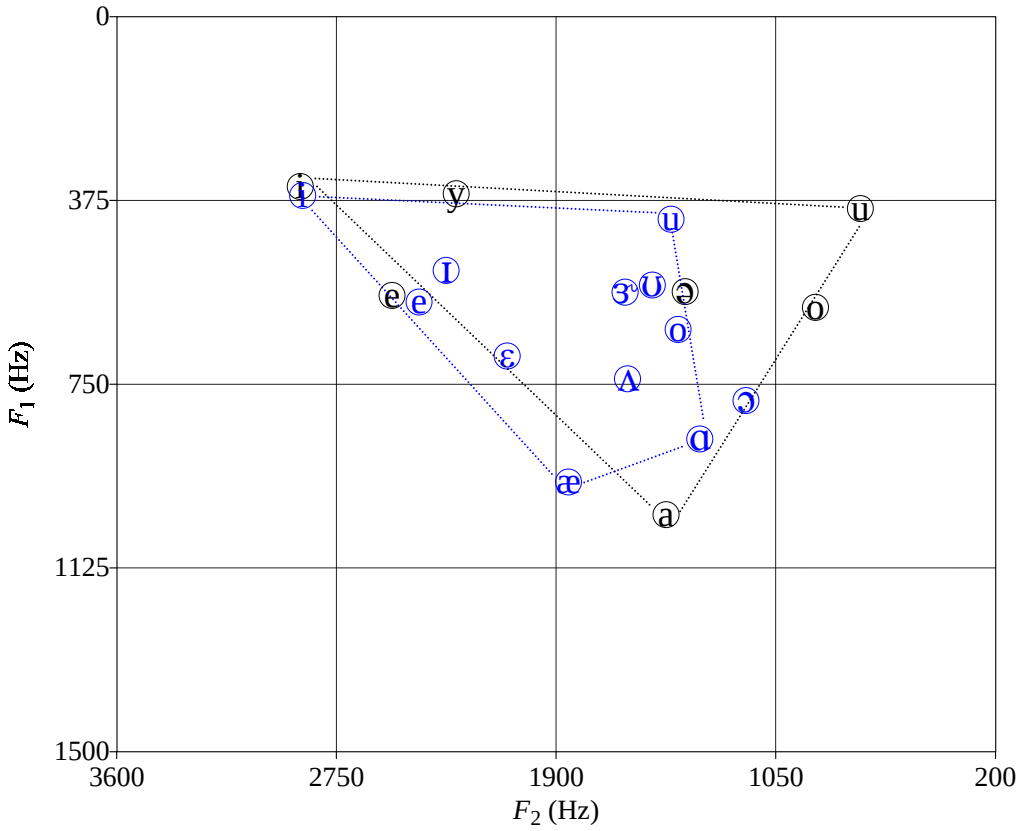
5.1.1.2 Mandarin and English Vowel Space in Native Speakers of Mandarin

The English vowel space in Mandarin speakers is quadrilateral (Figures 5.3 and 5.4). This finding is in agreement with the findings of Chen *et al*. (2001) that male and female Mandarin subjects are able to expand their vowel space and produce phonemes which do not exist in Mandarin. Further research is needed to examine whether the new English vowel categories created as complements to Mandarin vowel categories are acoustically the same as the vowel categories from native speakers of English or not.



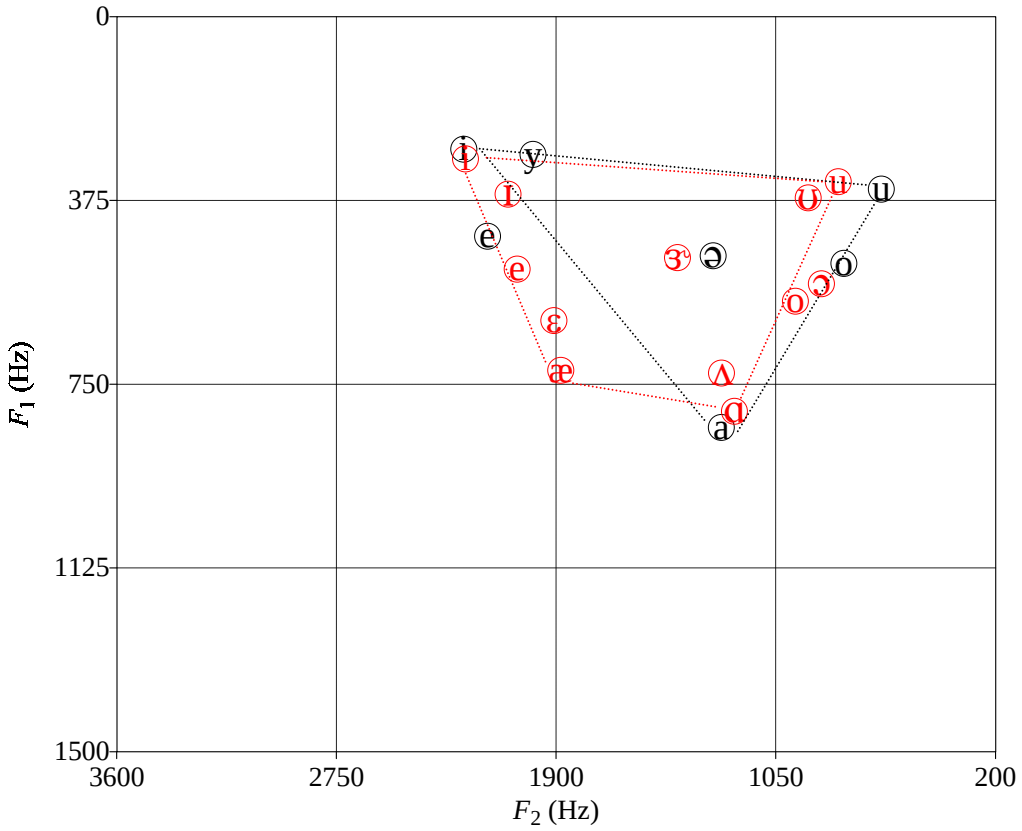
Black: Male Mandarin.
Black lines: Attached to three Mandarin corner vowels.
Blue: Male Texan English.
Blue lines: Attached to four English corner vowels.
IPA symbols represent F1 and F2 mean values.

Figure 5.1: Vowel spaces of male native speakers of Mandarin and English.



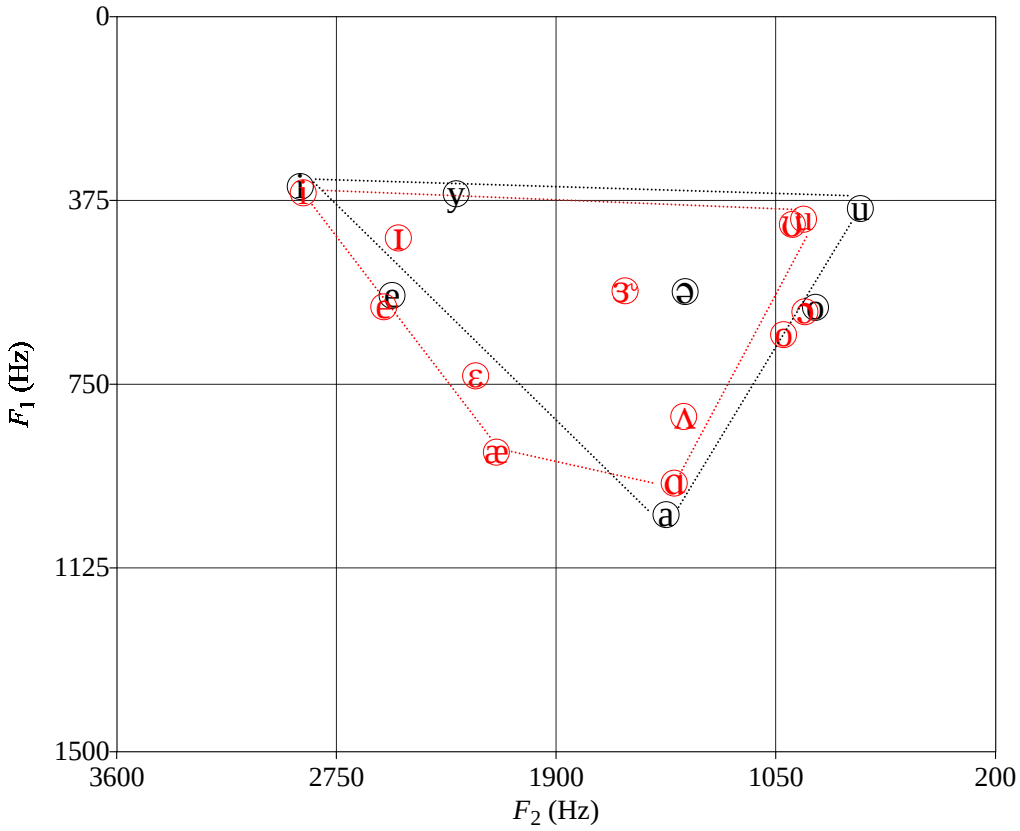
Black: Female Mandarin.
Black lines: Attached to three Mandarin corner vowels.
Blue: Female Texan English.
Blue lines: Attached to four English corner vowels.
IPA symbols represent F1 and F2 mean values.

Figure 5.2: Vowel spaces of female native speakers of Mandarin and English.



Red: English vowels from male subjects from Taiwan.
Red lines: Attached to four English corner vowels.
Black: Mandarin vowels from male subjects from Taiwan.
Black lines: Attached to three Mandarin corner vowels.
IPA symbols represent F1 and F2 mean values.

Figure 5.3: Male Mandarin and English vowels from subjects from Taiwan.



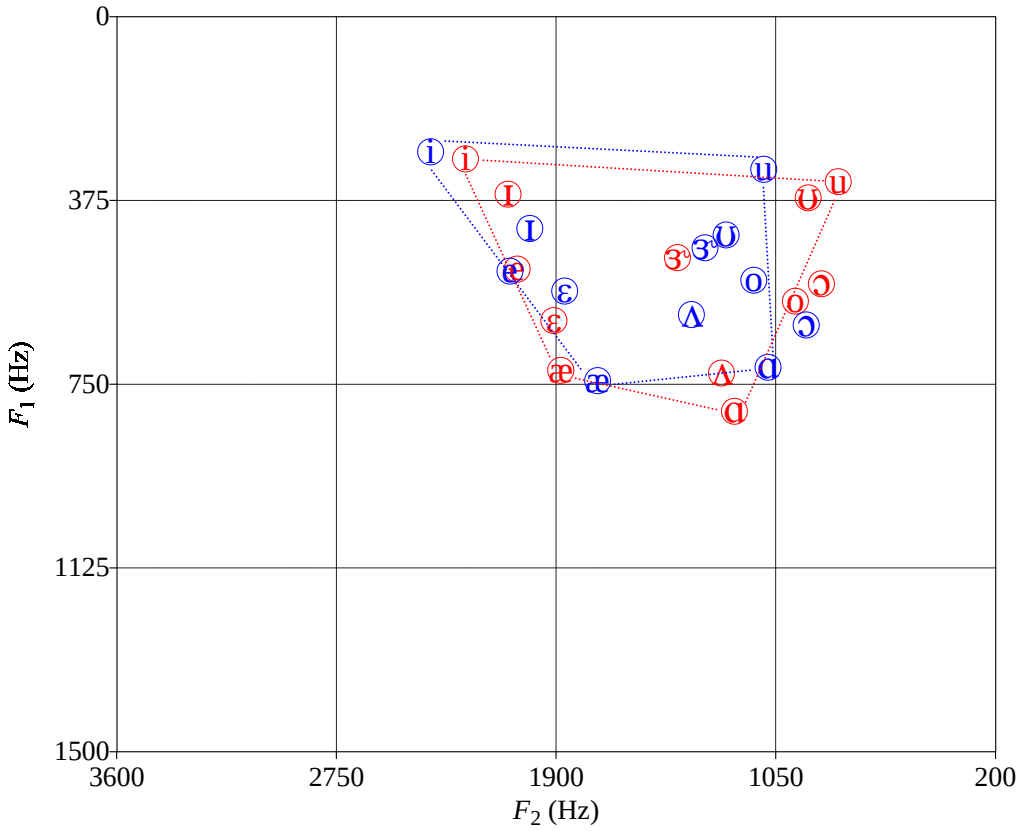
Red: English vowels from female subjects from Taiwan.
Red lines: Attached to four English corner vowels.
Black: Mandarin vowels from female subjects from Taiwan.
Black lines: Attached to three Mandarin corner vowels.
IPA symbols represent F1 and F2 mean values.

Figure 5.4: Female Mandarin and English vowels from subjects from Taiwan.

5.1.1.3 English Vowel Space in Subjects from Texas and Taiwan

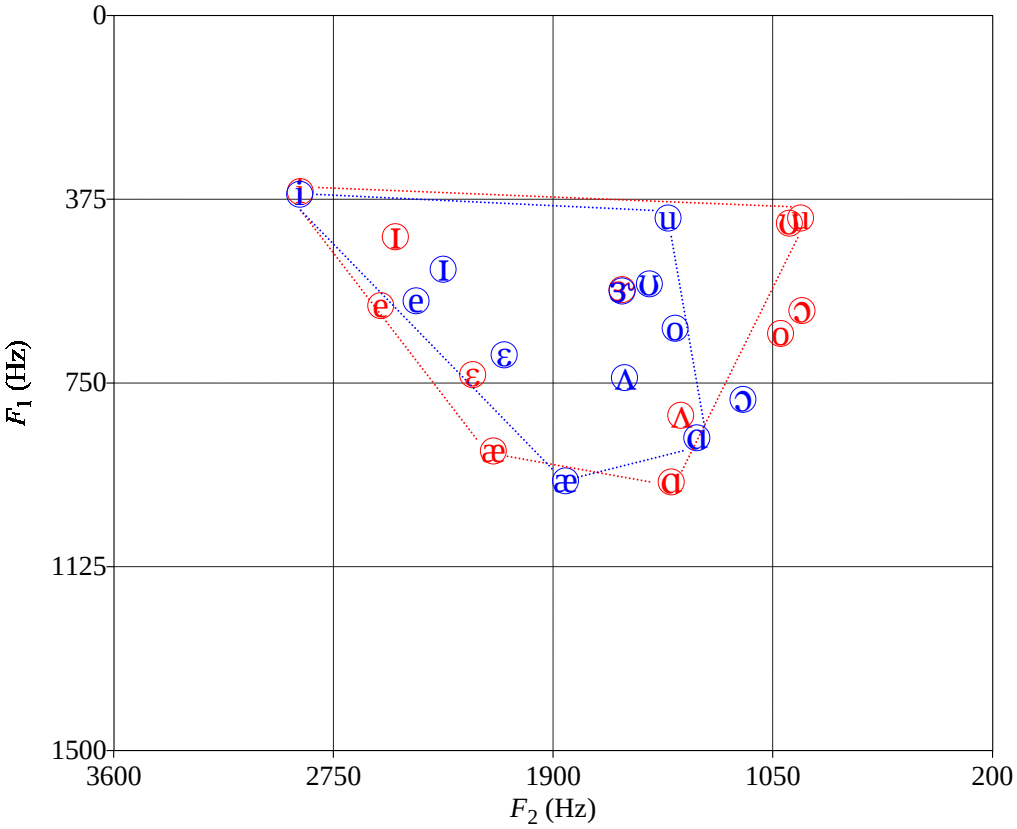
The shapes of the English vowel spaces from subjects from Texas and Taiwan look quadrilateral, but the configurations of the vowel spaces from subjects from Texas and Taiwan are different (Figures 5.5 and 5.6). Furthermore, the area of the vowel space from subjects from Taiwan is not smaller than that of the vowel space from native speakers of English in this study, which contradicts the findings of Chen *et al*. (2001). This may be attributable to how subjects from Taiwan pronounce their Mandarin vowels. The distances between the Mandarin corner vowels are bigger than those between the English corner vowels in Figures 5.3 and 5.4.

In general, in Figures 4.6, 4.7, 4.11, 4.12, 5.5 and 5.6, the data of each English vowel phoneme from subjects from Texas are more condensed and the data of some English vowel phonemes such as /u/ vs. /ʊ/ and /o/ vs. /ɔ/ from non-native speakers of English from Taiwan are more dispersed, which means that the boundaries of English phonemes from native speakers of English are clearer than those of English vowels from subjects from Taiwan in terms of acoustic dimensions in this study.



Red: English vowels from male subjects from Taiwan.
Red lines: Attached to four English corner vowels.
Blue: English vowels from male subjects from Texas.
Blue lines: Attached to four English corner vowels.

Figure 5.5: English vowels from male subjects from Texas and Taiwan.



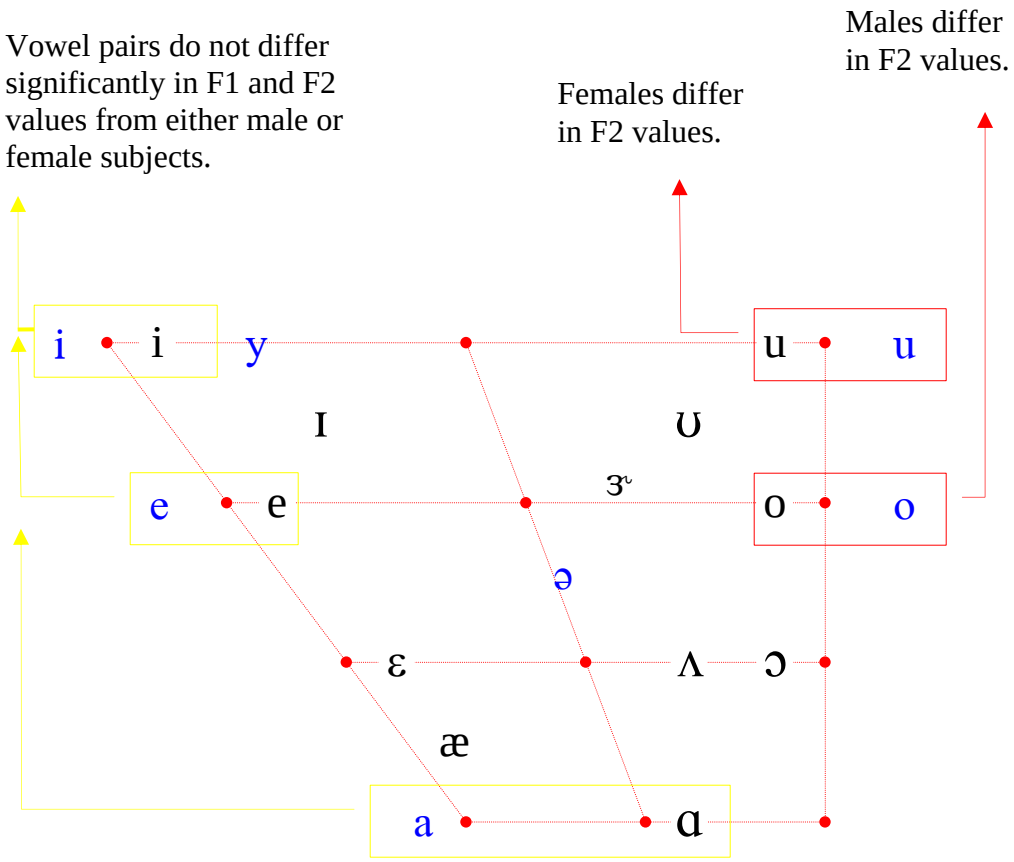
Red: English vowels from female subjects from Taiwan.
Red lines: Attached to four English corner vowels.
Blue: English vowels from female subjects from Texas.
Blue lines: Attached to four English corner vowels.

Figure 5.6: English vowels from female subjects from Texas and Taiwan.

5.1.2 Hypotheses 1 and 4: Vowels, including diphthongs, in Mandarin and English

Vowels existing in Mandarin and English from subjects from Taiwan are discussed in this section. There are seven Mandarin monophthongs (/i, y, e, ə, o, u, a/) in this study. All Mandarin monophthongs have English equivalents, except for /y/ and /ə/, in this project: Mandarin /i/ and English /i/, Mandarin /u/ and English /u/, Mandarin /e/ and English /e/, Mandarin /o/ and English /o/, and Mandarin /a/ and English /ɑ/.

Significantly different articulatory features are not found when male and female subjects from Taiwan pronounce Mandarin /i/ and English /i/ (Tables 4.44 and 4.46), Mandarin /u/ and English /u/ (Tables 4.48, and 4.50), Mandarin /e/ and English /e/ (Tables 4.52 and 4.55), Mandarin /o/ and English /o/ (Table 4.58 and 4.60), and Mandarin /a/ and English /ɑ/ (Tables 4.62 and 4.63); but they are found in the female pronunciations of Mandarin /u/ vs. English /u/ (Table 4.50) and in the male pronunciations of Mandarin /o/ vs. English /o/ (Table 4.58).

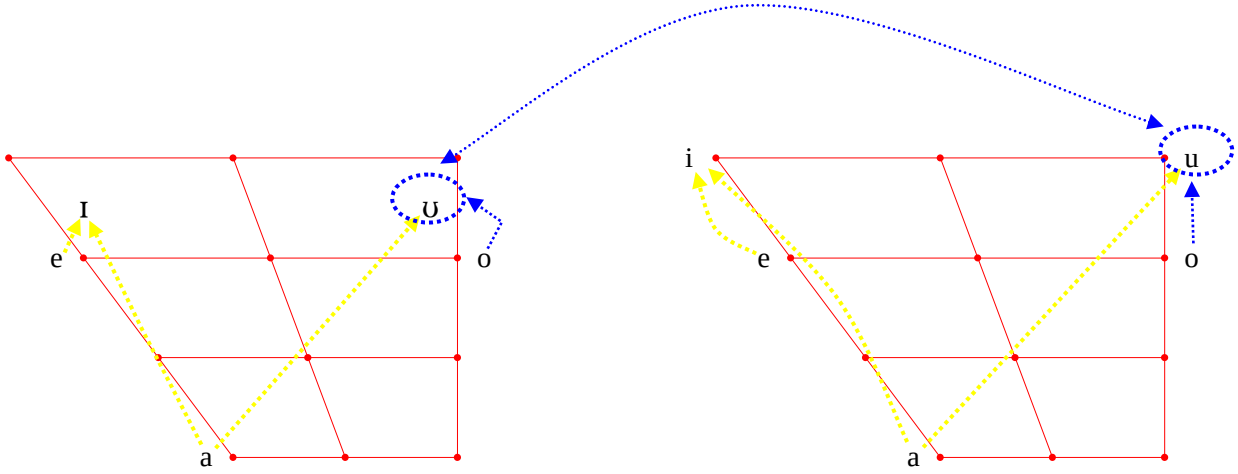


Blue: Mandarin; Black: English.

Figure 5.7: Mandarin and English vowel production from Mandarin speakers.

There are three interpretations of this finding. First, the finding is in accordance with a view that when L2 sounds are "identified" as sounds in L1, L2 sounds will be replaced by L1 sounds (Flege, 1995) in L2 subjects' speech production. Second, the Mandarin subjects perceive the differences between the L1 and the L2 sounds; however, they are not able to pronounce them differently. Third, vowels existing in both Mandarin and English are identical. This study does not normalize the formant values of English vowels and Mandarin vowels from their native speakers. Therefore, it is not known whether the vowels in Mandarin and English produced by their native speakers are identical. Based on the formant values, if the vowels exist in both English and Mandarin, generally speaking, the articulatory features of the English vowels from Mandarin speakers do not differ significantly from those of their Mandarin equivalents.

Another example of using the same way to pronounce vowels existing in both L1 and L2 can be found in the diphthongs in this study. Based on the statistical results in Section 4.7, both male and female subjects' tongue elevation and tongue advancement, as attested at the measurement points, do not differ significantly between the vowels in Mandarin diphthongs /ai/, /au/, /ei/, and /ou/ and the vowels in English diphthongs /aɪ/, /aʊ/, /eɪ/, and /oʊ/, respectively, except for F2 values of Mandarin /u/ from /ou/ and English /ʊ/ from /oʊ/ (see Figure 5.8).



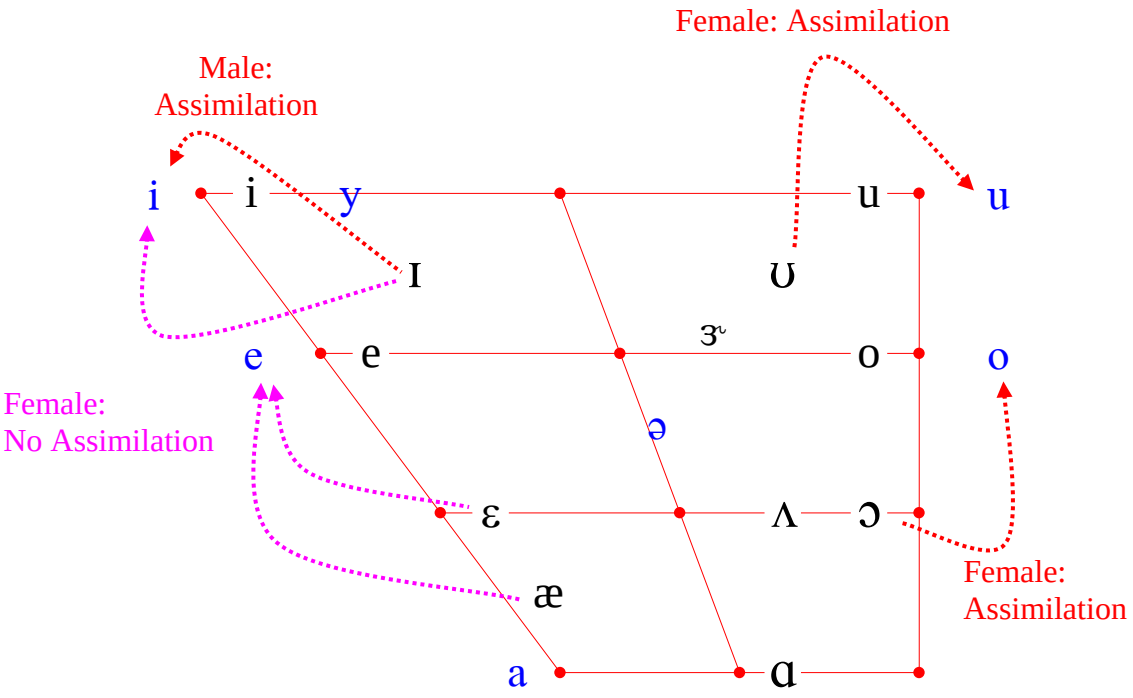
English diphthongs: /aɪ/, /aʊ/, /eɪ/, and /oʊ/ Mandarin diphthongs: /ai/, /au/, /ei/, and /ou/

Figure 5.8: English and Mandarin diphthongs used in this study.

5.1.3 Hypothesis 2: English Vowels without Mandarin Equivalents

The English vowels not existing in Mandarin are pronounced by Mandarin subjects as their closest L1 sounds. Based on the F1 and F2 values, this pattern was found in: male English /ɪ/ vs. Mandarin /i/; female English /ʊ/ vs. Mandarin /u/; and female English /ɔ/ vs. Mandarin /o/. Differences are found in female English /ɪ/ vs. Mandarin /i/, female English /ɛ/ vs. Mandarin /e/, and female English /æ/ vs. Mandarin /e/, with respect to F1 and F2 values. Other vowel pairs from different genders contrasted either in F1 or F2 values.

Assimilation does not occur in all the English and Mandarin vowels that are shown in Figures 4.11 to 4.13 and Figure 5.9. Mandarin male and female subjects show different patterns of assimilation either in their F1 or F2 values. Since the assimilation patterns differ by gender, it may suggest that the difficulties of perceiving or producing phonetic differences between L2 speech sounds and their closest L1 sounds (Best 1994; Flege, 1995, 2003) differ by gender.



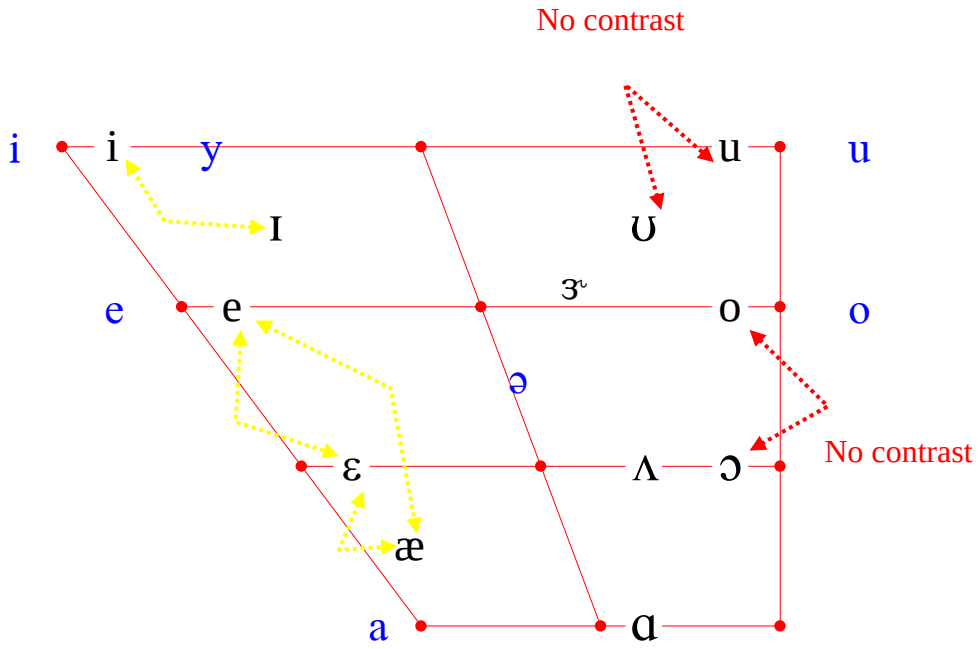
Blue: Mandarin; Black: English; Red: Assimilation; Pink: No Assimilation.

Figure 5.9: Assimilation of English vowels to their closest Mandarin vowels.

5.1.4 Hypothesis 3: Contrasting Similar English Vowels

English vowels from native speakers of English disperse in the vowel space, and the boundary of each English vowel phoneme is clear based on one standard deviation about the mean except in the cases of /ɝ/ and /ʊ/ (Figures 4.6 and 4.7). This confirms that native speakers of English tend to contrast each English vowel clearly in their vowel production. However, contrasts between some phonemes in English that do not exist in Mandarin are difficult for subjects from Taiwan. In general, Mandarin speakers have difficulties contrasting the vowels that do not exist in Mandarin with their minimally paired English vowels—contrasts such as /i/ vs. /ɪ/, /e/ vs. /ɛ/, /e/ vs. /æ/, /ɛ/ vs. /æ/, /ʊ/ vs. /u/, and /ɔ/ vs. /o/.

According to the statistical results from Section 4.4, the English vowel pairs /u/ vs. /ʊ/, and /o/ vs. /ɔ/ are the most difficult for subjects from Taiwan to distinguish. Subjects from Taiwan do not differentiate /u/ from /ʊ/ (Tables 4.26, and 4.27), and /o/ from /ɔ/ (Table 4.42 and Table 4.43) either in tongue height or in tongue advancement.



Blue: Mandarin; Black: English

Figure 5.10: English vowel pairs difficult for Mandarin subjects to distinguish.

Distinction is not made in male tongue height and tongue advancement in the production of the English vowel pair /ɛ/ and /æ/. Female subjects differ significantly in tongue height between English /ɛ/ and /æ/. Male and female subjects from Taiwan differ in tongue height and tongue advancement for the vowel pair /i/ and /ɪ/. Male subjects from Taiwan differ significantly in tongue height for the vowel pair /i/ and /ɪ/. Female subjects from Taiwan differ significantly in tongue height and tongue advancement for the vowel pair /i/ and /ɪ/.

For the English vowel pairs that Mandarin subjects from Taiwan cannot significantly contrast either in F1 or F2 values (such as English /u/ vs. /ʊ/), the English vowel which does not exist in Mandarin (/ʊ/) is highly likely to be pronounced with the acoustic properties of its minimally paired Mandarin equivalent (/u/). Subjects from Taiwan do not significantly differentiate Mandarin from English vowels if they are highly similar.

Difficulties for Mandarin subjects in contrasting English vowels pairs may be explained by Flege (1995, 2003). Important L2 features are filtered out by the Mandarin subjects' L1 sound system (Flege 1995, 2003), which leads L2 learners to fail to perceive the phonetic differences between L1 and L2 sounds or between different L2 sounds. Or, L2 learners may have discerned the features that differentiate between L1 and L2 sounds or between pairs of L2 sounds, but not be familiar with

making the new articulatory movements. Therefore, the non-native phonemes are assimilated to the phonemes with which they are more familiar.

The extent to which English vowels contrast varies with English vowel pairs. For example, back vowel pairs such /u/ vs. /ʊ/ and /o/ vs. /ɔ/ are more difficult to distinguish than front vowel pairs such as /ɪ/ vs. /i/. Female subjects from Taiwan differ significantly in tongue height and tongue advancement for English /i/ and /ɪ/, which shows that female subjects from Taiwan have established a new feature for differentiating /ɪ/. Figures 5.1 and 5.2 show that male and female subjects, respectively, from Taiwan have established an English vowel category for /æ/. Whether these new categories are the same vowels as produced by native speakers of English needs further investigation. As suggested in studies by Grosjean (1989) and Mack (1990), when a bilingual engages more than one language system, bidirectional influence of their L1 and L2 is inevitable, and the cost of maintaining phonetic contrast is losing accuracy in both their L1 and their L2.

5.2 Implications

The process of teaching or learning English as a second language can be greatly improved by considering the results of this study. The comparison of the acoustic properties of English vowels from native speakers of English with those of Mandarin speakers provides ESL teachers with information about difficulties that Mandarin speakers who learn English as a second language might encounter. For example, Mandarin subjects in this study do not contrast /ʊ/ from /u/ in their English vowel production. The description of the tongue elevation and tongue advancement of English vowels from native speakers of English and Mandarin speakers should give ESL teachers a direction in which to assist their students to adjust their speech organs when pronouncing English vowels.

Phonetic descriptions of acoustic properties for each English vowel are important because they characterize the physical movement inside the vocal tract (Peterson & Barney, 1952; Lindblom & Sundberg, 1971; Pickett, 1999). Therefore, the results of this study are also relevant to speech pathologists. The features of the accented English vowels of Mandarin speakers can be compared with the English phonetic features of Mandarin ESL speech disorder patients by speech language pathologists (Chen *et al*., 2001; Langdon, 1999).

5.3 The Limitations of the Study

In order to collect English vowel data, subjects read from a list of English words. It is not clear whether Mandarin subjects did not contrast some English vowel pairs in their English vowel production because the subjects could not perceive the important English sound features that distinguish between two or more English phonemes, or because they could perceive the differences between English vowels but not pronounce them correctly, or both. To clarify this uncertainty, a future study might play the L2 speech sound first to the L2 participants and then ask them to repeat what they hear.

It is also unclear whether some L2 subjects do not contrast some English vowel pairs because that is the way they were taught to pronounce those English vowels or because they are unable to discern the differences among those vowels. Therefore, the English vowel production of Mandarin subjects may differ depending on how they were taught to pronounce English vowels.

This study does not investigate whether the vowels existing in both Mandarin and English are identical. Future studies could work on the normalization of English and Mandarin vowels. Following normalization, the Mandarin and English vowel production could be compared across language groups. After this, the possible link between the articulatory features of English and Mandarin from Mandarin speakers would be clearer.

The Mandarin subjects speak Taiwanese as their native language. The degree of influence from their Taiwanese on their Mandarin and English vowel production is unknown. Future research might focus on the interference in speech production from Taiwanese to Mandarin or from Taiwanese to English.

5.4 Conclusion

The goal of this study is to investigate how the vowels of native speakers of English differ from those of non-native speakers of English. Moreover, it also examines to what degree crossover effects from the non-native speakers' prior learned language interfere with their later learned language. To achieve this goal, this author examines the acoustic characteristics of English vowels produced by English speakers from Texas and Mandarin speakers from Taiwan. In addition, Mandarin vowels spoken by Mandarin speakers from Taiwan are investigated.

The acoustic comparison of English vowels from native speakers of English and non-native speakers of English from Taiwan shows that Taiwanese Mandarin speakers have difficulty contrasting English vowels which do not have Mandarin equivalents from their minimally paired English vowels (e.g., /i/ vs. /ɪ/, /ɛ/ vs. /æ/, /o/ vs. /ɔ/, and /u/ vs. /ʊ/), in tongue advancement, tongue elevation, or both. For the English vowels which have Mandarin equivalents, Taiwan Mandarin subjects use the way they pronounce Mandarin vowels to pronounce their English equivalents, such as /i/, /u/, /e/, /o/, and /ɑ/, both in tongue advancement and tongue elevation—except for

female Mandarin subjects' /u/ and male Mandarin subjects' /o/. Further interference from Mandarin to English can be observed from F1/F2 vowel space plots. The distance between the corner vowels of Mandarin is not smaller than that of the English of Taiwanese Mandarin speakers in this study. The distances between English corner vowels from Mandarin subjects are similar to the distances between Mandarin corner vowels from Mandarin subjects.

This study describes the acoustic distributions of English and Mandarin vowels and illustrates that Mandarin subjects are able to form a new vowel phoneme which does not exist in Mandarin, *i.e.*, /æ/. However, whether this vowel phoneme is acoustically identical to the vowel phoneme produced by native speakers of English needs to be further investigated. Future research might also work on normalizing formant values to exclude the anthropometric and gender differences between the two language groups.

The results of this study reveal English pronunciation problems that Mandarin speakers who speak English as a second language might encounter, and further serve as a reference for English teachers or Mandarin speakers who speak English as a second language. The acoustic properties of the vocal tract of non-native speakers of English could also provide useful comparative information for future studies of Mandarin speech disorder patients who speak English as a second language (Chen *et al*., 2001).

Appendix A

This research involved making a language background information survey of graduate students from Taiwan attending UT. Although the twenty Mandarin subjects' English and Mandarin vowel production in this study can be taken as representative of a wider population of students from Taiwan at UT, only by including a survey in the study can we achieve a more complete understanding of the Mandarin accent in English. The survey documents how Mandarin subjects participating in voice recording for this study, and other students from Taiwan attending UT, perceive their own use of Mandarin and English. Their self-reported language experiences should help us more clearly understand their speech production. One hundred and twenty-three out of two hundred graduates from Taiwan at UT responded to the survey, including the subjects who participated in the voice recording for this study. The first part of Appendix A is an English translation of the Mandarin questionnaire delivered to the participants. The second part of Appendix A shows selected results of the questionnaire.

All two hundred of the graduate students surveyed were enrolled at UT in spring 2005, as was this investigator. The response rate of the group of students that this investigator surveyed reached 61.5%. Data from the group of students from Taiwan are representative of the UT graduate students from Taiwan. This means that

the data are generalizable and the research findings can be generalized to the wider population of the group of graduate students from Taiwan at UT.

The questionnaire includes four types of questions. The first type of question provides demographic information. The second type of question is about the informants' language attitudes—towards their own English accent, and whether it is important to achieve a native-like English accent. The third type of question is about their internal motivations for learning English, such as to what degree they appreciate American culture. The fourth type of question is about their instrumental motivation for learning English, such as whether an accent that approximates a native English accent is helpful in getting a job in the U.S.

The results of the survey suggest that most survey subjects think that having smooth English communication skills is a higher priority than having native-like English pronunciation. Furthermore, there is no significant relationship between the desire for a native-like English accent and the responses about the subjects' degree of immersion in and appreciation for American culture. There is a low positive correlation between desiring a native-like English accent and wanting to find employment in an English-speaking country.

Questionnaire (Translated from Mandarin)

1. In general, you pay attention to your pronunciation when you speak English.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

2. You are satisfied with your English pronunciation.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

3. You pay attention to fashion trends or information from the fashion industry, music circles, art circles or athletic news, etc. in the U.S.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

4. Conveying your idea clearly is more important than using proper English pronunciation.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

5. You want to have a native-like English accent. (You want your English pronunciation to be as good as that of native speakers of English.)
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

6. Your English pronunciation is never a problem when asking questions in class or during class presentations.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

7. In general, you listen to more English songs than Mandarin songs when you are in the U.S.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

8. In general, you prefer not to be identified as a non-native speaker of English.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

9. You prefer brands of products that you see U.S. movie stars or athletes advertising or wearing. (Assume money is not an issue.)
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

10. You feel it is desirable to get rid of your non-native English accent as best as you can.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

11. In general, you listen to more English songs than Mandarin songs when you are in Taiwan.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

12. You are willing to build relationships with American friends.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

13. In general, you appreciate American culture.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

14. Because of your English pronunciation, your academic performance was inhibited (as in asking questions in class or during class presentations).
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

15. You would accept a green card if you had the chance.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

16. You have a native-like English accent. (Your English pronunciation is like that of a native speaker of English.)
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

17. You would like to stay in America to work after you graduate.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

18. Good English pronunciation helps non-native speakers of English to obtain jobs in the U.S.
□ strongly disagree □ disagree □ neutral □ agree □ strongly agree

Personal Information:

1. Your gender □ Male □ Female

2. Your major _____

3. The degree your are pursuing

   □ undergraduate □ M.A./M.S. □ Ph.D. □ other (please specify)___

4. Did you get your bachelor or M.A. degree in English, Linguistics, or English translation?
   □ Yes

   □ No

5. In general, in your daily conversation in the U.S., how often do you speak English?

   □ 0 - 20% □ 21 - 40% □ 41 - 60% □ 61 - 80% □ 81 - 100%

6. In general, how often do you speak English in the U.S.?

   □ All the time.
   □ Mostly, except for talking with Chinese speaking people
   □ I speak more English than Mandarin.
   □ The opportunities for speaking English are the same as for speaking Mandarin.
   □ I speak more Mandarin than English.
   □ I mainly speak in Mandarin but I will mix English words or sentences with Mandarin sometimes.
   □ Not at all.
   □ None of the above.

7. What language do you most commonly use in the U.S. to speak to___?

Please fill in the blanks with the appropriate number:
1. English 2. Mandarin 3.Min-nan yu (Taiwanese)
4. Hakka 5. none 6. other (please specify_____)

	Language
Your professors	
Your American colleagues / classmates	
Your Chinese friends / classmates (e.g., friends from Taiwan, mainland China, Singapore, etc.)	
Your spouse (please fill out the answer as "none" if you don't have a spouse)	
Your child/children (please fill out the answer as "none" if you don't have children)	

8. What is the order in which you acquired the following languages?

□ Min-nan yu (Taiwanese), Mandarin, English
□ Mandarin, Min-nan yu (Taiwanese), English
□ Hakka, Mandarin, English
□ Other (please specify_____)

9. Please use this scale to choose the number to indicate your proficiency in Min-nan yu (Taiwanese).

□ 0: You cannot speak in Min-nan yu (Taiwanese).
□ 1: beginner
□ 2: get by
□ 3: fluent
□ 4: near excellent
□ 5. excellent

10. In general, in your daily conversation in Taiwan, how often do you speak Mandarin?

□ 0 - 20% □ 21 - 40% □ 41 - 60% □ 61 - 80% □ 81 - 100%

11. In general, how often do you speak in English when you are in Taiwan?

□ All the time.
□ Mostly, except for talking with Chinese speaking friends / colleagues.
□ I speak more English than Mandarin.
□ The opportunities for speaking English are the same as for speaking Mandarin.
□ I speak more Mandarin than English.
□ I mainly speak in Mandarin but I will mix English words or sentences with Mandarin sometimes.
□ Not at all.
□ None of the above.

12. What is the common language that you use in Taiwan when speaking to ___? Please fill in the blanks with the appropriate number:
1. English 2. Mandarin 3. Min-nan yu (Taiwanese)
4. Hakka 5. none 6. other (please specify_____)

	Language
Your grandparents	
Your father	
Your mother	
Brothers or sisters	
People in your workplace / school	
Friends / classmates	
Your spouse (please fill out the answer as "none" if you don't have a spouse)	
Your child / children (please fill out the answer as "none" if you don't have children)	

13. You have lived in the US for _____year(s) and _____ month(s).

14. How old were you when you arrived in the U.S. to pursue your current degree? _____

15. You learned English when you were

□ 9-10 years old (4th grade),
□ 10-11 years old (5th grade),
□ 11-12 years old (6th grade),
□ 12-13 years old (7th grade),
□ other (please specify_____)

16. After you graduated from high school and before you entered UT, did you_____to practice English?

□ join an English club (society)
□ listen to English programs on the radio
□ make friends with English speakers
□ go to English cram school
□ take additional English classes besides required English classes?
□ watch English TV programs or English movies
□ other (please specify_____)

17. Did you live in an English speaking country for at least six months before you came to the U.S. to pursue your current degree?

□ Yes
□ No

18. Did you learn to play any instruments or to sing?

□ No
□ Yes, for about 1-2 years
□ Yes, for about 2-3 years
□ Yes, for about 3-4 years
□ Yes, for about 4-5 years
□ Yes, for more than 5 years.
□ Other (please specify_____)

19. Your age is _____.

20. Comments_____

Selected responses to the questionnaire

Personal Information

One hundred and twenty-three out of two hundred graduates from Taiwan at UT responded to the survey, including the 20 subjects who participated in the voice recording for this study. Their responses to the questionnaire are presented as follows.

Table A1: Survey subjects' genders.

123 subjects		20 subjects	
Male	Female	Male	Female
%	%	%	%
35.8	64.2	50.0	50.0

Table A2: Degrees that survey subjects are pursuing.

123 subjects		20 subjects	
M.A./M.S.	Ph.D.	M.A./M.S.	Ph.D.
%	%	%	%
24.4	75.6	0.0	100.0

Table A3: The order of acquisition of Min-nan yu (Taiwanese), Mandarin, and English.

	123 subjects	20 subjects
	%	%
Min-nan yu (Taiwanese), Mandarin, English	48.0	100.0
Mandarin, Min-nan yu (Taiwanese), English	38.2	0.0
Hakka, Mandarin, English	0.8	0.0
Other	13.0	0.0
Total	100.0	100.0

Table A4: Proficiency in Min-nan yu (Taiwanese).

	123 subjects	20 subjects
	%	%
You cannot speak in Min-nan yu (Taiwanese)	3.3	0.0
beginner	12.2	5.3
get by	35.8	26.3
fluent	20.3	31.6
near excellent	14.6	26.3
excellent	13.8	10.5
Total	100.0	100.0

Table A5: Age of English acquisition.

	123 subjects	20 subjects
	%	%
9-10 years old (4th grade)	22.0	20.0
10-11 years old (5th grade)	16.0	20.0
11-12 years old (6th grade)	17.1	15.0
12-13 years old (7th grade)	43.9	40.0
other	0.8	5.0
Total	100.0	100.0

Language Use in Taiwan and the U.S.

Table A6: In general, how often do you speak in English when you are in Taiwan?

	123 subjects	20 subjects
	%	%
All the time.	0.0	0.0
Mostly, except for talking with Chinese speaking people.	0.0	0.0
I speak more English than Mandarin.	0.0	0.0
The opportunities for speaking English are the same as speaking Mandarin.	3.3	5.0
I speak more Mandarin than English.	3.3	5.0
I mainly speak in Mandarin but I will mix English words or sentences with Mandarin sometimes.	53.7	50.0
Not at all.	39.8	40.0
None of the above.	0.0	0.0
Total	100.0	100.0

Table A7: In general, how often do you speak English in the U.S.?

	123 subjects	20 subjects
	%	%
All the time.	0.8	0.0
Mostly, except for talking with Chinese speaking people.	26.8	35.0
I speak more English than Mandarin.	9.8	5.0
The opportunities for speaking English are the same as for speaking Mandarin.	17.9	25.0
I speak more Mandarin than English.	32.5	20.0
I mainly speak in Mandarin but I will mix English words or sentences with Mandarin sometimes.	9.8	10.0
Not at all.	1.6	0.0
None of the above.	0.8	5.0
Total	100.0	100.0

Language Attitude Towards English Pronunciation

Table A8: Language attitude towards English pronunciation.

	123 subjects						20 subjects					
	Disagree		Neutral		Agree		Disagree		Neutral		Agree	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
In general, you pay attention to your pronunciation when you speak English.	7	6	16	13	100	81	2	10	4	20	14	70
You are satisfied with your English pronunciation.	27	22	45	37	51	42	1	5	11	55	8	40
Conveying your idea clearly is more important than using proper English pronunciation.	12	10	20	16	91	74	3	15	2	10	15	75
You want to have a native-like English accent.	10	8	17	14	96	78	1	5	3	15	16	80
In general, you prefer not to be identified as a non-native speaker of English.	35	29	31	25	57	46	5	35	4	20	11	55
You feel it is desirable to get rid of your non-native English accent as best as you can.	12	10	17	14	94	76	4	20	2	10	14	70
Your English pronunciation is like that of a native speaker of English.	85	69	25	20	13	11	16	80	2	10	2	10

Internal Motivations

Table A9: Internal motivations.

	123 subjects						20 subjects					
	Disagree		Neutral		Agree		Disagree		Neutral		Agree	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
You pay attention to fashion trends or information from the fashion industry, music circles, art circles or athletic news, etc. in the U.S.	44	36	34	28	45	37	8	40	5	25	7	35
In general, you listen to more English songs than Mandarin songs when you are in the U.S.	34	28	24	20	65	53	5	25	3	15	12	60
You prefer brands of products that you see U.S. movie stars or athletes advertising or wearing.	102	83	16	13	5	4	17	85	3	15	0	0
In general, you listen to more English songs than Mandarin songs when you are in Taiwan.	69	56	30	24	24	20	10	50	6	30	4	20
You are willing to build relationships with American friends.	3	2	13	11	107	87	1	5	3	15	16	80
In general, you appreciate American culture.	14	11	53	43	56	46	4	20	8	40	8	40

Instrumental Motivations

Table A10: Instrumental Motivation.

	123 subjects						20 subjects					
	Disagree		Neutral		Agree		Disagree		Neutral		Agree	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
Your English pronunciation is never a problem when asking questions in class or during class presentations.	38	31	30	24	55	45	5	25	6	30	9	45
Because of your English pronunciation, your academic performance was inhibited (as in asking questions in class or during class presentations).	76	62	20	16	27	22	17	85	2	10	1	5
You would accept a green card if you had the chance.	5	4	16	13	102	83	2	10	2	10	16	80
You would like to stay in America to work after you graduate.	24	20	47	38	52	42	4	20	10	50	6	30
Good English pronunciation helps non-native speakers of English to obtain jobs in the U.S.	2	2	12	10	109	89	1	5	1	5	18	90

There is a significant correlation between how much subjects want to have a native-like English accent and the perceived opportunity to get a job in the U.S. *P* value is 0.038. Spearman's rho is 0.187, a low positive correlation (n=123).

Table A11: Correlation between how much subjects want to have a native-like English accent and the perception of job opportunities in the U.S.

	Spearman's rho	You want to have a native-like English accent. (You want your English pronunciation to be as good as that of native speakers of English.)
You would like to stay in America to work after you graduate.	Correlation Coefficient	0.187
	p value	0.038*
	Number (subjects)	123

* Correlation is significant at the 0.05 level (2-tailed).

There is no significant relationship between wanting a native-like English accent and degree of immersion in and appreciation for American culture (n=123).

Table A12: Relationship between wanting a native-like English accent and degree of immersion in and appreciation for American culture.

Spearman's rho		You feel it is desirable to get rid of non-native English accent as best as you can.
You pay attention to fashion trends or information from the fashion industry, music circles, art circles or athletic news, etc. in the U.S.	Correlation Coefficient	0.046
	p value	0.624
	Number (subjects)	123
In general, you listen to more English songs than Mandarin songs when you are in the U.S.	Correlation Coefficient	0.088
	p value	0.331
	Number (subjects)	123
You prefer brands of products that you see U.S. movie stars or athletes advertising or wearing.	Correlation Coefficient	0.048
	p value	0.594
	Number (subjects)	123
In general, you listen to more English songs than Mandarin songs when you are in Taiwan.	Correlation Coefficient	-.100
	p value	0.270
	N (subjects)	123
You are willing to build relationships with American friends.	Correlation Coefficient	0.004
	p value	0.962
	Number (subjects)	123
In general, you appreciate American culture.	Correlation Coefficient	0.054
	p value	0.554
	Number (subjects)	123

* Correlation is significant at the 0.05 level (2-tailed).

Appendix B

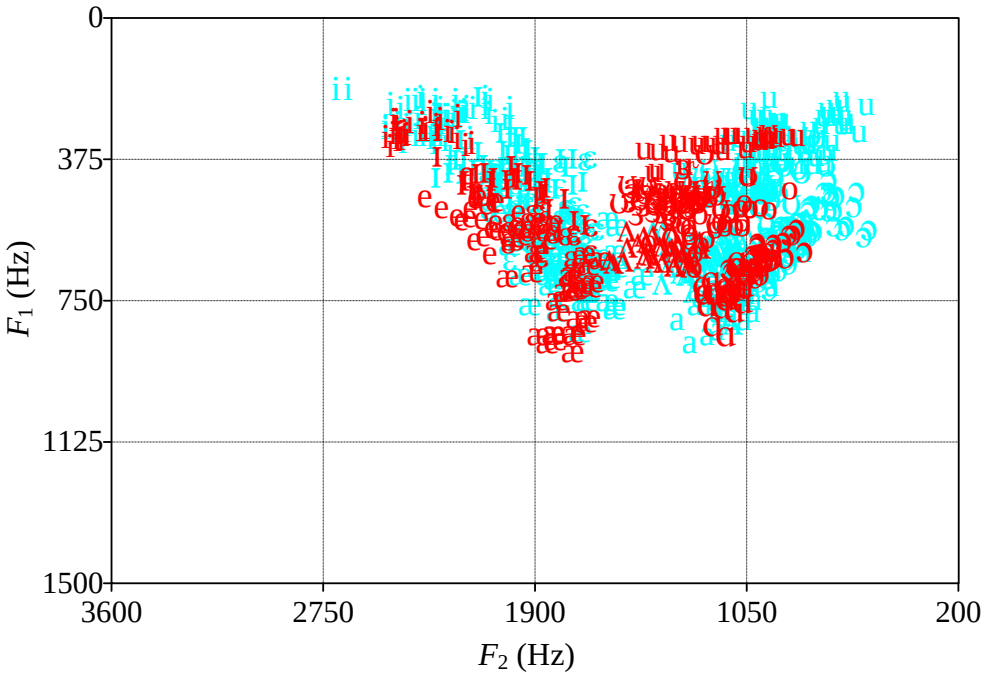
Mandarin Phonetic Symbols 1[8]

	MPS I	MPS II
(1) Initials		
Labials	ㄅ ㄆ ㄇ ㄈ	b p m f
Dentals	ㄉ ㄊ ㄋ ㄌ	d t n l
Velars	ㄍ ㄎ ㄏ	g k h
Palatals	ㄐ ㄑ ㄒ	j(i) ch(i) sh(i)
Retroflexes	ㄓ ㄔ ㄕ ㄖ	j ch sh r
Dentals	ㄗ ㄘ ㄙ	tz ts s
(2) Finals		
Single Final	(ㄭ)	r,z
	ㄧ ㄨ ㄩ	i,yi u,wu iu,yu
	ㄚ ㄛ ㄜ ㄝ	a o e ê
Double Finals	ㄞ ㄟ ㄠ ㄡ	ai ei au ou
Nasal-end Finals	ㄢ ㄣ ㄤ ㄥ	an en ang eng
Retroflex Final	ㄦ	er
(3) Compound Finals (Used with Initials)		
With i on-glide	ㄧㄚ ㄧㄛ ㄧㄝ ㄧㄞ	ia io ie iai
	ㄧㄠ ㄧㄡ ㄧㄢ ㄧㄣ	iau iou ian in
	ㄧㄤ ㄧㄥ	iang ing
With u on-glide	ㄨㄚ ㄨㄛ ㄨㄞ ㄨㄟ	ua uo uai uei
	ㄨㄢ ㄨㄣ ㄨㄤ ㄨㄥ	uan uen uang ung
With iu on-glide	ㄩㄝ ㄩㄢ ㄩㄣ ㄩㄥ	iue iuan iun iung
(4) Tones		
First Tone	(unmarked)	¯
Second Tone	ˊ	ˊ
Third Tone	ˇ	ˇ
Fourth Tone	ˋ	ˋ
Neutral Tone	·	(unmarked)

.

[8] Ministry of Education, Taiwan. (1986). Mandarin Phonetic Symbols 1. Retrieved March 20, 2006, from http://www.edu.tw/EDU_WEB/EDU_MGT/MANDR/EDU6300001/allbook/er/p20-21.htm?open.

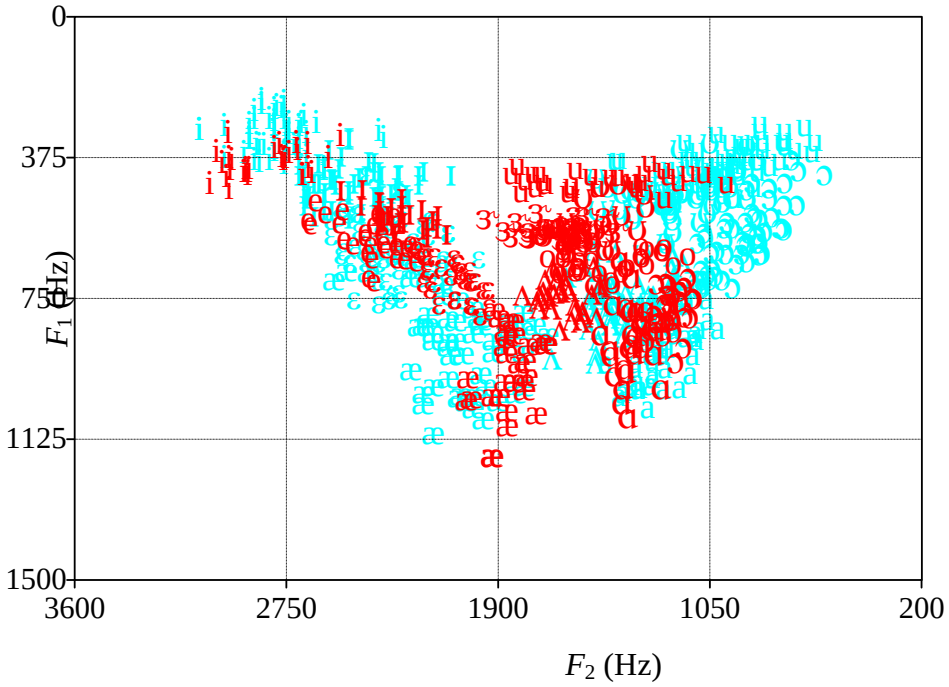
Appendix C



Cyan: scatter plot of male subjects for each monophthong.
Data are from Peterson and Barney (1952).[9]
Red: scatter plot of Texan male subjects for each monophthong.
Data are from this current study.

Figure C1: Male F1 and F2 scatter plots of English vowels.

[9] Plichta, B. (2004). Peterson and Barney formants. Retrieved March 20, 2006, from http://bartus.org/akustyk/documentation.php.



Cyan: scatter plot of female subjects for each monophthong.
Data are from Peterson and Barney (1952).[10]
Red: scatter plot of Texan female subjects for each monophthong.
Data are from this current study.

Figure C2: Female F1 and F2 scatter plots of English vowels.

[10] Plichta, B. (2004). Peterson and Barney formants. Retrieved March 20, 2006, from http://bartus.org/akustyk/documentation.php.

Appendix D

Subjects' Background Information

Subject	Gender	Ethnicity	First Language	Length of Stay in Texas (years)[11]	Age	Height (cm)
AF	female	Caucasian	English	22.0	22	175
BF	female	Caucasian	English	20.0	20	163
CF	female	White-Hispanic	English	25.0	25	155
DF	female	Caucasian	English	18.0	18	165
EF	female	Caucasian	English	18.0	18	173
FF	female	Caucasian	English	23.0	23	155
GF	female	Caucasian	English	26.0	27	175
HF	female	White-Hispanic	English	31.0	37	165
IF	female	Caucasian	English	20.0	20	180
JF	female	Caucasian	English	31.0	32	170
Subject	Gender	Ethnicity	First Language	Length of Stay in Texas (years)	Age	Height (cm)
AM	male	Caucasian	English	24.0	25	180
BM	male	Caucasian	English	28.0	28	170
CM	male	Caucasian	English	35.0	35	175
DM	male	Caucasian	English	18.0	18	180
EM	male	Caucasian	English	26.0	27	177
FM	male	Caucasian	English	22.0	22	178
GM	male	Caucasian	English	38.0	39	165
HM	male	Caucasian	English	21.0	25	193
IM	male	Caucasian	English	29.0	30	180
JM	male	Caucasian	English	19.0	19	180

[11] For the long term residents, the length of stay in Texas is rounded to the nearest whole year.

Subject	Gender	Ethnicity	First Language	Length of Stay in the U.S. (years)	Age	Height (cm)
ATF	female	Chinese	Min-nan yu	3.8	28	157
BTF	female	Chinese	Min-nan yu	3.8	31	170
CTF	female	Chinese	Min-nan yu	4.0	27	163
DTF	female	Chinese	Min-nan yu	4.0	34	155
ETF	female	Chinese	Min-nan yu	3.0	40	160
FTF[12]	female	Chinese	Min-nan yu	3.0	26	159
GTF	female	Chinese	Min-nan yu	4.3	31	160
HTF	female	Chinese	Min-nan yu	3.0	32	162
ITF	female	Chinese	Min-nan yu	8.0	33	160
JTF	female	Chinese	Min-nan yu	2.0	35	152
Subject	Gender	Ethnicity	First Language	Length of Stay in the U.S. (years)	Age	Height (cm)
ATM	male	Chinese	Min-nan yu	6.8	33	167
BTM	male	Chinese	Min-nan yu	5.9	32	175
CTM	male	Chinese	Min-nan yu	6.0	31	173
DTM	male	Chinese	Min-nan yu	2.8	29	172
ETM	male	Chinese	Min-nan yu	3.8	32	168
FTM	male	Chinese	Min-nan yu	3.0	32	173
GTM	male	Chinese	Min-nan yu	2.8	25	185
HTM	male	Chinese	Min-nan yu	3.0	33	168
ITM	male	Chinese	Min-nan yu	4.0	30	174
JTM	male	Chinese	Min-nan yu	2.8	32	174

[12] FTF spent a year in Australia after graduating from elementary school.

Appendix E

The full list of test English words in this study[13]

1.	ɑ	hod
2.	ɔ	hawed
3.	ɝ	herd
4.	u	who'd
5.	æ	had
6.	i	heed
7.	ɛ	head
8.	o	hoed
9.	ɔ	hawed
10.	ʊ	hood

[13] Most people in Taiwan learn phonetic symbols based on Kenyon & Knott's 1953 *A Pronouncing Dictionary of American English* (Yang, 1994). The main difference between IPA symbols and the phonetic symbols from Kenyon & Knott (1953) in Appendix E relates to /e/ and /o/. /e/ and /o/ are diphthongs represented as /eɪ/ and /oʊ/ in IPA, respectively. English words and phonetic symbols are simultaneously presented to the participants in this word list.

11.	i	heed
12.	ɝ	herd
13.	ɛ	head
14.	aɪ	hide
15.	ʌ	Hudd
16.	ɔɪ	hoid
17.	ɔɪ	hoid
18.	aʊ	how’d
19.	ʌ	Hudd
20.	ɪ	hid

21.	e	hayed
22.	aɪ	hide
23.	ɔ	hawed
24.	aɪ	hide
25.	ʊ	hood
26.	e	hayed
27.	u	who’d
28.	ɛ	head
29.	ɔɪ	hoid
30.	u	who’d

31.	i	heed
32.	u	who’d
33.	aʊ	how’d
34.	ɛ	head
35.	ʌ	Hudd
36.	e	hayed
37.	ɪ	hid
38.	ɔ	hawed
39.	ʊ	hood
40.	ɝ	herd

41.	ʌ	Hudd
42.	ɔ	hawed
43.	i	heed
44.	ɔɪ	hoid
45.	ʊ	hood
46.	aʊ	how’d
47.	e	hayed
48.	aɪ	hide
49.	ɑ	hod
50.	ɔɪ	hoid

51.	ɝ	herd
52.	æ	had
53.	o	hoed
54.	æ	had
55.	æ	had
56.	i	heed
57.	ɛ	head
58.	æ	had
59.	ʊ	hood
60.	e	hayed

61.	ɪ	hid
62.	aʊ	how’d
63.	aʊ	how’d
64.	aɪ	hide
65.	o	hoed
66.	ʌ	Hudd
67.	ɪ	hid
68.	o	hoed
69.	ɪ	hid
70.	ɝ	herd

71.	ɑ	hod
72.	o	hoed
73.	ɑ	hod
74.	u	who’d
75.	ɑ	hod

Appendix F

The full list of test Mandarin phrases in this study[14]

1.	ㄏㄟˋ	嘿	的
2.	ㄏㄠˇ	好	的
3.	ㄏㄞ	嗨	的
4.		ㄏㄧㄡˊ	的
5.	ㄏㄚˊ	蛤	的
6.	ㄏㄨˇ	虎	的
7.	ㄏㄠˊ	豪	的
8.	ㄏㄨˇ	吼	的
9.		護	的
10.		ㄏㄧˊ	的

[14] The MPS 1 symbols in the second column might in some cases have served to remind the Mandarin subjects of the characters in the third column.

11.		厂丶 ㄩ	的
12.		河	的
13.		黑	的
14.		厂丶 一	的
15.		害	的
16.		厂丶 丫	的
17.	厂丶 幺	號	的
18.	厂 ㄞ	嗨	的
19.		胡	的
20.		厂丶 ㄩ	的

21.		ㄏㄨㄛ	的
22.		ㄏㄡ	的
23.	ㄏㄟ	黑	的
24.		ㄏㄨㄧ	的
25.		護	的
26.		ㄏㄨㄛ	的
27.		ㄏㄛ	的
28.		ㄏㄨㄝ	的
29.		孩	的
30.		ㄏㄧ	的

31.		ㄏㄩ	的
32.		ㄏㄧ	的
33.		ㄏㄩ	的
34.		ㄏㄡ	的
35.		虎	的
36.		ㄏㄨㄚ	的
37.		ㄏㄝ	的
38.		ㄏㄨㄝ	的
39.		ㄏㄟㄝ	的
40.		ㄏㄟㄛ	的

41.		ㄏㄟˋ	的
42.		猴	的
43.		賀	的
44.		賀	的
45.		護	的
46.		賀	的
47.		ㄏㄜˇ	的
48.		ㄏㄧˋ	的
49.		虎	的
50.		ㄏㄟˊ	的

51.		河	的
52.		ㄏㄨㄛˊ	的
53.	ㄏㄠˋ	號	的
54.		ㄏㄟˋ	的
55.		ㄏㄜˊ	的
56.		厚	的
57.	ㄏㄚˋ	蛤	的
58.		哈	的
59.		ㄏㄚˋ	的
60.		哈	的

61.		好	的
62.		ㄏㄠˇ	的
63.	ㄏㄟˊ	蛤	的
64.		ㄏㄟˊ	的
65.		ㄏㄨˇ	的
66.		胡	的
67.		ㄏㄡˊ	的
68.		猴	的
69.		ㄏㄡˊ	的
70.		ㄏㄨˇ	的

71.		ㄏㄟˊㄝ	的
72.		ㄏㄟˋㄚ	的
73.	ㄏㄟˋㄠ	號	的
74.		ㄏㄟˊㄛ	的
75.		河	的
76.		ㄏㄟˊㄟˋ	的
77.		ㄏㄟˋㄛ	的
78.		ㄏㄟˇㄛ	的
79.		ㄏㄟˇㄟˋ	的
80.		呼	的

81.		虎	的
82.		ㄏㄧˊㄧ	的
83.		ㄏㄧˋㄝ	的
84.		哈	的
85.	ㄏㄠ	蒿	的
86.		ㄏㄧˇㄧ	的
87.		ㄏㄧˋㄩ	的
88.	ㄏㄧˊㄚ	蛤	的
89.		好	的
90.		ㄏㄧˋㄩ	的

91.		ㄏㄨㄩ	的
92.		ㄏㄧㄩ	的
93.		猴	的
94.		海	的
95.		ㄏㄨㄟ	的
96.		ㄏㄩ	的
97.		ㄏㄨㄛ	的
98.	ㄏㄧㄠ	豪	的
99.		呼	的
100.		ㄏㄧㄝ	的

101.		ㄏㄧㄩ	的
102.		ㄏㄚㄝ	的
103.		虎	的
104.	ㄏㄟ	嘿	的
105.		ㄏㄧㄛ	的
106.		厚	的
107.		孩	的
108.	ㄏㄡ	厚	的
109.		ㄏㄧㄟ	的
110.	ㄏㄠ	號	的

111.		厂ㄟ ㄝ	的
112.		胡	的
113.		厂 ㄩ	的
114.		厂ㄟ ㄚ	的
115.		厂 ㄡ	的
116.		海	的
117.	厂ㄟ ㄠ	豪	的
118.		厂 ㄡ	的
119.	厂ㄟ ㄟ	嘿	的
120.	厂ㄟ ㄡ	吼	的

121.		ㄏㄨㄛ	的
122.	ㄏㄟ	黑	的
123.		胡	的
124.		ㄏㄨㄝ	的
125.		ㄏㄨㄛ	的
126.		ㄏㄧㄧ	的
127.		ㄏㄨㄩ	的
128.		ㄏㄧ	的
129.	ㄏㄠ	蒿	的
130.		ㄏㄨㄧ	的

131.		胡	的
132.		喝	的
133.	ㄏㄨㄞ	吼	的
134.		ㄏㄟˋ	的
135.		好	的
136.	ㄏㄟˋ	嘿	的
137.		ㄏㄨㄚ	的
138.		ㄏㄨㄟ	的
139.		ㄏㄧ	的
140.		ㄏㄧˊ	的

141.		ㄏㄚˋ	的
142.		ㄏㄝ	的
143.		害	的
144.		ㄏㄡ	的
145.		ㄏㄝˋ	的
146.	ㄏㄟˋ	嘿	的
147.		ㄏㄛˋ	的
148.	ㄏㄡˇ	吼	的
149.		厚	的
150.		喝	的

151.	ㄏㄟˊㄚ	蛤	的
152.		護	的
153.		喝	的
154.		ㄏㄜˇㄧ	的
155.		ㄏㄜˇㄝ	的
156.		ㄏㄛ	的
157.		ㄏㄝ	的
158.	ㄏㄞ	嗨	的
159.		ㄏㄛ	的
160.		ㄏㄟˋㄚ	的

161.		害	的
162.		呼	的
163.		ㄏㄝ	的
164.		ㄏㄟˋ	的
165.	ㄏㄠˊ	豪	的
166.		ㄏㄟˇ	的
167.		孩	的
168.		賀	的
169.		ㄏㄜˋ	的
170.		ㄏㄡˋ	的

171.		害	的
172.		哈	的
173.		河	的
174.		ㄏㄨ	的
175.		呼	的
176.		海	的
177.		孩	的
178.	ㄏㄠ	蒿	的
179.		ㄏㄚㄜ	的
180.		賀	的

181.		ㄏㄟˇ	的
182.		ㄏㄝ	的
183.	ㄏㄟ	黑	的
184.		ㄏㄧ	的
185.		喝	的
186.		ㄏㄧˋ	的
187.		ㄏㄛˇ	的
188.	ㄏㄠ	蒿	的
189.		猴	的
190.		海	的

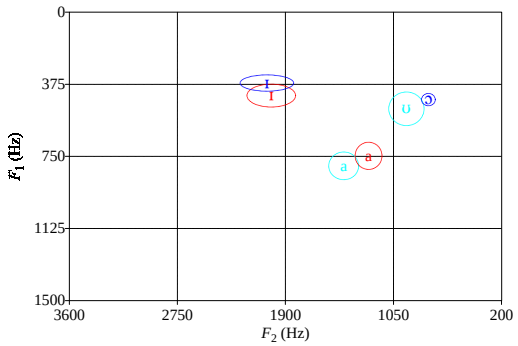
191.	ㄏˇㄡ	吼	的
192.	ㄏㄞ	嗨	的
193.		ㄏˊㄟ	的
194.		ㄏˊㄧ	的
195.		ㄏˇㄚ	的
196.		ㄏˇㄧ	的
197.		哈	的
198.		ㄏˋㄛ	的
199.		ㄏㄛ	的
200.		ㄏˇㄩ	的

201.		豪	的
202.		孩	的
203.	厂 幺	蒿	的
204.	厂 乀	黑	的
205.		喝	的
206.		厚	的
207.		厂丿 口	的
208.		河	的
209.		害	的
210.		厂丶 口	的

211.		ㄏㄟˊ	的
212.	ㄏㄞˇ	嗨	的
213.		呼	的
214.		護	的
215.		海	的
216.	ㄏㄠˋ	號	的
217.		好	的
218.		ㄏㄡˊ	的
219.		ㄏㄡˊ	的
220.		猴	的

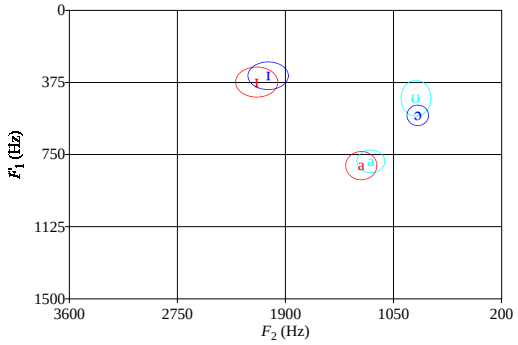
Appendix G

The acoustic distribution of English diphthongs from subjects from Texas and Taiwan



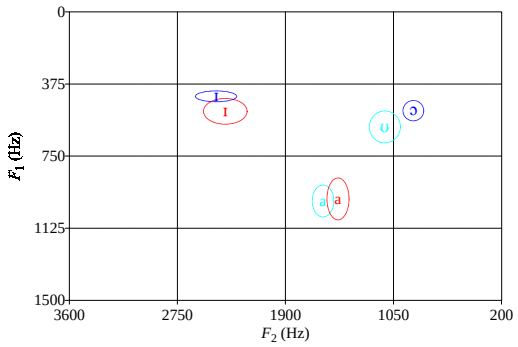
Red: /aɪ/; Cyan: /aʊ/; Blue: /ɔɪ/.
IPA symbols represent F1 and F2 mean values.
Ellipses represent one standard deviation about the mean.

Figure G1: F1 and F2 mean values of male Texas subjects' diphthongs, /aɪ/, /aʊ/, and /ɔɪ/.



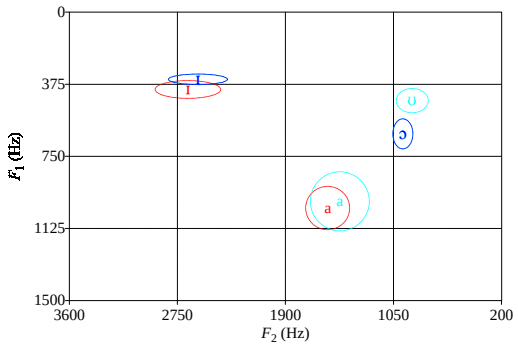
Red: /aɪ/; Cyan: /aʊ/; Blue: /ɔɪ/.
IPA symbols represent F1 and F2 mean values.
Ellipses represent one standard deviation about the mean.

Figure G2: F1 and F2 mean values of male Taiwan subjects' diphthongs, /aɪ/, /aʊ/, and /ɔɪ/.



Red: /aɪ/; Cyan: /aʊ/; Blue: /ɔɪ/.
IPA symbols represent F1 and F2 mean values.
Ellipses represent one standard deviation about the mean.

Figure G3: F1 and F2 mean values of female Texas subjects' diphthongs, /aɪ/, /aʊ/, and /ɔɪ/.



Red: /aɪ/; Cyan: /aʊ/; Blue: /ɔɪ/.
IPA symbols represent F1 and F2 mean values.
Ellipses represent one standard deviation about the mean.

Figure G4: F1 and F2 mean values of female Taiwan subjects' diphthongs, /aɪ/, /aʊ/, and /ɔɪ/.

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