SPEECH PROCESSING OF HAI-LU HAKKA FALLING TONES AND TONE SANDHI

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ABSTRACT

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This dissertation investigates speech processing of Hai-lu Hakka falling tones (high, low) and tone sandhi (low-rising, high-checked) by focusing on how variations influence the perception of the contrast of falling tones and the application of tone sandhi. Some recent studies (Bent 2005; Huang 2004; Wang 1995; Zhang & Lai 2010; Zhang et al 2011) indicated that tonal contrasts may not be as distinctive as assumed previously and that tone sandhi may not be fully productive, since earlier studies tended to neglect the role variations play in tonal processing. In addition, the target language Hai-lu Hakka has been understudied, and was found to undergo language attrition in recent decades (Yeh 2011; Yeh & Lu 2013; Yeh & Lin 2015). The dissertation hopes to clarify how tonal variations affect tonal contrasts and tone sandhi application by explicating Hai-lu Hakka' tonal processing.

The first experiment examines 30 Hai-lu Hakka speakers' contrast of falling tones by tonal identification and lexical recognition tasks. These tasks require participants to identify monosyllabic stimuli's tonal categories (either high-falling or low-falling) and to recognize their lexical meanings (either a high-falling word [ti53] 'to know' or a low-falling word [ti31] 'emperor'). The second experiment examines 31 Hai-lu Hakka speakers' processing of two sandhi rules by tonal discrimination, tonal identification, lexical recognition, and production tasks. These tasks require participants to discriminate underlying and sandhi tones, to identify their tonal categories, to recognize their corresponding meanings, and to produce tone sandhi in disyllabic compounds. The results show that (i) various lexical and phonetic/phonological factors play a role in the tonal contrast and the sandhi processes, (ii) lexical and

phonetic/phonological effects can be more or less significant in different tasks, and (iii) lexical factors exhibit a more consistent pattern across different tasks than phonetic/phonological factors. These findings indicate three general implications as follows.

First, the lexical and phonetic/phonological effects indicate that the contrast of two falling tones varies with both lexical and phonetic/phonological factors, so does the application of two sandhi rules. These factors may result in tonal confusion between two falling tones and lower application rates of two sandhi rules. Second, the lexical and phonetic/phonological effects indicate that variations occur frequently and extensively across different tasks in the two experiments, which calls into question those derivational theoretical models that assume a transition from variations to invariance during speech processing. Third, the results indicate that lexical effects exhibit a more consistent pattern than phonetic/phonological effects, since phonetic/phonological effects exhibit an asymmetry between perception and production patterns. These findings suggest a more crucial role of lexical influences in tonal processing, which hence favors a lexically-based model for speech processing in general.

To sum up, this dissertation has three general contributions. First, relating phonetic modifications/processes to variations and phonological modifications/processes to invariance is called into questions. Second, the findings uncover specific issues such as tonal confusion and a perception-production asymmetry in Hai-lu Hakka's tonal phonetics and phonology, supporting the crucial need to carefully examine a less-studied language like Hai-lu Hakka. Third, the findings indicate a more crucial role of lexical influences in tonal processing, suggesting that an exemplar-based processing model that argues for a non-derivational and lexically-driven account is a more reasonable approach to speech processing.

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I kept questioning myself what this dissertation means to me over the past three years when I had a hard time finishing it up. I have never thought about giving up, but felt like losing something meaningful to pursue the PhD degree. I used to believe it means everything. Whatever I want could come true with the doctorate in hand. In fact I can do all I like right away even without it. The real question is what it means whatever I want and all I like. I did not realize the meaning until my advisor Dr. Yen-Hwei Lin and I decided to focus on my mother tongue. The recent revision reminds me of the teenage years when I reacquired Hai-lu Hakka from my parents. I did not really want to relearn my native language, but was left with no choices by my parents. As long as I spoke Mandarin, my father never responded. As long as I mispronounced Hakka, he made mean remarks. No matter how hard I tried, I could hardly meet his expectations. I could not really understand why he was so harsh. After working on Hai-lu Hakka for so many years, I begin to realize what he meant to do. I should be grateful to be still able to speak my parents' tongue, and to have the chance to study it. Finishing up the dissertation on Hai-lu Hakka definitely means something to me.

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KEY TO ABBREVIATIONS

Adj.	adjective
f0	fundamental frequency
H	high features
L	low features
L1	first language
L2	second language
M	middle, non-high and non-low
T1	Mandarin's high-level tone, Tone-55
T2	Mandarin's mid-rising tone, Tone-35
T3	Mandarin's low-falling tone, Tone-21(4)
T4	Mandarin's high-falling tone, Tone-51

CHAPTER ONE

INTRODUCTION

This dissertation evaluates the role of variations in tonal processing by investigating various lexical and phonetic/phonological effects on Hai-lu Hakka's two falling tones and two sandhi rules. The research purpose is twofold: at an empirical level and at a theoretical level. The former tries to explain whether variations induced by different factors (lexical and phonetic/phonological) play a role in the tonal contrast and the application of tone sandhi, and the latter tries to formalize/model these variations and their influences on speech processing. In general, this dissertation has three research interests: (i) the role of variations: to understand different kinds of variations and their roles in tonal phonetics and phonology, (ii) the Hai-lu variety of Hakka: to revisit this endangered and less-studied language's falling tones and tone sandhi in an empirical manner, and (iii) tonal processing: to explain how different tonal variations are processed and how they affect tonal perception and production.

In order to evaluate the role variations play in the tonal contrast and the sandhi processes, this dissertation asks two research questions: whether lexical factors, phonetic/phonological factors, and other factors affect Hai-lu Hakka's contrast of two falling tones (high-falling versus low-falling) and whether lexical factors, phonetic/phonological factors, and other factors affect the application of two tone sandhi rules (low-rising tone sandhi and high-checked tone sandhi). Each question consists of three subsets: (a) the lexical effects, (b) the phonetic/phonological effects, and (c) interaction and processing effects. The presence of these various effects arguably supports the significant influences of variations on tonal contrasts and tone sandhi processes. Since the perception of tonal contrasts and the application of tone sandhi vary with different factors, some tonal contrasts may not be as distinctive as assumed previously, and tone sandhi may not be as productive as assumed previously. The current findings clarify how tonal variations affect tonal contrasts and tone-sandhi application by explicating Hai-lu Hakka's tonal processing. This study also has implications for linguistic theory and speech processing in general.

1.0 The dissertation's key terms

Before recapping this dissertation's interests, research questions, and general claims, this introductory section tentatively defines several key terms: Hai-lu Hakka, speech processing, tones, tone sandhi, lexical factors, phonetic/phonological factors, processing factors, variations, and exemplars. These key terms are discussed as follows:

- ✓ **[Hai-lu Hakka]**: As indicated by the Council of Hakka Affairs in Taiwan (2008), Hakka languages generally include six dialects: Si-xian (四縣), Hai-lu (海陸), Da-pu (大埔), Rao-ping (饒平), Shao-an (紹安), and others, such as Yong-ding (永定). The target language, the Hai-lu variety of Hakka, has the second largest speaking-population among the six dialects. It is basically distributed in northern Taiwan, such as Hsinchu (新竹) and Taoyuan (桃園) cities, so it is also called the Hsinchu variety.
- ✓ **[Speech processing]**: Speech processing basically refers to speech perception and production, and includes a series of psychological processes which listeners/speakers utilize to decode and encode speech signals from input to output, such as stimulation, organization, interpretation, memory (storage), recalls, selection and implementation. These serial processes are supposedly governed by both language systems and motor-sensor mechanisms. In other words, speech perception and production integrate both mechanical and lexical processes by the current definition.
- ✓ **[Tones]**: Chinese languages tend to classify tonal categories by (i) syllable types, (ii) pitch contour, and (iii) pitch height. First, the syllable types contrast non-checked and checked tones. Non-checked tones refer to those with open syllables or those with nasal codas, while checked tones refer to those with unaspirated voiceless stop codas (i.e. -p,

-t, and -k). Second, the pitch contour contrasts level and contour tones, and contour tones include rising and falling tones. Level tones refer to those with constant onset and offset pitch height, while contour tones refer to those with varying pitch height. Rising tones refer to those with lower onset pitch and higher offset pitch, while falling tones refer to those with higher onset pitch and lower offset pitch. Third, the pitch height contrast high and low tones. As indicated by Chao (1968), these tonal categories are represented by a two-digit system (the first digit as onset pitch height, and the second digit as offset pitch) on a five-level scale (the digit 5 as the highest normalized pitch, and the digit 1 as the lowest). For instance, Tone-13 is low-rising tone which consists of the lowest onset pitch and the mid-level offset pitch, and Tone-53 is high-falling tone which consists of the highest onset pitch and the mid-level offset pitch. Checked tones may be represented by one digit only with an underline, since they are shorter in syllable duration. For instance, Tone-$\underline{5}$ is high-checked tone, and Tone-$\underline{2}$ is low-checked tone in Hai-lu Hakka.

- ✓ **[Tone sandhi]**: Tone sandhi is a specific kind of tonal changes, which is typically assumed to occur for paradigmatic/phonological reasons in particular prosodic contexts, e.g. non-final position. In Hai-lu Hakka, there are two tone sandhi rules: low-rising tone sandhi and high-checked tone sandhi. The former changes low-rising tone Tone-13 to low-level tone Tone-22 before any tone in non-final position, and the latter changes high-checked tone Tone-$\underline{5}$ to low-checked tone Tone-$\underline{2}$ in the same context.
- ✓ **[Lexical factors]**: Lexical factors refer to word types (i.e. actual words, novel words) and lexical frequency (i.e. frequent, less frequent). Since frequency variables are not always available from actual word counts in a given corpus, they may be obtained from subjective ratings referred as lexical familiarity (i.e. familiar, less familiar) in some cases.
- ✓ **[Phonetic/Phonological factors]**: Phonetic/phonological factors refer to features (e.g.

pitch height, pitch contour), segments or categories (e.g. vowels, tones), and constraints (e.g. rules, contexts). This dissertation chooses not to distinguish phonetic and phonological factors for two reasons. First, it is not always easy to distinguish one from the other, as indicated by Hayes et al (2004), in that many phonological patterns have a strong phonetic basis. Second, it is not necessary to do so for the current research purpose that simply focuses on a contrast between lexical and non-lexical types. The phonetic and phonological factors are both non-lexical by the current definition.

- ✓ **[Processing factors]**: Processing factors are also known as processing strategies: top-down and bottom-up processes. It is a top-down strategy when listeners/speakers would rather process speech signals by lexical knowledge than by acoustic details, while it is a bottom-up strategy when they would rather process speech signals by acoustic details than by lexical knowledge. Although it is disputable how to set up the two strategies as independent variables, the processing strategies seem to be correlated with task types. Different tasks may require participants to apply different problem-resolving skills/strategies. As a result, this dissertation sets up processing factors as each task type. The processing factors in this study basically refer to two kinds: (i) different degrees of lexical access and (ii) a difference between perception and production processes.
- ✓ **[Variations]**: This dissertation defines variations in two following senses: (i) in contrast to invariance and (ii) in contrast to standard patterns. The former case refers to different degrees, whereas the latter refers to different kinds (i.e. exceptions or deviations).
- ✓ **[Exemplar(s)]**: Exemplars refer to a fundamental unit of speech processing as a token of memory/experiences (on a basis of words or sounds) in contrast with perceptual abstractions and articulatory gestures. This processing unit integrates all information (concrete and/or abstract: phonetic details, phonological constraints, and others) into a token of words in a probabilistic manner.

1.1 The dissertation's research purposes and interests

As mentioned in the introductory section above, this dissertation has two research purposes: first, to examine whether tonal contrasts are as distinctive as assumed previously, and then to examine whether tone sandhi rules are as productive as assumed previously. In order to answer the two questions, this dissertation brings up three research interests: the role of tonal variations, the Hai-lu variety of Hakka, and the lexical effects and the phonetic/phonological effects on tonal processing. This section explains how the two purposes and three interests motivate this dissertation and how they are relevant to some theoretical issues and processing models.

1.1.1 The role of variations

The role of variations in tonal processing motivates this dissertation, since it is underestimated for two reasons. First, variations may lead to tonal confusion which indicates the distinctiveness issue: some tonal contrasts may not be as distinctive as assumed previously. Second, variations may bring down application of tone sandhi. The lower application rates indicate the productivity issue: tone sandhi may not be as productive as assumed previously.

1.1.1.1 The distinctiveness issue

Tonal contrasts were assumed to be distinctive by previous studies for two reasons. First, previous studies (Bent 2005; Fon & Hsu 2007; Garding et al 1986; Pan & Tai 2006; Peng 1997; Xu 1997, 1999, 2004; Yeh & Huang 2011) mostly adopted a production approach to tones and tonal variations, and seldom attended to a perception approach, as summarized in Table 1.1 below. The summary indicates a disparity between production and perception studies. Since most previous studies rarely examine the potential effect of variations on tonal perception, tonal contrasts were previously assumed to be distinctive, except for the noted T2-T3 confusion in Mandarin shown by Fon & Hsu (2007), Huang (2004), and Moore &

Jongman (1997).

Table 1.1 Summary of previous studies on tonal perception and production.

	Production approach	Perception approach
Amount of studies	More	Fewer
	Bent 2005; Fon & Hsu 2007; Garding et al 1986; Pan & Tai 2006; Peng 1997; Xu 1997, 1999, 2004; Yeh & Huang 2011; and many others	Bent 2005; Peng 1997
Factors examined	More	Fewer
	Neighboring tones, prosodic boundaries, prosodic positions, intonation and the like	Only neighboring tones
Effects found	Significant	Significant, but restricted
	Across each level of factors examined	Restricted to a specific condition (e.g. a level-falling tonal frame, or before low-falling tone)

Second, some studies (Hsu 1989; So & Dodd 1995; Tsay 2001; Tse 1978; Zhu & Dodd 2000) found that tonal categories are acquired as early as two years old in many Chinese languages (Cantonese, Mandarin, and Taiwan Southern Min). They also indicated that tonal inventories are acquired earlier than vowels and consonants, and tonal perception is developed earlier than tonal production. In addition, other studies (Jongman et al 2006; Miracle 1989; Wang et al 2003) found that Mandarin speakers have higher perceptual accuracy than L2 learners. These findings suggest that tonal categories are acquired very early during learning processes because tonal contrasts are distinctive inherently. As a result, tonal contrasts were previously assumed to be distinctive.

However, some recent findings suggested that some tonal contrasts may not be as distinctive as assumed previously. Yeh & Lin (2013, 2015) found that similar pitch height and pitch contour may lead to tonal confusion in Hai-lu Hakka. For instance, high-level tone and low-level tone are phonetically similar in pitch contour, so they tend to be misperceived as each other. Low-level tone and low-falling tone are phonetically similar in pitch height, so they tend to be mispronounced as each other. Liu et al (2007, 2009) and Wong et al (2003) found that young Mandarin learners have not fully acquired tonal perception and production until the age of five to six. The potential tonal confusion and the not-so-early tonal acquisition call into question previous assumptions on distinctive tonal contrasts, and motivate this dissertation to investigate the distinctiveness issue.

1.1.1.2 The productivity issue

Tone sandhi rules were assumed to be fully productive by previous studies for two reasons as well. First, previous studies (Hsu 1989; Tsay 2001; Zhu & Dodd 2000) indicated that tone sandhi rules are acquired as early as tonal inventories. For instance, the noted Mandarin T3 sandhi changes T3 to a T2-like variant before another T3, as illustrated in (1) below. Zhu & Dodd (2000) found that two-year-olds can apply the tonal rule accurately to various compound words. Since tone sandhi rules are acquired earlier than the age of two, they were assumed to be fully productive among adult speakers. Second, tone sandhi was argued to derive from various factors in the post-lexical stratum (Xu 2004: 383). According to the theory of lexical phonology (e.g. Hargus & Kaisse 1993; Kiparsky 1982, 1988), post-lexical rules are fully productive in contrast to lexical rules that are partially productive. Since tone sandhi was argued to be a post-lexical rule, it was assumed to be fully productive.

(1) T3 Sandhi in Mandarin

T3 (Tone-21/214: low-falling/dipping)→ T2 (Tone-35: rising) / ____ before another T3

However, some recent findings suggested that tone sandhi may not be as productive as assumed previously. Wang (2011) found that both adult and young speakers apply Mandarin T3 sandhi to various syntactic/prosodic structures in different manners. Their different processing strategies give rise to an extensive amount of variations. For instance, they produced five 5s, 五 wu3 'five' in Mandarin, as either wu**2**wu3wu**2**wu**2**wu3 or wu**2**wu**2**wu**2**wu**2**wu3. The former involves a pitch reset between the second and the third wu3 'five', whereas the latter does not. The pitch reset is optional, and the optionality leads to variations. Zhang et al (2011) found that Taiwan Southern Min's tone sandhi application varies with word types, sandhi types, and many other factors. These different factors are responsible for variations in the application of tone sandhi. For instance, low-rising tone sandhi that changes low-rising tone to low-level tone is more productive than low-falling tone sandhi that changes low-falling tone to high-falling tone, indicating an effect of sandhi types. These variations in different kinds and degrees call into question previous assumptions on tone sandhi, and motivate this dissertation to investigate the productivity issue.

In sum, the distinctiveness issue and the productivity issue suggest a potentially important role of variations in tonal processing. The distinctiveness issue indicates that some tonal contrasts may not be fully distinctive, since variations may lead to tonal confusion. The productivity issue indicates that tone sandhi may not be fully productive, since variations may result from different effects on the application of tone sandhi. Therefore, the potential role of variations in tonal processing motivates this dissertation.

1.1.2 The endangered and less-studied language: Hai-lu Hakka

According to the official report issued by the Council of Hakka Affairs in Taiwan (2008), there are about three million Hakka 'people' in Taiwan. They are called Hakka 'people' instead of Hakka speakers, since most of them cannot really speak Hakka. The estimate of speaking population makes Hakka the third largest language, only fewer than Mandarin and Southern Min (i.e. Mandarin > Southern Min > Hakka > other languages). Since Hakka people make up only 15% of total population in Taiwan, their speaking environment is greatly threatened by the two largest languages. Compared to Mandarin and Southern Min, Hakka is not only less spoken and heard in public, but also less investigated. Since it is used less and less frequently nowadays, the decrease in frequency of use leads to language attrition (i.e. the attrition issue). Since it was seldom investigated previously, its complicated varieties and patterns tend to be simplified as being represented by its largest speaking dialect Si-xian Hakka (i.e. the simplification issue). Although Hai-lu Hakka has the second most speaking population among the six Hakka dialects, its tonal patterns are less known. The attrition issue and the simplification issue motivate this dissertation to focus on Hai-lu Hakka's tonal phonetics and phonology.

1.1.2.1 The attrition issue

Hakka speakers are mostly bilingual or multilingual due to Mandarin and Southern Min's socioeconomic influences. They have become more and more Mandarin-dominant in recent years, since they have fewer and fewer opportunities to hear and speak Hakka. As indicated by Lo (1990: 36), Hakka-speaking population has declined dramatically since the government enacted the Mandarin-speaking policy in early 1950s. The Mandarin-speaking-only movement privileged the official language Mandarin in public domains, such as schools and mass communication, and prohibited Hakka people (as well as Southern Min people and aboriginal people) from speaking their mother tongue in public. Hakka people can simply acquire and use Hakka at home and in other private domains such as family gatherings. The movement continued until late 1980s, and led to a great loss of speaking population. Although the language policy was repealed in 1980s, Mandarin still plays a leading role in public domains, and the decline of Hakka-speaking population has never slowed down. In late 1990s, Tsao (1997) found that Hakka speakers no longer used their mother tongue even at home and other private gatherings, and then rural areas became the last sanctuary for the use of Hakka. The incessant decline of speaking population made only 11.6% of Hakka children below the age of 13 able to speak fluent Hakka, indicating a critical sign of endangered languages issued by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2003.

These signs of language crisis prompted the government to initiate the Council of Hakka Affairs and the Hakka TV station in 2001 and 2003 respectively for preserving Hakka's languages and cultures. A series of public restoration makes Hakka more likely to be heard in public transportation, mass communication, and education systems. For instance, Hakka becomes an optional course in elementary and middle schools. However, most of these restoring/preserving processes simply focus on Si-xian Hakka, and barely attend to other dialects. Various restrictions still make it difficult to restore Hakka's speaking population, as the loss of speaking-population hardly stops even after the government's new language policy. Hsiao (2007) found that nowadays young speakers barely speak Hakka at home even in rural areas, and most parents do not speak Hakka to their children, either. These findings indicated that new generations may not acquire Hakka as their first language any longer. Language attrition has become more and more critical to Hakka, especially those dialects other than Si-xian Hakka. Therefore, it is urgent to examine each Hakka dialect for the sake of linguistic preservation.

1.1.2.2 The simplification issue

All Hakka dialects not only suffer from a great loss of speaking population, but also tend to be simplified as being represented by their largest speaking variety Si-xian Hakka. Since Hakka per se consists of many dialects, previous studies (Chung 1992, 2004; Gu 2005; Lo 1990; Lu 2000, 2004) mostly chose to focus on the largest speaking dialect. Even if they analyzed one specific dialect, they tended to adopt the general term Hakka, and implied the same particular findings for the other dialects. The simplification issue makes it difficult to distinguish one dialect from another, and tends to ignore variations among different dialects. Each Hakka dialect exhibits its own particular patterns and variations, and it is indispensible to examine each dialect individually.

This dissertation focuses on Taiwan Hakka's second largest speaking dialect Hai-lu Hakka. As indicated by Chang (2002), Fan (1996), Gu (2005), Hsu (2009), Jiang (2003), Yeh & Lu (2013), Yeh & Lin (2013, 2015), Hai-lu Hakka generally exhibits an extensive amount of variations derived from four different tonal modifications. As summarized in (2) below, the four tonal modifications are (a) phonetic modifications, (b) phonological modifications, (c) morpho-phonological modifications, and (d) ongoing sound change. They are briefly introduced below, and are further discussed in the next chapter.

(2) Hai-lu Hakka's tonal modifications

a. Phonetic modifications (Jiang 2003):

   They refer to tonal co-articulation and other influences from prosodic contexts, and give rise to variations, such as a high-onset-pitch variant of low-falling tone.

b. Phonological modifications (Fan 1996; Hsu 2009):

   They refer to tone sandhi and other paradigmatic influences, and give rise to variations, such as a low-level-tone-like variant of low-rising tone.

c. Morpho-phonological modifications (Gu 2005; Hsu 2009):

   They refer to morphological and morpho-phonological rules, and give rise to variations, such as low-rising-tone-like variant of low-level tone.

d. Ongoing sound change (Yeh & Lu 2013; Yeh & Lin 2013, 2015):

   They refer to some tonal mergers in progress, and give rise to variations, such as a low-falling-like variant of low-level tone.

As indicated in (2a) above, phonetic modifications refer to tonal co-articulation and other influences from prosodic contexts, such as prosodic boundaries and prosodic positions. Hai-lu Hakka's phonetic variations (i.e. those modified/induced by tonal co-articulation and other prosodic factors) were barely examined by previous studies, except for an informal report conducted by Jiang (2003). As indicated in (2b) above, phonological modifications refer to tone sandhi and other paradigmatic influences. Hai-lu Hakka's phonological variations (i.e. those modified/induced by tone sandhi and other phonological factors) generally include two kinds: a low-level-tone-like variant of low-rising tone and a low-checked-tone-like variant of high-checked tone. As indicated in (2c), morpho-phonological modifications refer to morphological and morpho-phonological rules. Hai-lu Hakka's morpho-phonological variations generally include two kinds: a low-rising-tone-like variant and a high-checked-tone-like variant. As indicated in (2d), the fourth kind of tonal modifications refer to ongoing sound change in Hai-lu Hakka's tone system. Huang (2001), Yeh (2011), Yeh & Lin (2013, 2015) and Yeh & Lu (2013) found that low-level tone gradually changes to low-falling tone. Yeh & Lin (2013) also found that two checked tones gradually become non-checked. These tonal mergers in progress give rise to variations such as a low-falling-tone-like variant of low-level tone, a high-level-tone-like variant of high-checked tone, and a low-falling-tone-like variant of low-checked tone. In general, Hai-lu Hakka seems to exhibit an extensive amount of variations, but its tonal patterns were barely investigated by previous studies. In order to preserve Hai-lu Hakka and to understand its tonal patterns, it is indispensible to examine these different variations. As a result, this dissertation focuses on the potential role variations play in Hai-lu Hakka's contrast of two falling tones and the application of two sandhi rules.

1.1.3 The lexical and phonetic/phonological effects on tonal processing

This dissertation examines the role variations play in tonal processing by evaluating effects of lexical and phonetic/phonological factors on the perception of tonal contrasts and the application of tone sandhi. As summarized in Table 1.2 below, both kinds of factors were previously found to exert an influence on tonal processing. For instance, Huang (2004) found that Mandarin participants' discrimination accuracy between T2 and T3 is significant lower than that of any other tonal contrast. The finding suggested an effect of tone sandhi on tonal discrimination, since T3 sandhi results in a T3 variant similar to T2. Zhang et al (2011) found that application rates of Taiwan Southern Min tone sandhi are higher in actual words than in novel words, suggesting an effect of word types. However, previous studies show a disparity in that those interested in tonal contrasts (i.e. Bent 2005; Huang 2004; Moore & Jongman 1997; Peng 1997, 2000) tended to focus on phonetic/phonological factors, such as tone sandhi, tone types, and others, whereas those interested in productivity of tone sandhi (Chuang et al 2011; Hsieh 1976; Wang 1995; Zhang et al 2011) tended to focus on lexical factors, such as word types and lexical frequency. Very few of them (e.g. Zhang et al 2011) attended to both kinds of influences on tonal processing. As a result, this dissertation focuses on both the lexical and phonetic/phonological effects on tonal processing to investigate whether lexical and phonetic/phonological factors play a different role and how they interact and are represented.

Table 1.2 Summary of lexical and phonetic/phonological effects on tonal processing.

	Lexical Effects	Phonetic/Phonological Effects
Tonal contrasts	Fewer	More
	Word types.	Tone sandhi, neighboring tones' tone types, prosodic boundaries, prosodic positions, and others.
Productivity of tone sandhi	More	Fewer
	Word types, word-likeliness, lexical frequency, and others.	Sandhi types.

1.2 The dissertation's research questions

This dissertation proposes two general questions to examine the role variations play in tonal processing, (i) the distinctiveness issue: whether the contrast of two falling tones varies in different conditions and (ii) the productivity issue: whether the application of two tone sandhi rules varies in different conditions. As shown in (3) below, each research question includes three subset questions concerning how the three factors, a. lexical factors, b. phonetic/phonological factors, and c. interaction or processing factors, affect the tonal contrast and the tone sandhi processes in Hai-lu Hakka. Each of these factors indicates how variations take place and to what extent they may affect tonal processing.

(3) The dissertation's two research questions

a. The role of variations in the contrast of falling tones: Does the contrast of falling tones vary with different factors?
   (i) The lexical effect: Does the tonal contrast vary with any lexical factors?
   (ii) The phonetic/phonological effect: Does the tonal contrast vary with any phonetic/phonological factors?
   (iii) The interaction effect: Does the tonal contrast vary according to the interaction between lexical and phonetic/phonological factors?

b. The role of variations in the application of tone sandhi: Does the application of tone sandhi vary with different factors?
   (i) The lexical effect: Does the application of tone sandhi vary with any lexical factors?
   (ii) The phonetic/phonological effect: Does the application of tone sandhi vary with any phonetic/phonological factors?
   (iii) The interaction and processing effects: Does the application of tone sandhi vary with interaction and processing factors?

As shown in (3a), the first question asks whether the contrast of two falling tones varies with different factors such as (i) lexical factors, (ii) phonetic/phonological factors, and (iii) interaction factors. As mentioned in section 1.1.3 above, some previous studies (Huang 2004; Moore & Jongman 1997) found that Mandarin T3 sandhi exerts an influence on the T2-T3 contrast, and others (Bent 2005; Peng 1997) found that neighboring tones affect target tones' perceptual accuracy. These studies consistently indicated phonetic/phonological effects on tonal perception, suggesting that tonal contrasts may vary with different phonetic/phonological factors. However, it is still unclear whether tonal contrasts may vary with lexical factors and other factors. The lexical and phonetic/phonological effects may clarify whether tonal contrasts are as distinctive as previously assumed and whether L1 speakers can get confused with some tonal contrasts.

As shown in (3b), the second question asks whether the application of tone sandhi varies with different factors such as (i) lexical factors, (ii) phonetic/phonological factors, and (iii) interaction and processing factors. As mentioned earlier, most previous studies (Chuang et al 2011; Hsieh 1976; Wang 1995; Zhang et al 2011) found lexical effects on the application of tone sandhi, but seldom attended to phonetic/phonological effects, except for an influence of sandhi types (e.g. more phonetically natural rules vs. less phonetically grounded rules). It is well established that lexical factors exert an influence on sandhi processes, but it is less clear how phonetic/phonological factors play a role. In addition, Zhang et al (2011) argued that sandhi types may exert a more significant effect on novel words than actual words. As illustrated as (a) in Figure 1.1 below, the additional phonetic/phonological influence indicates a statistic interaction between word types and sandhi types, whereas (b) indicates no additional influence and no interaction. The interaction suggests that L1 speakers may access different degrees of phonetic/phonological knowledge in different words. These various effects may clarify whether tone sandhi is as fully productive as other post-lexical rules.

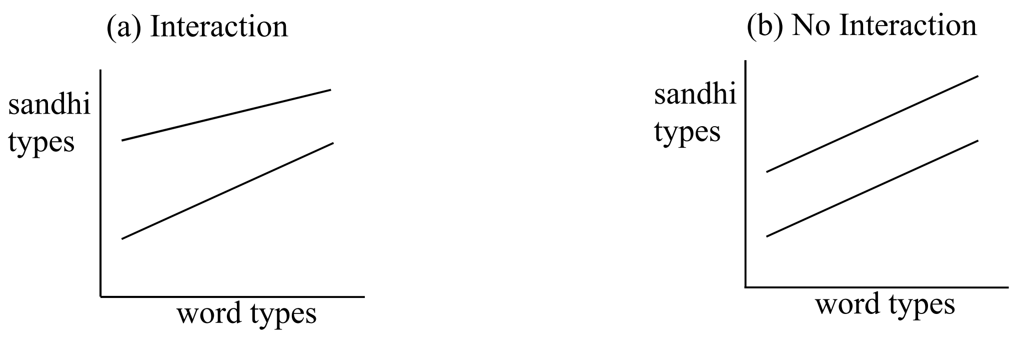

Figure 1.1 The two effects (word types and sandhi types) and their possible interactions: (a) indicating an additional influence and (b) indicating no additional influence.

1.3 The current methods

In order to answer the two research questions, this dissertation designs two experiments to evaluate the role variations play in the perception of the falling-tone contrast and the application of tone sandhi respectively. The experiment on the tonal contrast sets up 30 stimuli (i.e. three pitch-height continua x 10 variations) as three phonetic/phonological factors (i.e. onset-pitch height, offset-pitch height, and overall-pitch height) and two perceptual tasks (i.e. a tonal identification task and a lexical recognition task) as a lexical factor (i.e. word types). The tonal identification task requires 30 participants to identify each monosyllabic stimulus as either high-falling tone or low-falling tone for four times (i.e. 30 stimuli x 4 repetitions = 120 trials total), and the lexical recognition task requires them to recognize each stimulus' corresponding meaning. The results are analyzed to examine whether the tonal contrast varies with different pitch-height variations and whether the contrast varies with different tonal and lexical processes. The experiment on the tone-sandhi application sets up 72 disyllabic stimuli (i.e. 3 lexical factors x 2 sandhi types x 2 sandhi forms x 2 vowel types x 3 prosodic types) as different lexical and phonetic/phonological factors and four tasks (i.e. an AXB tonal discrimination task, a tonal identification task, a lexical recognition task, and a production task) as processing factors. The first three perception tasks require 31 participants to differentiate sandhi-induced tonal changes by discriminating one from the other, identifying their tonal categories, and recognizing their lexical meanings, while the production task requires them to produce two monosyllabic words as a disyllabic compound. The results are analyzed to examine whether the application of tone sandhi varies with different lexical and phonetic/phonological factors, and whether these lexical and phonetic/phonological factors play a different role in each task.

1.4 The dissertation's three general claims

Based on the experimental results of Hai-lu Hakka falling tones and tone sandhi, this dissertation makes three general claims below:

(4) The dissertation’s three general claims

a. The contrast of falling tones varies with lexical, phonetic/phonological, and processing factors, so does the application of tone sandhi, indicating the significant role variations play in tonal processing.

b. The common occurrence and significant influence of tonal variations call into question the generally assumed transition from variations to invariance in linguistic derivations from phonetics to phonology, suggesting a theoretical issue of relating variations to phonetic processes and invariance to phonological processes.

c. Lexical effects exhibit a more consistent pattern than phonetic/phonological effects, supporting a more crucial role of lexical attributes in speech processing.

First, the current results show that lexical factors, phonetic/phonological factors, and others (e.g. interaction and processing factors) exert an influence on Hai-lu Hakka speakers’ tonal processing of two falling tones and two tone sandhi rules. These various influences indicate that the contrast of falling tones varies with different factors, so does the application of tone sandhi. Some variations may cause Hai-lu Hakka speakers to confuse high-falling tone as low-falling tone. Other variations may cause Hai-lu Hakka speakers to under-apply low-rising tone sandhi. These findings indicate that variations may lead to tonal confusion and lower application of tone sandhi. In other words, some tonal contrasts may not be as distinctive as assumed previously, and tone sandhi may not be as productive as assumed previously, due to a potential influence from variations. The current findings clarify how tonal contrasts are perceived and how tone sandhi are applied, and demonstrate the significant role variations play in tonal processing, as claimed in (4a) above.

Second, as generalized in (4b), the current results show that lexical factors and phonetic/phonological factors give rise to different kinds of variations across tasks (speech processes) in the tonal contrast and the application of tone sandhi, indicating a common occurrence of variations in tonal processing. These findings suggest that variations are extensive and substantial in each process, which calls into question a derivational approach that assumes a transition from variations to invariance in speech processing. It also casts doubt on the classification issue that strictly relates variations to phonetic processes and invariance to phonological processes. Therefore, it can be problematic to distinguish different tonal modifications such as tonal co-articulation and tone sandhi based on variations.

Third, the current findings indicate that lexical effects exhibit a more consistent pattern than phonetic/phonological effects. Lexical effects consistently demonstrate that frequent words are more likely to enhance tonal perception and production than less frequent words and novel words (frequent > less frequent > novel). Phonetic/phonological effects demonstrate that low-rising tone sandhi is more likely to enhance productivity than high-checked tone sandhi (low-rising > high-checked), but high-checked tone sandhi is more likely to enhance perceptibility (high-checked > low-rising). These findings indicate that phonetic/phonological effects exhibit an asymmetry between perception and production patterns. In other words, lexical effects exhibit a more consistent pattern than phonetic/phonological effects across different processes. In addition, the falling-tone experiment shows that Hai-lu Hakka speakers are more likely to perceive stimuli as ambiguous tones (neither high-falling tone nor low-falling tone on a 75% basis of frequency rates) in tonal identification than in lexical recognition. The finding indicates that variations exert a more significant influence on tonal responses than lexical responses, and suggests that lexical responses are more resistant to variations. These lexical characteristics generally support a more crucial role of lexical influences in tonal processing, as summarized in (4c) above.

In general, this dissertation addresses (i) the significant role variations play in tonal processing, (ii) the classification issue that relates variations to phonetics and invariance to phonology, and (iii) the crucial role of lexical influences in speech processing. Although our experiments were not designed to evaluate different proposals for speech processing, the current findings favor a model that argues for a lexically-based account with no transition from variations to invariance. As discussed in chapter 3, three principal approaches are compared: the functional model, the direct-realist model, and the exemplar-based model, which differ crucially in two aspects: (a) the level issue concerning whether there are different levels of speech processes, and (b) the representation issue concerning how different lexical and phonetic/phonological factors are represented in speech processing. The current findings seem to support the exemplar-based model that argues for a non-derivational and lexically-based account for speech processing.

1.5 The dissertation's organization

The sections above briefly summarize this dissertation's three general claims and introduce this dissertation's three research interests and two research questions. As illustrated in Figure 1.1 below, in order to clarify the two previous assumptions (the distinctiveness issue and the productivity issue), this dissertation evaluates the influence of tonal variations by investigating lexical and phonetic/phonological effects on Hai-lu Hakka's contrast of two falling tones and the application of two sandhi rules. The three subset questions concern the lexical effect, the phonetic/phonological effect, and the interaction/processing effects respectively. This study thus contributes to Hai-lu Hakka tonology and the general theory of tonal processing. Then the following chapters are organized as follows.

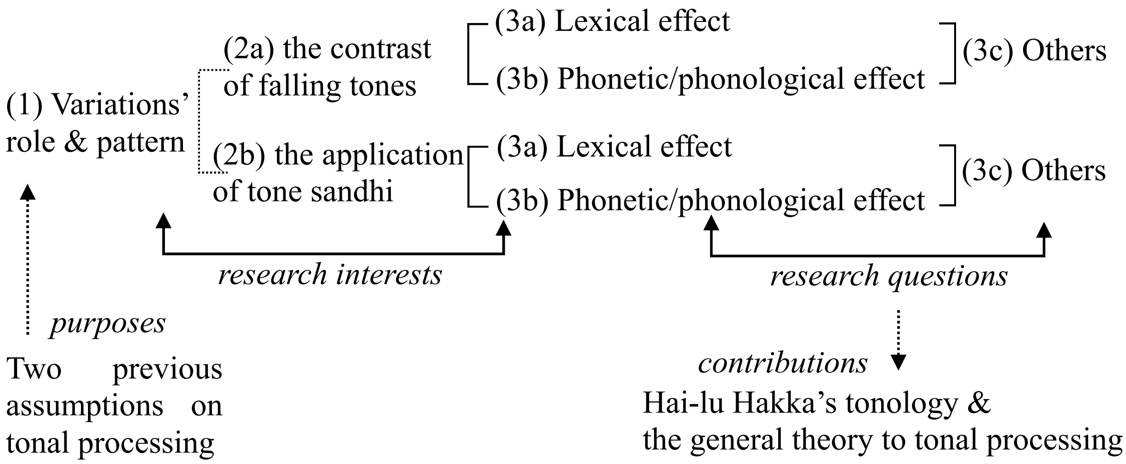

Figure 1.2 The overview of the dissertation's research purpose, research interests, research questions, and contributions.

Chapter 2 presents Hai-lu Hakka's tonal inventory as well as different tonal variations. Hai-lu Hakka's tonal variations include phonetic variations induced by tonal co-articulation, phonological variations induced by tone sandhi, morpho-phonological alternations, and ongoing tonal mergers. The second chapter focuses on two falling tones (high-falling vs. low-falling) and two sandhi rules (low-rising tone sandhi and high-checked tone sandhi). Since morpho-phonological alternations and ongoing tonal mergers may affect sandhi tones, they are also briefly discussed. These extensive and substantial variations in Hai-lu Hakka are argued to exert some influence on the tonal contrast and the tone-sandhi application.

Chapter 3 discusses two previous assumptions: tonal contrasts are perceptually distinctive (i.e. the distinctiveness issue) and tone sandhi rules are fully productive (i.e. the productivity issue). The two issues are arguably derived from the theoretical question of how to define and distinguish phonetics and phonology in speech processing (i.e. the classification issue). In order to account for the difference, this chapter compares three different processing models (the functional model, the direct-realist model, and the exemplar-based model) which differ essentially in two aspects: how phonetic and phonological factors are organized (i.e. the level issue) and how they are represented (the representation issue). The last section concludes this chapter with three hypotheses on lexical effects, phonetic/phonological effects, and interaction/processing effects.

Chapter 4 presents the experiment on Hai-lu Hakka's contrast of two falling tones. This chapter first demonstrates previous studies on tonal contrasts, and points out some potential cases of tonal confusion induced by variations. Various lexical factors (lexical familiarity and lexical frequency) and phonetic/phonological factors (onset pitch, offset pitch, and overall pitch) are hypothesized accordingly to affect the tonal contrast. The results and analyses are shown and discussed in terms of each hypothesis. This chapter verifies the proposed hypotheses (the lexical hypothesis, the phonetic/phonological hypothesis, and the interaction hypothesis), and supports the crucial role variations play in the tonal contrast.

Chapter 5 presents the experiment on two Hai-lu Hakka's tone sandhi rules. This chapter first summarizes previous studies on the application of tone sandhi in Mandarin and Taiwan Southern Min, and indicates that tone sandhi may exhibit some variations. Various lexical factors (word types and lexical frequency) and phonetic/phonological factors (sandhi types, sandhi tones' vowel types, and sandhi tones' prosodic contexts) are hypothesized accordingly to affect the application of tone sandhi. In addition to the three general hypotheses, the processing hypothesis is proposed to compare cross-task results. The results are shown and analyzed in terms of each hypothesis. This chapter verifies the proposed hypotheses, and supports the crucial role variations play in the application of tone sandhi.

Chapter 6 discusses the results of both experiments, compares the results to the predictions, interprets the crucial findings in terms of each research question, and suggests crucial implications for modeling speech processing. This dissertation's findings generally favor a non-derivational and lexically-based account for tonal processing, supporting an exemplar-based model rather than a perception-based or a production-based model. The final section also addresses methodological restrictions and directions for further studies.

CHAPTER TWO

HAI-LU HAKKA'S TONAL PHONETICS AND PHONOLOGY

This dissertation's primary purpose is to evaluate the role variations play in tonal processing. In order to do so, it is indispensable to discuss how those tonal variations are derived in Hai-lu Hakka. Hai-lu Hakka basically exhibits four kinds of tonal variations modified by different phonetic and phonological factors, and the four kinds are (i) phonetic modifications, (ii) phonological modifications, (iii) morpho-phonological alternations, and (iv) ongoing tonal mergers. These variations may influence Hai-lu Hakka's tonal processing, but they were seldom examined by previous studies. This dissertation focuses on the first two kinds, since they are more relevant to the contrast of falling tones and the application of tone sandhi. In general, this chapter demonstrates that variations are common and extensive in Hai-lu Hakka, and they may exert a substantial influence on tonal processing.

2.0 Hai-lu Hakka's tones and tonal variations

Before discussing different tonal variations, this chapter first introduces Hai-lu Hakka's tonal inventories. According to Lo (1990), Hai-lu Hakka has seven tones, which are one to two more tones than the other dialects. The seven categories are Tone-53 (high-falling tone), Tone-55 (high-level tone), Tone-13 (low-rising tone), Tone-31 (low-falling tone), Tone-22 (low-level tone), Tone-5 (high-checked tone) and Tone-2 (low-checked tone), as illustrated in Figure 2.1 below. The first five categories (Tone-53, Tone-55, Tone-13, Tone31, and Tone-22) are non-checked tones, and the last two (Tone-5 and Tone-2) are checked tones. The checked and non-checked tones contrast in syllable structures: the former consist of unaspirated voiceless stop codas, and the latter consist of open syllables or nasal codas. In general, there are one rising tone, two level tones, two falling tones, and two checked tones in Hai-lu Hakka.

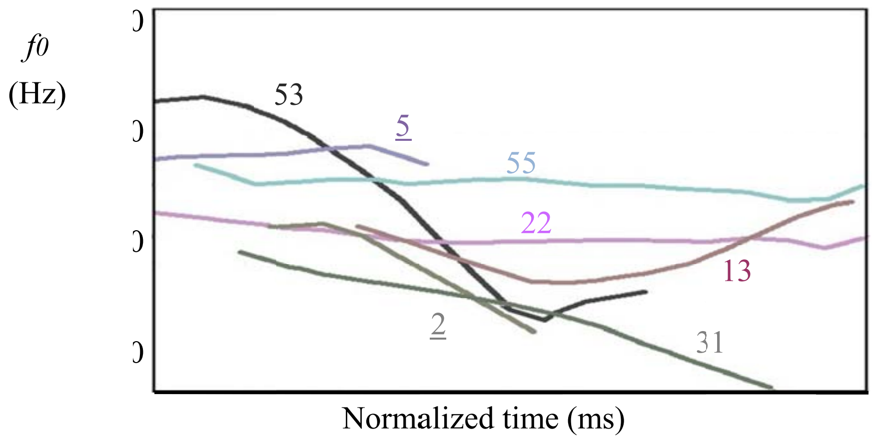

Figure 2.1 Seven Hai-lu Hakka tones produced in isolation: Tone-53 (high-falling tone), Tone-55 (high-level tone), Tone-13 (low-rising tone), Tone-31 (low-falling tone), Tone-22 (low-level tone), Tone-<u>5</u> (high-checked tone), and Tone-<u>2</u> (low-checked tone) (Adapted from Jiang 2003: 12).

As illustrated in Table 2.1 below, the first two row indicate the traditional Chinese labels: Píng 平 'level', Shǎng 上 'rising', Qù 去 'departing', and Rù 入 'entering,' and each label has two sub-categories: Yīn 陰 'high' and Yáng 陽 'low'. These traditional labels increased and decreased in history, as tones split and merged for various synchronic and diachronic reasons (Chen 2000: 4-12). The same factors may account for three ongoing tonal mergers in Hai-lu Hakka: a loss of two Rù tones (both checked tones) and a merger of two Qù tones (both low tones), as found by Lu (2004, 2008), Yeh & Lin (2013) and Yeh & Lu (2013).

Table 2.1 Hai-lu Hakka's seven-tone system (Adapted from Lo 1990: 24).

Traditional labels	Píng		Shǎng	Qù		Rù	
	Yīn	Yáng		Yīn	Yáng	Yīn	Yáng
Descriptive labels	High Falling	High Level	Low Rising	Low Falling	Low Level	High Checked	Low Checked
Pitch value	53	55	13	31	22	<u>5</u>	<u>2</u>
Pit. register	HL	HH	LM	ML	LL	<u>H</u>	<u>L</u>
Examples (1)	fù 父 dad	fū 湖 lake	fú 府 office	fǔ 褲 pants	fû 護 protect	fūk 福 luck	fûk 服 obey
Examples (2)	tì 知 know	t^{h}ī 題 theme	tí 抵 conceal	tǐ 帝 king	t^{h}î 地 ground	tīt 轉 turn	t^{h}ît 特 very
MC labels	T4	T1	T2	T3	-	-	-

As illustrated in Table 2.1 above, the third and fourth rows refer to the descriptive labels defined by pitch height and pitch contour. The pitch height conventionally displays a three-way contrast: high, mid, and low, and so does the pitch contour: level, rising, and falling. The two next rows refer to pitch value and pitch register respectively, and represent a perceptual property more than a physical one. The pitch value conventionally consists of one to three digits to represent both pitch height and pitch contour. Each digit indicates a pitch target in pitch height along with pitch contour, and follows Chao's (1968) five-point scale: with 5 indicating the highest pitch, and 1 indicating the lowest (a logarithmic value of actual frequency; further discussed in section 4.3.2.2). For instance, one digit with an underline indicates a short tone, basically a checked tone; two same digits indicate a level tone, and two different digits indicate a contour tone (digit value increasing: rising tone, digit value decreasing: falling tone); and three digits indicate a complex contour tone.

This dissertation adopts Lo's (1990) tone system for several reasons. Foremost, Lo's (1990) notation fits in with most of our participants' pronunciations known as Chutung accents of Hai-lu Hakka. Furthermore, these tonal categories[1] were extensively supported by Jiang (2003), Yeh (2011), Yeh & Lin (2013, 2015), Yeh & Lu (2013), and the official publications from the Council of Hakka Affairs in Taiwan. As to the pitch register, it refers to relative pitch height with a three-way contrast: high, mid, and low. The pitch register is also known as a prosodic feature, similar to but not identical to the [±H, ±L] features proposed by Yip (2002: 39-40) and her early works to represent pitch height in linguistic derivations.

The antepenultimate and penultimate rows are two examples of each tonal category in minimal pairs. The high-falling words are 父 fù 'father' and 知 tì 'to know'; the high-level words are 湖 fū 'lake' and 題 t^hī 'theme'; the low-rising words are 府 fú 'office,

[1] Lo's (1990) pitch value and descriptive labels are mostly similar to others', except for the Yīn-Qù tone. Lo (1990) categorized the Yīn-Qù as low-falling tone (Tone-31), but others (e.g. Gu 2005) regarded the Yīn-Qù as low-level tone (Tone-11).

government' and 抵 tí 'to conceal'; the low-falling words are 褲 fŭ 'pants' and 帝 tĭ 'king'; the low-level words are 護 fû 'to protect' and 地 t^{h}î 'ground'; the high-checked words are 福 fūk 'luck' and 轉 tīt 'to turn'; and the low-checked words are 服 fûk 'to obey' and 特 t^{h}ît 'very'. As to the last row, it refers to the corresponding tonal category in Mandarin, and the correspondence was proposed by Yeh (2011), Yeh & Lin (2013, 2015), Yeh & Lu (2013), and the official publications issued by the Council of Hakka Affairs in Taiwan. In general, the high-falling tone Tone-51 sounds like T4 in Mandarin, the high-level tone Tone-55 sounds like T1, the low-rising tone Tone-13 sounds like T2, the low-falling tone Tone-31 sounds like T3, and the others have no counterparts in Mandarin.

These tones exhibit many different variations. As mentioned earlier in section 1.2.2.2, tonal variations are basically derived from four kinds of modifications: (1) phonetic modifications such as tonal co-articulation, (2) phonological modifications such as tone sandhi, (3) morpho-phonological alternations such as focus/emphasis rules, and (4) ongoing tonal mergers. They are further discussed below.

2.1 Hai-lu Hakka's variations and phonetic modifications

Hai-lu Hakka's phonetic variations were less investigated by previous studies, except for an informal report by Jiang (2003). Jiang (2003) recruited one Hai-lu Hakka monolingual (64 yrs; female) to read seven monosyllabic tones and 49 non-word disyllabic sequences (i.e. 7 tones x 7 tones) respectively. The results showed that each tone varies with its preceding or following tone (i.e. neighboring tone) in pitch height and vowel duration, indicating that tonal co-articulation gives rise to different phonetic variations. The effect of tonal co-articulation is more significant on high-falling tone. As illustrated in Figure 2.2 below, Tone-51's offset pitch is getting higher when preceding high tones, such as Tone-51 (in black), Tone-55 (in azure) and Tone-<u>5</u> (in indigo), whereas its offset pitch is getting lower when preceding low tones, such as Tone-22 (in pink), Tone-13 (in red), Tone-31 (in green) and Tone-<u>2</u> (in brown).

In other words, predecing tones' offset pitch varies with following tones' onset pitch in Hai-lu Hakka. The higher the following onset pitch is, the higher the preceding tones' offset pitch will be. As high-falling tone's offset pitch becomes higher for the sake of tonal co-articulation, its pitch contour then becomes flatter than its original dimension, and may sound like high-level tone and other categories.

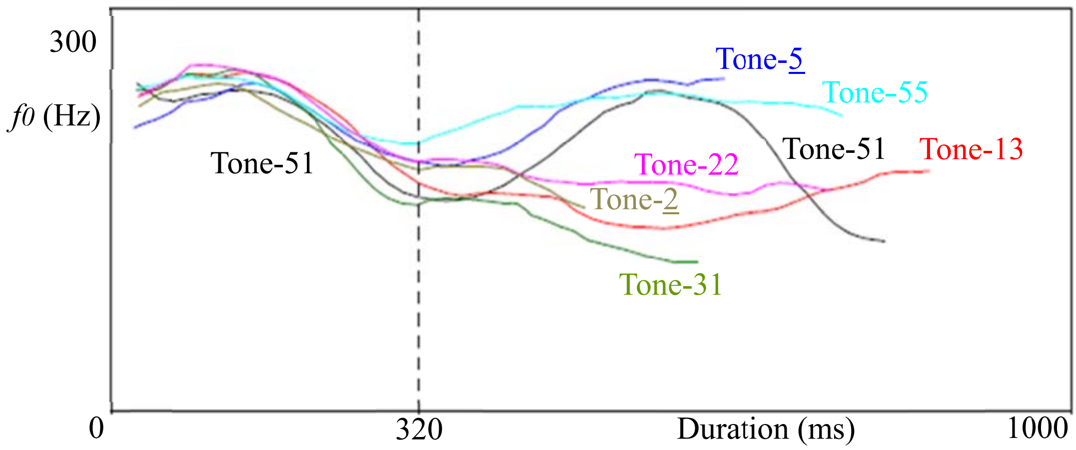

Figure 2.2 Effects of following tones on preceding tones in Hai-lu Hakka (Tone-51: high-falling, Tone-55: high-level, Tone-13: low-rising, Tone-31: low-falling, Tone-22: low-level, Tone-5: high-checked and Tone-2: low-checked; adapted from Jiang 2003: 15).

In addition, Jiang (2003) found that following tones' onset pitch also varies with preceding tones' offset pitch in an assimilatory manner. The higher the preceding tone offset pitch is, the higher the following tone onset pitch will be. As illustrated in Figure 2.3 below, Tone-51's onset pitch is getting higher when preceding high tones, whereas its offset pitch is getting lower when preceding low tones. As high-falling tone's onset pitch becomes lower for the sake of tonal co-articulation, it results in a variant with lower onset pitch. The low-onset-pitch variant may sound like low-falling tone or other categories.

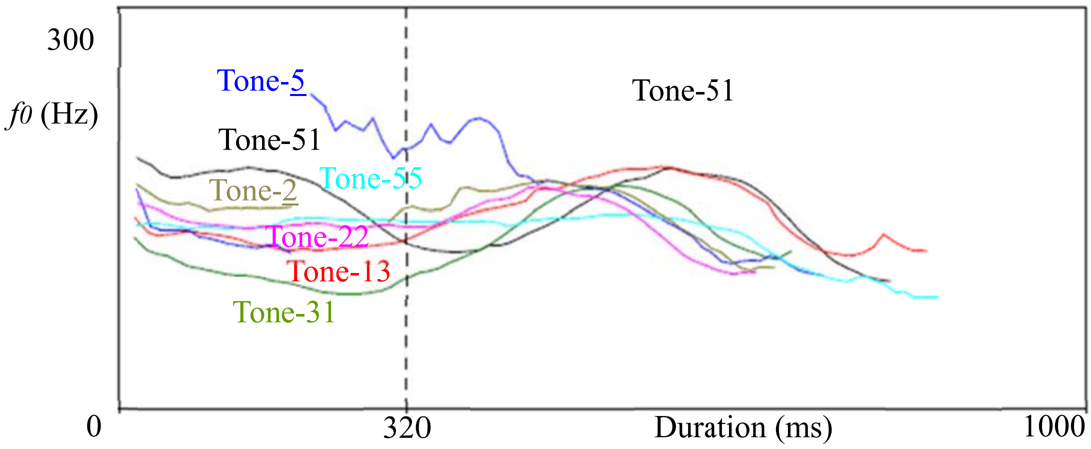

Figure 2.3 Effects of preceding tones on following tones in Hai-lu Hakka (Adapted from Jiang 2003: 15).

Jiang's (2003) study simply focused on the influence of tonal co-articulation on phonetic variations in Hai-lu Hakka, and did not attend to other contextual factors such as prosodic positions and prosidic boundaries. As found by Peng (1997) and Xu (1997, 2004), prosodic positions (i.e. initial, medial, and final) and prosodic boundaries (i.e. at the word-level, phrase-level, and/or utterance-level) exert an influence on target tones' overall pitch and vowel duration in Mandarin and Taiwan Southern Min. For instance, target tones tend to be lower in overall pitch and longer in vowel duration when they occur in final position. These contextual effects may also be responsible for phonetic variations in Hai-lu Hakka, but they need to be further investigated.

To sum up, Jiang (2003) found that neighboring tones exert an assimilatory influence on target tones' onset pitch, offset pitch, and vowel duration via tonal co-articulation. The effect of tonal co-articulation gives rise to many different phonetic variaitons, especially those variants of high-falling tone. It is unclear why high-falling tone is more susceptible to tonal co-articulaiton, probably due to its wider pitch range, but its larger amount of phonetic variants undoubtedly makes high-falling tone less distinct from other tones, e.g., high-falling tone is more likely to be confused as low-falling tone. Since the two falling tones contrast crucially in pitch height, the tonal contrast is closely correlated to the influence of tonal co-articulation. This correlation makes it more likely to examine how variaitons induced by tonal co-articulation affect the contrast of falling tones in Hai-lu Hakka.

2.2 Hai-lu Hakka's variations and phonological modifications

Hai-lu Hakka's phonological variations result from two tone sandhi rules: low-rising tone sandhi and high-checked tone sandhi. As illustrated in (5a) below, low-rising tone sandhi changes low-rising tone into low-level tone in non-final position, which gives rise to a low-level-tone-like variant of low-rising tone. As illustrated in (5b), high-checked tone sandhi changes high-checked tone into low-checked tone in non-final position, which gives rise to a low-checked-tone-like variant of high-checked tone. That is, there are two types of phonological variations in Hai-lu Hakka.

(5) Hai-lu Hakka's tone sandhi rules

a. Low-rising tone sandhi:

Tone-13 (low-rising tone)→ Tone-22 (low-level tone)/ ____ in non-final position

b. High-checked tone sandhi:

Tone-5 (high-checked tone)→ Tone-2 (low-checked tone)/ ____ in non-final position

Although Hai-lu Hakka's phonological variations are relatively simple, they exhibit two specific patterns which may give rise to variations in the application of tone sandhi. As indicated in (6a) below, Chang (2002) and Chung (1992) found that Hai-lu Hakka tends to reset its sandhi domains across different phrases. The finding suggests that the sandhi rules tend to be non-cyclic, and tend not to apply across phrasal boundaries. As indicated in (6b), Fan (1996) and Hsu (2009) found that tone sandhi exhibits a large amount of exceptions. These exceptions occur constantly in four kinds of words: (i) numerals and classifiers, such as 八 [pat-5] 'eight,' 九 [kju-13] 'nine,' and 本 [pun-13] 'a classifier for books,' (ii) demonstratives, such as 這 [lja13] ‘this,’ (iii) resultatives and serial verbs, such as 轉來 [**tʂɔn13**-lɔi55] ‘come back,’ and (iv) adverbs, such as 頂高 [**taŋ13**-ko53] ‘very high’. These words do not undergo tone sandhi, for instance: the numeral 八 [pat-5] ‘eight’ and the classifier 本 [pun-13] ‘a classifier for books’ in the phrase 八本書 [pat5- pun13-ʂu53] ‘eight books’. The two specific patterns indicate that Hai-lu Hakka’s tone sandhi rules tend to be under-applied. The application of tone sandhi may vary with different words and phrases. That is to say, these restrictions and exceptions may give rise to some variations in the application of tone sandhi.

(6) Two specific patterns in Hai-lu Hakka tone sandhi

a. Tone sandhi tends to be non-cyclic (Chung 1992).

b. Tone sandhi exhibits a large amount of exceptions (Fan 1996; Hsu 2009).

In addition, there are two potential issues that may affect the actual surface forms of the two phonological variations and the application of tone sandhi. As indicated in (7a) below, the two ongoing tonal mergers, i.e. low-level tone change and low-checked tone change, may affect the two surface forms, i.e. low-level-like sandhi tone and low-checked-like sandhi tone. First, low-level tone change interferes with low-rising tone sandhi, and changes low-level-like sandhi tone into low-falling tone. The two tone changes conspire to turn low-rising tone into low-falling tone as the emerging pattern: low-rising tone → low-falling tone. Second, low-checked tone change interferes with high-checked tone sandhi, and changes low-checked-like sandhi tone into low-falling tone. The two tone changes conspire to turn high-checked tone into low-falling tone as the emerging pattern: high-checked tone → low-falling tone. As indicated in (7b) below, the two emphasis rules, i.e. the rising-tone rule and the high-checked-tone rule, may overturn the two sandhi rules, and result in exceptions to tone sandhi. First, the rising emphasis rule interferes with low-rising tone sandhi, and changes low-level-like sandhi tone into rising tone. The emphasis rule simply overturns low-rising tone sandhi, and leads to an exception-like surface form. Second, the high-checked emphasis rule interferes with high-checked tone sandhi, and changes low-checked-like sandhi tone into high-checked tone. The emphasis rule simply overturns high-checked tone sandhi, and leads to an exception-like surface form. Although the two potential issues do not directly affect the application of tone sandhi, they may give rise to some variations. Therefore, they are further discussed below in section 2.2.1and 2.2.2.

(7) Two additional issues in Hai-lu Hakka tone sandhi

a. Effects of ongoing tonal mergers on tone sandhi's surface forms:

(i) Low-rising tone sandhi: Tone-13→ Tone-22

+ Low-level tone change: Tone-22→ Tone-31

= New Pattern: Tone-13→ ø→Tone-31

(ii) High-checked tone sandhi: Tone-$\underline{5}$→ Tone-$\underline{2}$

+Low-checked tone change: Tone-$\underline{2}$→ Tone-31

= New Pattern: Tone-$\underline{5}$→ ø→ Tone-31

b. Effects of emphasis rules on application of tone sandhi:

(i) Low-rising tone sandhi: Tone-13→ Tone-22

+Rising emphasis rule: all tones→ Tone-13

= Exceptions to tone sandhi: Tone-13→ Tone-13

(ii) High-checked tone sandhi: Tone-$\underline{5}$→ Tone-$\underline{2}$

+ High-checked emphasis rule: all checked tones→ Tone-$\underline{5}$

= Exceptions to tone sandhi: Tone-$\underline{5}$→ Tone-$\underline{5}$

2.2.1 Effects of ongoing tonal mergers and emerging sandhi patterns

Hai-lu Hakka's low-level tone and two checked tones were found to undergo sound change extensively by Huang Y. (2001), Lo (1990), Lu (2004), Yeh (2011), Yeh & Lin (2013; 2015), and Yeh & Lu (2013). As indicated by Lo (1990), Lu (2004) and Yeh & Lin (2013), two checked tones have gradually become non-checked tones by dropping coda consonants [-p, -t, -k]. Yeh & Lin (2013) further pointed out that high-checked tone has gradually changed into high-level tone, and low-checked tone has changed into low-falling tone, as illustrated in (8a) and (8b) below. Huang Y. (2001), Yeh (2011), Yeh & Lin (2013; 2015), and Yeh & Lu (2013) also found that low-level tone has gradually changed into low-falling tone, as illustrated in (8c).

(8) Three ongoing tonal mergers in Hai-lu Hakka

a. Tone-5̲ (high-checked tone)→ Tone-55 (high-level tone)

b. Tone-2̲ (low-checked tone)→ Tone-31 (low-falling tone)

c. Tone-22 (low-level tone)→ Tone-31 (low-falling tone)

As indicated in (7a) above, two of these tonal mergers, i.e. low-checked tone change and low-level tone change as illustrated in (8b) and (8c), may interfere with Hai-lu Hakka's two tone sandhi rules. Yeh & Lin (2015) and Yeh & Lu (2013) pointed out that younger generations tend to pronounce low-rising words 水 [ʂui13] 'water' and 火 [fo13] 'fire' as low-falling ones in disyllabic compounds 水果 [**ʂui31**-ko13] 'fruit' and 火車 [**fo31**-tʂʰa53] 'train' which are originally read as [**ʂui22**-ko13] and [**fo22**-tʂʰa53]. As illustrated in (9) below, the two rising words, [ʂui13] and [fo13], first undergo low-rising tone sandhi, and change into low-level-like sandhi tone, [ʂui22] and [fo22]. The low-level-tone-like variants then undergo low-level sound change, and turn into low-falling words, [ʂui31] and [fo31]. The low-falling word [ʂui31] consists of a legitimate syllable without any corresponding meanings, known as an accidental gap, whereas the other one sounds like a low-falling word 貨 [fo31] 'goods'. Younger generations seem to read 火車 [**fo31**-tʂʰa53] 'train' and 貨車 [fo31-tʂʰa53] 'truck' alike. In other words, tone sandhi rules and ongoing tonal mergers may conspire to give rise to new sandhi patterns in Hai-lu Hakka. As illustrated in (10a) below, new low-rising tone sandhi changes low-rising tone into low-falling tone in non-final position.

As illustrated in (10b), new high-checked tone sandhi changes high-checked tone into low-falling tone. The new patterns seem to emerge from the imposing effect of ongoing sound change on tone sandhi.

(9) Derivations of tone sandhi and sound change in Hai-lu Hakka

a.	[ʂui-13	ko-13]	underlying form
	water	fruit	‘fruit’
	(**22**	+13)	rising tone sandhi: 13→ 22/ __ non-final
	(**31**	13)	low-level tone change: 22→ 31
	(31	13)	surface form
b.	[fo-13	tʂ^{h}a-53]	underlying form
	fire	vehicle	‘train’
	(**22**	+53)	rising tone sandhi: 13→ 22/ __ non-final
	(**31**	53)	low-level tone change: 22→ 31
	(31	53)	surface form (= ‘truck’)

(10) Emerging patterns of tone sandhi in Hai-lu Hakka

a. New low-rising tone sandhi: Tone-13→ Tone-31/ ____ in non-final position

b. New high-checked tone sandhi: Tone-5→ Tone-31/ ____ in non-final position

The similar emerging patterns of tone sandhi were also found by Chang (2012) in Taiwan Southern Min. Chang (2012) indicated that Southern Min’s low-rising tone sandhi changes low-rising tone (Tone-24) into mid-level tone (Tone-33) in non-final position, but some speakers tend to change low-rising tone into low-falling tone (Tone-21) instead. The tendency gives rise to the new pattern: Tone-24 → Tone-21/ ____ in non-final position. Similarly, Yeh & Tu (2012) also found a similar tonal merger that has gradually changed mid-level tone (Tone-33) into low-falling tone (Tone-21) in Taiwan Southern Min. The ongoing tonal merger thus arguably interferes with Southern Min’s low-rising tone sandhi in the same manner, and gives rise to the new pattern of rising tone sandhi. The imposing effect of sound change on tone sandhi needs to be further investigated.

2.2.2 Effects of emphasis rules and exceptions to tone sandhi

Two emphasis rules in Hai-lu Hakka produce patterns that are just opposite to the two sandhi rules. As illustrated in (11a) below, the rising emphasis rule changes all target tones into low-rising tone, whose pattern is opposite to rising tone change. As illustrated in (11b) below, the high-checked emphasis rule changes checked tones into high-checked tone, whose pattern is opposite to high-checked tone sandhi. These alternations were earlier proposed as modifiers in double adjectival reduplication by Gu (2005) and Hsu (2009), but some recent findings indicated that they may exhibit some phonetic characteristics similar to focus intonation/emphasis rules. For instance, Hsiao (2008) found that low-rising alternations of adjectival reduplication are higher in pitch height and longer in vowel duration. The two phonetic modifications are common strategies used as focus intonation to put an emphasis on target tones in Mandarin and Taiwan Southern Min (Pan 2007; Xu 1999; Yeh & Huang 2011). We thus suggest that these morpho-phonological alternations also function as emphasis rules.

(11) Two morpho-phonological alternations of emphasis rules in Hai-lu Hakka

a. The rising emphasis rule: all tones→ low-rising tone (Tone-13 or Tone-15)

b. The high-checked emphasis rule: checked tones→ high-checked tone (Tone-<u>5</u>)

As indicated in (7b) above, the two emphasis rules may be responsible for some exceptions to tone sandhi for two reasons. First, they happen to exhibit opposite patterns. Second, they tend to apply to modifiers that occur in the same position as where tone sandhi applies. For instance, the proximal demonstrative 這 [lja13] 'this' seldom undergoes tone sandhi (Hsu 2009: 62), and exhibits some free variations. As illustrated in (12a), it undergoes low-rising tone sandhi, and changes to a low-level-tone-like variant [lja**22**]. As illustrated in (12b), it undergoes low-rising tone sandhi first, and then becomes rising [lja**13**] for an emphasis purpose. The serial derivations lead to a rising-tone variant [lja**13**] that may sound like its original dimension, but the variant is derivationally different from the original low-rising tone. This issue needs to be further investigated. In general, the demonstrative case shows that the two emphasis patterns may account for some exceptions to tone sandhi, and thus may give rise to variations in the application of tone sandhi.

(12) Derivations of tone sandhi and morpho-phonological alternations in Hai-lu Hakka

a.	[lja-13	p^hjɛn-13]	underlying form
	this	side	‘this way’
	(**22**	+13)	rising tone sandhi: 13→ 22/ __ non-final
	(22	13)	surface form
b.	[lja-13	p^hjɛn-13]	underlying form
	this	side	‘this way (not that way)’
	(**22**	+13)	rising tone sandhi: 13→ 22/ __ non-final
	(**13**	13)	the emphasis rule: non-rising tone→ 13
	(13	13)	surface form

2.2.3 Summary of Hai-lu Hakka’s phonological variations

To sum up, although Hai-lu Hakka has only two types of phonological variations derived from two sandhi rules, the phonological variations exhibit two specific patterns and have two potential issues in the application of tone sandhi. As indicated in (6) above, Hai-lu Hakka tone sandhi tends to be non-cyclic, and exhibits a large amount of exceptions in words such as numerals and classifiers, demonstratives, and adverbs. The two specific patterns suggest that the two tone sandhi rules tend to be under-applied, which may affect the application of tone sandhi in general. As indicated in (7) above, two ongoing tonal mergers may interfere with the tone sandhi rules, and give rise to new sandhi patterns. The alternations produced by the emphasis rules may overturn tone sandhi, and lead to exception-like results. Since these variations can affect the application of tone sandhi, Hai-lu Hakka’s phonological variations may be more complicated than alleged previously.

2.3 Hai-lu Hakka’s morpho-phonological alternations

As indicated by Gu (2005: 159), Hsu (2009: 61), and Lo (1990: 186-188), Hai-lu Hakka has four kinds of morpho-phonological alternations. As generalized in (13) below, the four kinds of morpho-phonological alternations are: a. derivational devices, b. adjectival reduplication, c. emphasis rules, and d. nominal reduplication as kinship terms. Some of these alternations (e.g. derivational devices and kinship terms) are fixed and limited, and others (e.g. adjectival reduplication and emphasis rules) are more optional and productive. These variations may also play a role in tonal processing. Since they are less relevant to current interests, they are briefly discussed as follows.

(13) Hai-lu Hakka's morpho-phonological alternations

a. Derivational devices:

(i) Tone-53 (Yin-Ping) ←→ Tone-31 or Tone-22 (Qu)

(ii) Tone-55 (Yang-Ping) ←→ Tone-31 or Tone-22 (Qu)

(iii) Tone-13 (Shang) ←→ Tone-31 or Tone-22 (Qu)

b. Adjectival reduplication:

(i) All tones (except high-level tone)→ Tone-13/ ____ in base syllables

(ii) Checked tones→ Tone-5/ ____ in base syllables

(iii) Non-checked tones→Tone-55/ ____ in base syllables

c. Emphasis rules:

(i) All tones→ Tone-13

(ii) Checked tones→ Tone-5

(iii) Non-checked tones→ Tone-55

d. Nominal reduplication as kinship terms:

(i) Tone-55+Tone-53

As indicated in (13a), Hai-lu Hakka generally has three morpho-phonological alternations as derivational devices (Lo 1990: 186-188). The three alternations are fixed and limited to only a few particular words. They seem to be arbitrary in descriptive labels and pitch values, but they are more systematic in traditional labels. These patterns consistently indicate that Píng and Shăng tones (i.e. Tone-53, Tone-55, and Tone-13) change to Qù tones (Tone-31 and Tone-22). For instance, the verb 教 [kau53] as in 'to teach' becomes [kau31] as in the noun 'education'. The classifier 種 [tʂɔŋ13] 'a kind' becomes [tʂɔŋ31] as in the verb 'to plant'.

The patterns conform to a historical split (Píng, Shăng→ Qù→ Rù), suggesting an influence from diachronic changes (Lo 1990: 186-188; Hsu 2009: 56; Huang Y. 2001).

As indicated in (13b) and (13c), Hai-lu Hakka has three morpho-phonological alternations as modifiers in adjectival reduplication (Gu 2005: 159; Hsiao 2008; Hsu 2009: 61; Lai 2006), and three similar alternations function as emphasis rules. The three patterns are: (i) that all tones become low-rising, (ii) that checked tones may become high-checked, and (iii) that non-checked tones may become high-level. For instance, the adjective 烏 [vu53] 'black' can be read as 烏烏 [vu53-vu53] or 烏烏 [**vu13**-vu53] 'darkish' in double reduplication. The adjective 濕 [ʂip5] 'wet' can be read as 濕濕 [ʂip**2**-ʂip5] (undergoing tone sandhi), [ʂip**5**-ʂip5] or 濕濕 [**ʂip13**-ʂip5] 'a little wet'. The word 輕 [k^{h}jaŋ-53] 'gentle' can be read as 輕輕地 [k^{h}jaŋ53-k^{h}jaŋ53-ə55] or 輕輕地 [**k^{h}jaŋ55**-k^{h}jaŋ53-ə55] 'gently'. As found by Hsiao (2008), the low-rising alternation is higher in pitch, and it should be normalized as Tone-15 instead. Based on the finding, the three alterations, i.e. Tone-15, Tone-5, Tone-55, have a [+H] feature in common. In addition, two of these alternations exhibit patterns opposite to tone sandhi, As discussed in section 2.2, they may account for some exceptions to tone sandhi, and thus may give rise to variations in the application of tone sandhi.

As indicated in (13d), Hai-lu Hakka has a specific alternation in nominal reduplication as kinship terms. This pattern, i.e. Tone-55+Tone-53, is fixed and limited to a few kinship terms. For instance, the kinship term 阿爸 [a22-**pa53**] 'father' can be read as 爸爸 [pa**55**-pa**53**] in reduplication, and the other 阿姊 [a22-**tsɛ55**] 'elder sister' can be read as 姊姊 [tsɛ**55**-tsɛ**53**]. This alternation was barely mentioned and investigated by previous studies.

In general, this section shows that Hai-lu Hakka exhibits many different morpho-phonological alternations, and each of these alternations produces some variations. Some are fixed and limited to a few cases, and others are relatively more productive but optional. These variations are more complicated than attested previously, and will need to be carefully examined in the future studies.

2.4 Hai-lu Hakka's ongoing tonal mergers

Hai-lu Hakka has three ongoing tonal mergers: (i) low-level tone change, (ii) high-checked tone change, and (iii) low-checked tone change, as illustrated in (8) above. As indicated by Huang Y. (2001), Yeh (2011), Yeh & Lin (2013, 2015) and Yeh & Lu (2013), low-level tone has gradually changed into low-falling tone, and the change tends to occur in younger generations, especially those non-daily users/speakers. Yeh (2011), Yeh & Lin (2013) and Yeh & Lu (2013) argued that low-level tone change results from an impairing influence of language attrition which coincides with the great loss of Hakka-speaking population in the recent decades (Lo 1990; Tsao 1997; Hsiao 2007).

As indicated by Lo (1990), Lu (2004, 2008), and Yeh & Lin (2013), high-checked tone change and low-checked tone change result from a loss of unaspirated voiceless stop codas, and the loss of coda consonants turns checked syllables to non-checked. Lu (2008) demonstrated that unaspirated voiceless stop codas are dropped in different manners. As illustrated in (14) below, labial stops tend to disappear earlier, and then velar and dental stops. These occlusive endings sometimes change to a glottal stop before they delete completely. Yeh & Lin (2013) found that high-checked tone has gradually changed to high-level tone, and low-checked tone has gradually changed to low-falling tone. The two tonal mergers also tend to occur in younger generations, indicating a correlation between sound change and language attrition.

(14) Tendency for loss of unaspirated voiceless stop codas in Hai-lu Hakka

-p > -k ≧ -t → -ʔ → ø

In general, these going tonal mergers indicate three important characteristics in Hai-lu Hakka's sound change. First, Yeh & Lin (2013) indicated that the three changes are faithful to their original forms in pitch height, i.e. high-checked to high-level, and low-checked/low-level to low-falling. Second, Yeh & Lin (2013) indicated that the three changes are correlated to the influence of language attrition, as they tend to occur in younger non-daily users/speakers. Third, Chen (2000: 11-13), Hsu (2009: 54-56), and Huang Y. (2001) indicated that these changes may involve some diachronic factors due to historical tonal splits and mergers. More importantly for our purposes, as discussed in section 2.2.1 above, the low-level tone change and the low-checked tone change may affect the two phonological variations (i.e. low-level-tone-like sandhi tone and low-checked-tone-like sandhi tone), and give rise to new patterns of tone sandhi in Hai-lu Hakka. The effect of ongoing tonal mergers on sandhi tones should be further considered carefully.

2.5 Summary of Hai-lu Hakka's tonal variations

This chapter shows that Hai-lu Hakka has seven tones and many different variations derived from four primary tonal modifications: tonal co-articulation, tone sandhi, morpho-phonological alternations, and ongoing tonal mergers. Those variations and their patterns are generalized in each tonal modification below.

Table 2.2 Summary of Hai-lu Hakka's tonal variations.

Modifications	Patterns	Tones affected
(1) Phonetic (co-articulation)	a. The higher the following onset pitch, the higher the preceding tones' offset pitch. b. The higher the preceding tones' offset pitch, the higher the following tones' onset pitch.	All tones, especially high-falling tone.
(2) Phonological (tone sandhi)	a. Tone-13→ Tone-22 b. Tone-$\underline{5}$→ Tone-$\underline{2}$ c. Non-cyclic & more exceptions d. Effects of tonal mergers & emphasis rules	Low-rising tone, low-level tone, & two checked tones.
(3) Morph-phonological alternations	a. Derivational devices b. Emphasis rules & adjectival reduplication (i) All tones→ low-rising (ii) Checked tones→ high-checked (iii) Non-checked tones→ high-level c. Kinship terms	Low-rising tone, high-checked tone, & high-level tone.
(4) Ongoing tonal mergers	a. Tone-22→ Tone-31 b. Tone-$\underline{5}$→ Tone-55 c. Tone-$\underline{2}$→ Tone-31	Low-level tone & two checked tones.

As shown in the first row of Table 2.2 above, Jiang (2003) pointed out two patterns derived from the influence of neighboring tones via tonal co-articulation. First, preceding tones' offset pitch is assimilated to following tones' onset pitch. The higher the following onset pitch is, the higher the preceding tones' offset pitch will be. Second, following tones' onset pitch is also assimilated to preceding tones' offset pitch. The two phonetic variations play a role in all tones, especially high-falling tone. They are very likely to result in some tonal confusion between high-falling tone and low-falling tone. Since the two falling tones contrast crucially in pitch height, the tonal contrast is largely influenced by the effect of tonal co-articulation. Therefore, this dissertation focuses on this tonal contrast to examine how phonetic variations play a role in tonal processing.

As shown in the second row of Table 2.2, Hai-lu Hakka exhibits two types of phonological variations. First, low-rising tone sandhi changes low-rising tone into low-level tone before any other tone in non-final position. Second, high-checked tone sandhi changes high-checked tone into low-checked tone in the same condition. Chang (2002), Chung (1992), Fan (1996), and Hsu (2009) indicated that the two tone sandhi rules exhibit two specific patterns: non-cyclicity and more exceptions, suggesting that tone sandhi tends to be under-applied. In addition, the effects of two ongoing tonal mergers (i.e. low-level tone change and low-checked tone change) and two emphasis rules (i.e. low-rising emphasis rule and high-checked emphasis rule) may give rise to new sandhi patterns and exception-like results. These cases indicate that Hai-lu Hakka tone sandhi varies with many different factors, and these different variations may play a role in the application of tone sandhi.

As shown in the third row of Table 2.2, Hai-lu Hakka has four kinds of morpho-phonological alternations: derivational devices, adjectival reduplication, emphasis rules, and nominal reduplication as kinship terms. The alternations as derivational devices and kinship terms are fixed and limited to a few words, while the others are relatively productive but optional. Two of these alternations (i.e. all tones→ low-rising, checked tones→ high-checked) exhibit patterns opposite to two sandhi rules (low-rising→low-level, high-checked→ low-checked). These opposite patterns may account for some exceptions to tone sandhi, and they need to be further analyzed.

As shown in the last row of Table 2.2, Hai-lu Hakka undergoes three ongoing tonal mergers: low-level tone change, high-checked tone change, and low-checked tone change. Two of these tonal mergers (low-level tone change and low-checked tone change) may affect two sandhi tones (i.e. low-level and low-checked), and give rise to new sandhi patterns: (i) low-rising tone→ ø (low-level)→ low-falling tone and (ii) high-checked tone→ ø (low-checked)→ low-falling tone. The two new patterns should be carefully considered in the application of tone sandhi.

To sum up, this dissertation focuses on the first two cases to examine the role of pitch variations in the contrast of two falling tones and the role of different variations in the application of tone sandhi. Although the morpho-phonological alternations and ongoing tonal mergers are not relevant to current interests, they may also play a role in tonal processing. In general, this chapter shows that Hai-lu Hakka's tonal variations are complicated and extensive. The question is how substantially these variations can influence tonal processing.

CHAPTER THREE

THE THEORETICAL ISSUES ON TONAL VARIATIONS AND SPEECH PROCESSING

This dissertation focuses on the role variations play in tonal processing to investigate two issues: whether tonal contrasts are as distinctive as assumed previously (i.e. the distinctiveness issue) and whether tone sandhi is as productive as post-lexical rules (i.e. the productivity issue). These two assumptions arise from the theoretical issue of how to classify different phonetic/phonological rules and their derived variations (i.e. the classification issue) in speech processing. This dissertation introduces three processing models: the functional model, the direct-realist model, and the exemplar-based model, to compare how these models define phonetics and phonology as processing levels (i.e. the level issue) and processing representations (i.e. the representation issue). An appropriate approach to speech processing is expected to account for the role variations play in tonal processing.

3.0 Introduction

This chapter has three scopes. The next section starts with the potential role variations play in tonal processing, and brings up (i) the distinctiveness issue in that some tonal contrasts may not be distinctive and (ii) the productivity issue in that tone sandhi may not be fully productive. Since the two issues stem from the theoretical question of how to classify different phonetic and phonological patterns, the classification issue is also discussed in section 3.1. Then section 3.2 demonstrates how different processing models approach phonetics and phonology in terms of processing levels and representations. This section also compares three processing models, and discusses their primary arguments. The last section concludes with three hypotheses proposed to evaluate the role variations play in tonal processing.

3.1 Theoretical issues on tonal variations

Previous studies (Hsu 1989; Lai 2013; Miracle 1989; So & Dodd 1995; Tsay 2001; Tse 1978; Wang et al 2003; Zhu & Dodd 2000) mostly assumed that tonal contrasts are distinctive to L1 speakers. In addition, Chen (2000) and Xu (2004: 783) regarded tone sandhi as post-lexical rules which were agued to be fully productive by Hargus & Kaisse (1993), Kiparsky (1982, 1988); in contrast, Tsay & Myers (1996) considered tone sandhi to be partially productive lexical rules. These studies consistently indicated that tonal categories and tone sandhi are acquired earlier than the age of two, and L1 speakers significantly outperform L2 learners in tonal processing, i.e. higher accuracy of tonal perception and higher application rates of tone sandhi. Since these categories and rules are acquired early, they should be distinctive enough for L1 speakers to process tonal contrasts and tone sandhi rules without difficulty. These findings conform to the conventional distinction between phonetics and phonology. As indicated in (15) below, phonetic patterns were proposed to be continuous, gradient, and variant (full of variations), while phonological patterns to be distinctive, categorical, and invariant (with no variations) since Chomsky & Halle (1968). In other words, the assumptions on tonal contrasts and tone sandhi may be inferred from the distinction between phonetics and phonology.

(15) Distinction between phonetics and phonology

Phonetics	=	continuous, gradient, and variant (variations)
Phonology	=	distinctive, categorical, and invariant (no variations)

However, some recent studies (Liu et al 2007, 2009; Wang 2011) indicated that tonal categories and tone sandhi are not acquired as early as found previously. Other studies (Huang 2001, 2004; Moore & Jongman 1997; Yeh & Lin 2011, 2012; Yeh & Lu 2013) also indicated that some tonal contrasts (e.g. T2 and T3 in Mandarin) are not completely distinctive to L1 speakers. These findings cast doubt on the previous assumptions, and point out a potential role of variations in tonal processing. The role of variations in phonological patterns (i.e. tonal contrasts and tone sandhi rules) raises the theoretical issue that strictly relates variations to phonetics and invariance to phonology as shown in (15) above. The question is how to classify phonetics and phonology in speech processing.

This section briefly discusses the previous assumptions on tonal contrasts (i.e. the distinctiveness issue) and tone sandhi (the productivity issue) in section 3.1.1 and 3.1.2 respectively. The first two subsections also demonstrate some current challenges and implications. Then section 3.1.3 deals with the theoretical issue of how to classify different phonetic/phonological rules and their derived variations in tonal processing.

3.1.1 The distinctiveness issue

The distinctiveness issue concerns whether tonal contrasts are as distinctive as assumed by previous findings such as earlier acquisition and higher perceptual accuracy of tonal categories (Hsu 1989; Miracle 1989; So & Dodd 1995; Tsay 2001; Tse 1978; Wang et al 2003; Zhu & Dodd 2000). The previous assumption was challenged by some recent findings that tonal categories are not acquired as early as two-year old (Liu et al 2007, 2009), and L1 speakers may experience tonal confusion (Huang 2001, 2004; Moore & Jongman 1997; Yeh & Lin 2011, 2012). These recent findings indicate that tonal variations play a role in tonal acquisition and tonal perception. Hence, some tonal contrasts may not be clearly distinctive due to the role variations play in tonal perception.

3.1.1.1 Early acquisition and higher perceptual accuracy

Previous studies assumed that tonal contrasts are distinctive to L1 speakers for two reasons. First, tonal categories were found to be acquired early in Cantonese, Mandarin, and Taiwan Southern Min by Hsu (1989), So & Dodd (1995), Tsay (2001), Tse (1978), and Zhu & Dodd (2000). So & Dodd (1995) examined four Cantonese-speaking children’s tonal acquisition once a month for eight months. They found that Cantonese-speaking children acquire [-L] non-checked tones (i.e. Tone-55: high-level, Tone-35: mid-rising and Tone-33: mid-level) earlier than [+L] non-checked tones (Tone-22: low-level, Tone-23: low-rising and Tone-21: low-falling) and checked tones (i.e. high-checked, mid-checked, and low checked tones), and they acquire checked tones the least early. Regardless of the tone types, all tonal categories are acquired earlier than the age of two, and earlier than vowels and consonants. Tsay (2001) and Zhu & Dodd (2000) also found the similar results in Mandarin and Taiwan Southern Min. Zhu & Dodd (2000) concluded that tones are acquired earlier than vowels and consonants due to the phonological saliency defined by the amount of categories in a given system. They argued that tonal categories are phonologically more salient and are acquired earlier than vowels and consonants because of fewer tonal categories than segmental ones. Zhu & Dodd (2000: 35) concluded that “the number of options within a syllable component may determine the rate of acquisition when other factors are equal.” Thus, tonal categories are assumed to be distinctive to L1 speakers.

Second, tonal categories were found to be more perceptually accurate to L1 speakers than L2 learners by Bent (2005), Huang (2001, 2004), Miracle (1989), and Wang et al (2003). These studies showed that L1 speakers’ perceptual accuracy can be up to 95%, and their tonal performance is significantly better than L2 learners. For instance, Huang (2001) examined L1 speakers and American English speakers’ tonal discriminability of four Mandarin tones. As illustrated in Table 3.1 below, the results indicated that L1 speakers discriminate 12 tonal pairs with shorter response time and lower error rates than American English speakers. L1 speakers barely commit any tonal errors, except for the T2-T3 contrast. The findings suggest that Mandarin tones are perceptually distinctive to L1 speakers, but they can be perceptually difficult for L2 learners to acquire. In general, the early acquisition and higher perceptual accuracy of tonal categories seem to support that tonal contrasts are so distinctive that L1 speakers will hardly make any tonal confusion.

Table 3.1 Mandarin and English speakers' discrimination results in mean response time (ms) of correct responses and mean percentage of errors (%) (Adapted from Huang 2001: 30).

Tonal Pairs	T1/T2		T1/T3		T1/T4	
	T1T2	T2T1	T1T3	T3T1	T1T4	T4T1
Mandarin	569 (4%)	557 (7%)	573 (3%)	584 (6%)	602 (4%)	573 (4%)
Am English	558 (1%)	672 (1%)	517 (2%)	556 (2%)	607 (5%)	594 (2%)
Tonal Pairs	T2/T3		T2/T4		T3/T4	
	T2T3	T3T2	T2T4	T4T2	T3T4	T4T3
Mandarin	699 (11%)	667 (7%)	512 (0%)	583 (4%)	543 (0%)	547 (4%)
Am English	748 (16%)	664 (13%)	615 (11%)	569 (3%)	591 (5%)	624 (2%)

3.1.1.2 Recent challenges

However, some recent studies (Liu et al 2007, 2009; Wong et al 2003) indicated that tonal categories are not acquired early. Liu et al (2007, 2009) investigated Mandarin-speaking children and child-minders' tonal implementation of four Mandarin tones by a spectrographic analysis. The results showed that young speakers and child-minders tend to hyper-articulate each tone with higher pitch and wider pitch range, and their tonal hyper-articulation is considered to be typical in infant-directed speech. Their production of greater pitch perturbations gradually decreases, and approaches to an adult standard by the age of five. Their pitch variations indicate that young speakers may not fully acquire tonal categories to an adult level until a later stage of phonological acquisition.

In addition, other studies (Fon & Hsu 2007; Huang 2001, 2004; Moore & Jongman 1997; Yeh & Lin 2011, 2012) indicated that some tonal categories are not completely distinctive to L1 speakers, since they can be confused as other tones. Moore & Jongman (1997) indicated that Mandarin T2 and T3 tend to be confused as each other, since they are phonetically similar in pitch contour. Both tones have a dipping shape, i.e. falling contour in the beginning and rising contour in the end. As illustrated in Figure 3.1, they have two acoustic correlates: (i) a turning point of pitch contour and (ii) a pitch drop of initial falling, and T2 generally has a shorter turning point and a smaller pitch drop than T3. Fon & Hsu (2007) indicated that their acoustic correlates vary in different prosodic contexts (e.g. T3 with a shorter turning point in non-final position), and those different variations may result in tonal confusion between the two dipping tones in Taiwan Mandarin. As illustrated in Table 3.1 above, Huang (2001) indicated that the T2-T3 confusion is also likely to result from an influence of phonological variations derived from T3 sandhi. As found by Zee (1980: 101) and Peng (1996), T3 sandhi changes T3 into a T2-like variant that has lower overall pitch than underlying T2. Peng (1996) argued that the derived T2 is lower in overall pitch, since its underlying form T3 is a low tone. Although the derived and underlying T2s are phonetically different, they are not contrastive to L1 speakers. This T2-like variant of T3 makes T3 more phonetically similar to T2, so it may be responsible for the T2-T3 confusion. In general, these findings indicate that some tonal contrasts, e.g. the T2-T3 contrast, may not be distinctive to L1 speakers due to the influence of phonetic/phonological variations.

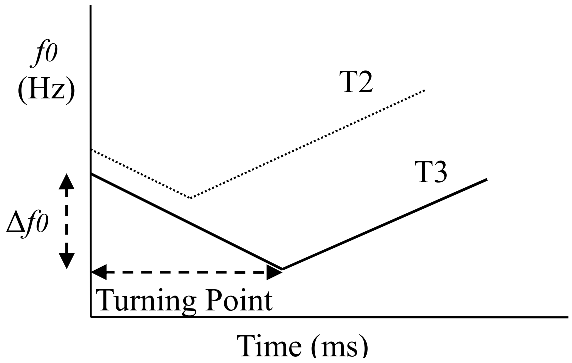

Figure 3.1 Acoustic correlates between T2 and T3: (a) a turning point of pitch contour and (b) pitch drop of initial falling (Δ*f0*) (Adapted from Moore & Jongman 1997: 1867).

To sum up, those recent studies indicate that tonal categories are not fully acquired to an adult level by the age of five, and they can be confusing to L1 speakers in some cases. These findings pose a challenge against the assumptions of early acquisition and higher perceptual accuracy of tonal categories, and indicate a potential role of variations in tonal processing. Since some tonal contrasts may not be as distinctive as assumed previously, whether variations play a role in tonal contrasts needs to be carefully examined.

3.1.1.3 The potential role of phonetic variations in tonal contrasts

Fon & Hsu (2007), Huang (2001, 2004), and Moore & Jongman (1997) indicated that some phonetic and phonological variations may play a role in tonal contrasts. According to the distinction between phonetics and phonology in (15) above, it is reasonable to expect phonological variations to play a role in tonal contrasts, but the question is how about phonetic variations.

As found by Bent (2005), Fon & Hsu (2007), Pan & Tai (2006), Peng (1997), and Xu (1997, 1999, 2004), tonal variations arise from various prosodic contexts such as (i) neighboring tones, (ii) prosodic positions, and (iii) prosodic boundaries. For instance, Peng (1997) found that falling tone' offset pitch tends to be higher when preceding high tones, and to be lower when preceding low tones in Taiwan Southern Min, indicating an effect of neighboring tones. She also pointed out that vowel duration tends to be longer, and pitch height tends to be lower in final position than in non-final position, indicating an effect of prosodic position. In addition, durational lengthening tends to more significant in phrase-final position, and pitch lowering tends to more significant in utterance-final position, indicating an effect of prosodic boundaries. These contextual factors give rise to many different phonetic variations.

Xu (2004) indicated that tonal variations are extensive and substantial in connected speech, and they make tonal space more crowded than its original dimension. According to the dispersion theory (Flemming 2004) of phonological contrasts, the denser the tonal space is, the less distinctive the tonal categories will be. The denser tonal space may result in tonal confusion. However, as discussed earlier in section 1.2.1.1 and as illustrated in Figure 1.1 above, those previous studies only examined contextual effects on tonal production, but hardly attended to the role of variations in tonal perception. It is still unclear how those extensive and substantial tonal variations derived from phonetic modifications play a role in tonal contrasts.

3.1.2 The productivity issue

The productivity issue concerns whether tone sandhi is as productive as assumed previously. Tone sandhi rules were previously assumed to occur at the post-lexical level (Chen 2000; Xu 2004: 783), so they were argued to be as fully productive based on the theory of lexical phonology (e.g. Hargus & Kaisse 1993; Kiparsky 1982, 1988). In addition, Zhu & Dodd (2000) found that Mandarin T3 sandhi is acquired as early as tonal categories before the age of two. The finding indicates that young speakers have no difficulty in producing tone sandhi, not to mention adult L1 speakers. The post-lexical account and the early acquisition suggest that tone sandhi is fully productive.

However, many studies indicated that tone sandhi may not be fully productive, and the application of tone sandhi varies with many different factors. Wang (2011) found that young and adult speakers apply Mandarin T3 sandhi in different manners, and both exhibit different variations in the application of tone sandhi. These findings indicate that young speakers haven't fully acquired T3 sandhi to an adult level until the age of six, so T3 sandhi is not acquired as early as found previously. In addition, Hsieh (1976), Wang (1995), and Zhang et al (2011) found that application rates of tone sandhi vary with different word types (i.e. actual words and accidental gaps) and sandhi types (e.g. more phonetically natural and less phonetically natural rules) in Taiwan Southern Min. These findings indicate that tone sandhi rules are not fully productive, and they exhibit many different variations. In order to account for the lower productivity and different variations, Tsay & Myers (1996) considered Taiwan Southern Min tone sandhi to be lexical rules instead, whereas Zhang et al (2011) argued for various phonetic/phonological and lexical factors in the application of tone sandhi. These studies point out the classification issue on how to define tone sandhi and how to distinguish tone sandhi from other rules in tonal phonetics and phonology.

To sum up, recent studies indicate that tone sandhi rules are not acquired early and may not be as fully productive as post-lexical rules. The application of tone sandhi varies with many different factors, such as word types and sandhi types. The various effects indicate that variations play a role in tonal processing, since they may lower the productivity of tone sandhi.

3.1.3 The classification issue

The previous assumptions on tonal contrasts and tone sandhi are currently challenged by the potential role of variations in tonal processing. As discussed above, the questions are (i) how come phonetic variations may play a role in tonal contrasts and (ii) how to distinguish tone sandhi from other tonal rules. These questions point to a classification issue that relates different tonal variations/rules to linguistic derivations/causes. As indicated in (16) below, Chen (2000: 23-31) generalized three kinds of tonal modifications/rules in Chinese tonology: a. tonal co-articulation, b. tone sandhi, and c. tone change.

(16) Three tonal modifications in context

a. Tonal co-articulation: A phonetic rule that gives rise to phonetic variations, such as a tonal variant with higher offset pitch when preceding high tones.
b. Tone sandhi: A phonological rule that gives rise to phonological variations, such as a T2-like variant derived from underlying T3 via T3 sandhi.
c. Tone change: A morpho-phonological rule that gives rise to morpho-phonological alternations, such as the change from T3 *hao**3*** 好 'good' to T4 *hao**4*** 好 'to like' as derivational devices.

As indicated in (16a) above, tonal co-articulation refers to a phonetic rule that gives rise to phonetic variations, such as a high-falling variant with higher offset pitch when preceding high tones. Xu (2004: 783) defined tonal co-articulation as implemental tonal modifications that are strictly conditioned by tonal contexts and phonetic factors. Bent (2005), Fon & Hsu (2007), Pan & Tai (2006), Peng (1997), and Xu (1997, 1999, 2004) found that tonal co-articulation and other contextual factors result in many pitch variations. As indicated in (16b), tone sandhi refers to a phonological rule that gives rise to phonological variations, such as a T2-like variant derived from underlying T3 via T3 sandhi in Mandarin. Xu (2004: 783) defined tone sandhi as post-lexical tonal modifications that are conditioned by various phonetic, morphological, and syntactic factors. Wang (2011), Zhang & Lai (2010), and Zhang et al (2011) found that application of tone sandhi varies with many different factors. As indicated in (16c), tone change refers to a morpho-phonological rule that gives rise to morpho-phonological alternations, such as the change from T3 hao**3** 'good' to T4 hao**4** 'to like' as derivational devices in Mandarin. Chen (2000: 30-31) defined tone change as *biànyīn* 變音 that only applies to a few fixed and limited words. Tone change tends to apply as inflectional and derivational devices, so it involves some semantic modifications as well.

This section demonstrates the relation between tonal variations/modifications and linguistic derivations/processes by Levelt's (1999) model of speech production below. As illustrated in Figure 3.2, Levelt (1999) proposed three output processes: (a) lexical selection, (b) phonological preparation, and (c) phonetic implementation to derive surface forms from internal lexicon. First, the selection stage is to retrieve some syntactically and semantically appropriate words from lexical memory. It corresponds to tone change that functions as inflectional and derivational devices, and it gives rise to different morpho-phonological alternations, as indicated in (16c) above. Then, the preparation stage is to prepare phonological properties and contextual information for phonetic implementation. It corresponds to tone sandhi that applies in the post-lexical stratum, and it gives rise to phonological variations, as indicated in (16b). The last stage is to implement surface forms by articulatory gestures. It corresponds to tonal co-articulation that derives from gestural coordination and different degrees of constrictions, and it gives rise to phonetic variations, as indicated in (16a).

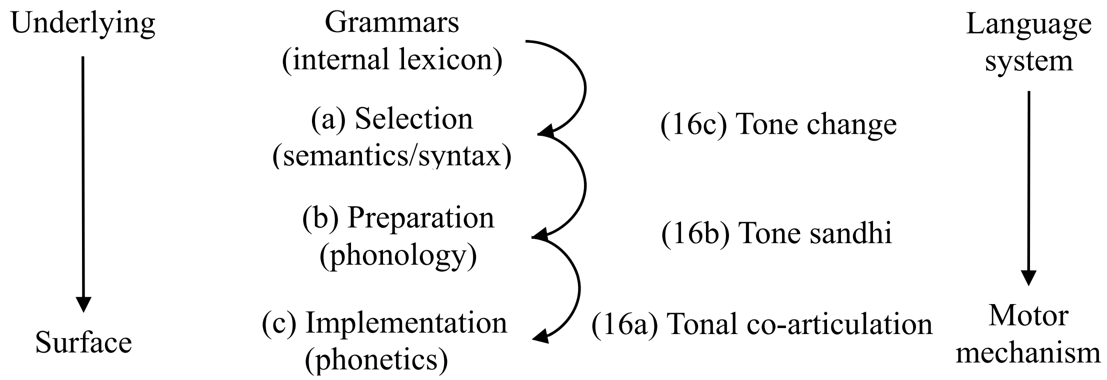

Figure 3.2 The relation between three tonal modifications (tonal co-articulation, tone sandhi, and tone change) and three linguistic levels (phonetics, phonology, and morphology) demonstrated in Levelt's (1999) model of speech production.

However, it can be problematic to relate different tonal variations/modifications to linguistic derivations/processes. For instance, Mandarin T3 sandhi changes T3 to T2 before another T3. The derived T2 also undergoes some phonetic processes as it was found to be lower in overall pitch than an underlying counterpart in the same context by Peng (1996) and Zee (1980: 101). Although the lower overall pitch does not contrast derived and underlying T2s in perception, indicating a trivial role of the pitch variation in tonal processing, what these findings show is that phonological variations may exhibit some phonetic characteristics. Likewise, phonetic variations may also exhibit some phonological properties. It is problematic to assume phonetic variations/modifications as continuous and gradient, and phonological variations/modifications as distinctive and categorical, based on the distinction between phonetics and phonology in (15) above. It can also be problematic to consider phonetic modifications/rules to be trivial and to consider post-lexical phonological modifications/rules to be fully productive. How different phonetic/phonological variations affect tonal processing needs to be carefully examined. In addition, as indicated by Chen (2000: 27) and Xu (2004: 783), it is not always easy to define different tonal variations and modifications by linguistic derivations/processes. This chapter further elaborates the classification issue by comparing tone sandhi to tonal co-articulation in section 3.1.3.1 and comparing post-lexical tone sandhi to lexical rules in section 3.1.3.2.

3.1.3.1 Tonal co-articulation and tone sandhi

As indicated in (16) above, tonal co-articulation rules are regarded as phonetically-driven tonal modifications, while tone sandhi rules are regarded as phonologically-conditioned tonal modifications. Xu (2004: 783) indicated that tonal co-articulation rules are strictly conditioned by tonal contexts and phonetic factors, while tone sandhi rules are conditioned by various phonetic, morphological, and syntactic factors. In other words, those previous studies tended to differentiate the two tonal rules by the distinction between phonetics and phonology as in (15) above. Shen (1992) specifically proposed three diagnostics to distinguish tone sandhi from tonal co-articulation. As indicated in (17a) below, the first diagnostic indicates that tonal co-articulation only exerts an assimilatory effect on tonal variations, but the effect of tone sandhi is either assimilatory or dissimilatory. As indicated in (17b), the second diagnostic indicates that tonal co-articulation is induced only by phonetic factors, but tone sandhi may result from various kinds of factors. As indicated in (17c), the last diagnostic indicates that tonal co-articulation only results in intra-category tonal variations, but tone sandhi may result in inter-category tonal variations.

(17) Three diagnostics of tone sandhi and tonal co-articulation rules

a. Only assimilation is considered tonal co-articulation, but tone sandhi may be assimilatory or dissimilatory.

b. Tonal co-articulation follows only language-independent biomechanical restrictions, but tone sandhi can be subject to language-specific morphological and phonological conditions.

c. Tonal co-articulation involves only allotonic variations, but tone sandhi may result in tonemic change.

However, Chen (2000: 25) pointed out that these diagnostics involve some potential flaws, and they cannot effectively distinguish tone sandhi from tonal co-articulation. First of all, Chen (2000: 25) demonstrated that tonal co-articulation is not purely assimilatory by the Mandarin case where T2 and T4 tend to be higher in overall pitch when preceding T3. The pitch variation expands the pitch difference between T2/T4 (high tone) and T3 (low tone), and it seems to dissimilate high and low tones. In addition, Peng (1997) indicated that contour tones and their following tones tend to be assimilatory, whereas level tones and their followers tend to be dissimilatory in Taiwan Southern Min. Tonal assimilation and dissimilation seem to be correlated to different tone types rather than different tonal rules. The Mandarin and Southern Min cases suggest that tonal co-articulation also can be assimilatory or dissimilatory. The difference between tonal assimilation and dissimilation cannot distinguish tonal co-articulation from tone sandhi.

Second, Chen (2000: 26) pointed out that tonal co-articulation is not exclusively biomechanical (i.e. phonetic), and it is also sensitive to some morpho-syntactic structures. For instance, as shown in (18) below, in Mandarin, *lan***3** of [[zhan3-*lan***3**]-guan3] 'exhibition hall' as in (18a) and *leng***3** of [he1-[*leng***3**-shui3]] 'drink cold water' as in (18b) are both T3 words occurring in the second syllable of tri-syllabic compounds. Both T3 words change into T2 as in [[zhan2-*lan***2**]-guan3] and [he1-[*leng***2**-shui3]] due to T3 sandhi, but not both of them undergo tonal co-articulation due to different sandhi domains illustrated by the brackets. The former has a **HM** shape derived from tonal co-articulation, whereas the latter still keeps a **MH** shape. The difference indicates that tonal co-articulation is affected by some morpho-syntactic factors. In addition, Fon & Hsu (2007), Pan & Tai (2006), Peng (1997), and Xu (1999) found that tonal co-articulation is also susceptible to different prosodic factors. These findings indicate that tonal co-articulation is not motivated only by phonetic factors.

(18)

a. [[zhan3-*lan***3**]-guan3] 'exhibition hall'

	L **L** L	base tone
	MH.**MH.**	T3 sandhi
	HM.	tonal co-articulation
	MH.**HM.** L	surface form
b.	[he1-[*leng***3**-shui3]]	'drink cold water'
	H **L** L	base tone
	MH.	T3 sandhi
	H **MH.** L	surface form

As to the last diagnostic shown in (17c), Chen (2000: 27) indicated that variations induced by tonal co-articulation are not always allotonic (i.e. gradient and continuous) and those induced by tone sandhi are also not always tonemic (i.e. categorical and distinctive). For instance, as shown in (18a) above, the derived T2 *lan***2** of [[zhan**2**-lan**2**]-guan3] 'exhibition hall' changes from MH (mid-rising) to HM (high-falling) due to tonal co-articulation. The change is somehow categorical, but not simply allotonic. In addition, Peng (1996) and Zee (1980: 101) found that T2 derived from T3 sandhi has lower overall pitch than underlying T2 in the same context. The derived T2 still keeps a [+L] feature as its original dimension (i.e. T3), so the change is not necessarily tonemic.

In general, Chen (2000: 27) and Xu (2004: 783) indicated that it is not always easy to distinguish tonal co-articulation from tone sandhi. Chen (2000: 27) eventually concluded that "there is no essential difference between tone sandhi and tonal co-articulation, except that tone sandhi processes are perceptible to the (trained but) unaided ears, and therefore more likely to be reported by fieldworkers and integrated to a greater extent into the phonological component of the grammar." The classification issue motivates Xu (2004) to propose an articulation-based account that focuses on pitch and duration properties to define different tonal modifications: variations due to target alternation and variations due to articulatory implementation, but it remains unclear how these variations are different empirically. Since it is difficult to define tonal co-articulation and tone sandhi by the distinction between phonetics and phonology, it can be problematic to relate different tonal modifications/variations to phonetic and phonological processes. Hence such a distinction can underestimate a role of variations in tonal contrasts and tone sandhi.

3.1.3.2 Post-lexical rules and lexical rules

As indicated in (16) above, tone sandhi rules are regarded as phonologically-conditioned tonal modifications, while tone change is regarded as a morpho-phonological alternation. Chen (2000: 30-31) indicated that tone change tends to function as inflectional and derivational devices, so it may involve some semantic modifications. Tone sandhi was argued to occur in the post-lexical stratum, since it does not seem to modify lexical meanings. It is less difficult to distinguish tone sandhi from tone change, but Tsay & Myers (1996) proposed that unproductive tone sandhi should be analyzed as lexical rules instead. Based on the theory of lexical phonology (Hargus & Kaisse 1993; Kiparsky 1982, 1988), Tsay & Myers (1996: 394) indicated that lexical tone sandhi and post-lexical tone sandhi differ in five diagnostics: a. word-bounded or not, b. morphology-related or not, c. exceptions or not, d. fully productive or not, and e. categorical or not. As illustrated in (19) below, lexical rules are considered to be word-bounded, whereas post-lexical are not. Second, lexical rules may be related to morphology, whereas post-lexical rules may not. Third, lexical rules may have exceptions, whereas post-lexical rules have no exceptions. Fourth, lexical rules are partially productive, whereas post-lexical rules are fully productive. Finally, lexical rules lead to categorical changes, whereas post-lexical rules may lead to gradient changes.

(19) Lexical rules vs. post-lexical rules

	Lexical	Post-lexical
a.	word-bounded	not word-bounded
b.	may refer to morphology	may not refer to morphology
c.	may have exceptions	have no exceptions (automatic)
d.	semi-productive	fully-productive
e.	categorical	may be gradient

Based on the five diagnostics above, Tsay & Myers (1996) indicated that Taiwan Southern Min tone sandhi is more likely to be lexical rules rather than post-lexical. First of all, they indicated that the mid-level word [ho33] 'to give' becomes low-falling tone as [ho21] in non-phrase-final position due to the mid-level tone sandhi that changes mid-level tone to low-falling tone. When preceding some specific pronouns [wa51] 'I' and [li51] 'you' as in verbal phrases such as 'to give me' and 'to give you', the verb has two free variations [ho21] and [ho33]. The former results from low-level tone sandhi, and the latter is an exception to tone sandhi. These free variations simply apply to the verb 'to give', and barely occur in other verbs. These findings indicate that Southern Min tone sandhi has exceptions, and its sandhi change may involve morphological factors. In addition, Hsieh (1976), Lin (1988), Wang (1995), and Zhang et al (2011) found that Southern Min's tone sandhi rules vary with different word types and sandhi types. The various lexical and phonetic/phonological effects indicate that Southern Min tone sandhi is word-bounded and is partially productive. Since Taiwan Southern Min tone sandhi exhibits these characteristics, it is more likely to be lexical rules rather than post-lexical.

Zhang et al (2011) interpreted the similar findings by other approaches such as phonetic naturalness and frequency effects. They argued that phonetically natural sandhi rules are more productive than those phonetically less natural ones, and frequently-occurring sandhi rules are more productive than those less frequently occurring. Their different proposals for the similar findings raise a question as to whether tone sandhi is post-lexical or not. It is still unclear how to define different tone sandhi patterns. Regardless of the classification issue, these findings indicate that tone sandhi may not be fully productive as assumed previously.

3.1.4 Summary of theoretical issues on tonal variations

This section indicates two issues on tonal variations: the distinctiveness issue and the productivity issue. As generalized in (20a) below, the distinctiveness issue concerns whether or not tonal contrasts are as distinctive as assumed previously. Some recent findings (Liu et al 2007, 2009; Moore & Jongman 1997) posed a challenge against early acquisition and higher perceptual accuracy of tonal categories, and indicated a potential role of variations in tonal contrasts. Some variations may lead to tonal confusion between phonetically similar tones. The question is whether phonetic variations may reduce distinctiveness of tonal contrasts. As generalized in (20b), the productivity issue concerns whether or not tone sandhi is as productive as assumed previously. Some recent findings (Wang 1995; Zhang et al 2011) indicated that application of tone sandhi varies with various lexical and phonetic/phonological factors, suggesting a role of variations in tone sandhi. Tone sandhi rules are not necessarily fully productive as post-lexical rules. Some (Tsay & Myers 1996) proposed some unproductive tone sandhi (e.g. Taiwan Southern Min's) as lexical rules, whereas others (Zhang et al 2011) argued for different characteristics of tone sandhi (e.g. more or less frequently-occurring, more or less phonetically-natural). The question is how to define different tone sandhi patterns. The two issues lead to a more theoretical issue on how to classify different tonal variations/modifications. As generalized in (20c), previous studies tended to relate different tonal variations/modifications to linguistic derivations/processes. Those recent challenges suggest that such a classification is problematic. It is the theoretical issue that motivates this dissertation to examine the role variations play in tonal processing.

(20) Two issues on tonal variations and the classification issue

a. The distinctiveness issue: Whether tonal contrasts are as distinctive as assumed previously?

b. The productivity issue: Whether tone sandhi rules are as productive as assumed previously?

c. The classification issue: Whether it is problematic to relate different tonal variations/modifications to linguistic derivations/processes?

To sum up, this dissertation examines the distinctiveness issue by showing how pitch variations affect Hai-lu Hakka's contrast of two falling tones. Then it examines the productivity issue by showing how different variations influence Hai-lu Hakka's application of two tone sandhi rules. The dissertation's findings may clarify the two previous assumptions on tonal contrasts and tone sandhi. More crucially, the findings may shed light on the more theoretical issue (i.e. the classification issue) that relates different tonal variations/modifications to linguistic derivations/processes.

3.2 Phonetics and phonology in speech processing

In order to classify different tonal variations/modifications in tonal processing, this dissertation evaluates various proposals presented in speech processing. These processing models generally proposed different phonetic and phonological factors as (i) processing mechanisms, (ii) processing levels, (iii) processing representations, and (iv) processing strategies, and they differ crucially with respect to the level issue and the representation issue. This dissertation compares three primary models: the functional model, the direct-realist model, and the exemplar-based model, to discuss how they define phonetics and phonology by different processing levels and representations.

This section first demonstrates speech processing in section 3.2.1, and discusses four different proposals for phonetics and phonology. Then section 3.2.2 explains the two controversial issues: the level issue and the representation issue in different processing models. The following sections compare the three primary models in section 3.2.3 and focus on the exemplar-based model in section 3.2.4.

3.2.1 Speech processing

Speech processing generally consists of speech perception, speech production, and lexical memory to explain how listeners/speakers decode and encode acoustic signals from physical to psychological dimensions and the other way around. As indicated by Schacter et al (2010), speech processing involves a series of psychological processes, including (i) stimulation or selection, (ii) organization, (iii) interpretation or evaluation, (iv) memory, and (v) recalls.

These psychological processes are generally consistent with what have been proposed in a psycholinguistic model. As shown in Figure 3.3 below, speech processing arguably consists of three primary components: a. auditory (sensory) mechanism, b. articulatory (motor) mechanism, and c. language system, and the three-component framework of speech processing integrates Fitzpatrick & Wheeldon's (2000) psycholinguistic model of speech perception and Levelt's (1999) model of word production into Boersma's (1998) model of functional phonology. As argued by Fitzpatrick & Wheeldon (2000), speech perception includes three stages: (1) extraction of features from acoustic signals, (2) mapping of perceptual representations onto underlying forms and (3) recognition of word meanings, and the three stages conventionally correspond to tonal discrimination, tonal identification and lexical recognition in a derivational manner. Similarly, Levelt (1999) proposed that speech production also includes three stages: (4) selection of syntactically and semantically appropriate words, (5) preparation of phonological properties and contextual information, and (6) implementation of articulatory gestures. The three production processes also correspond to distinctive levels of linguistic derivations: syntactic/semantic, phonological, and phonetic in order.

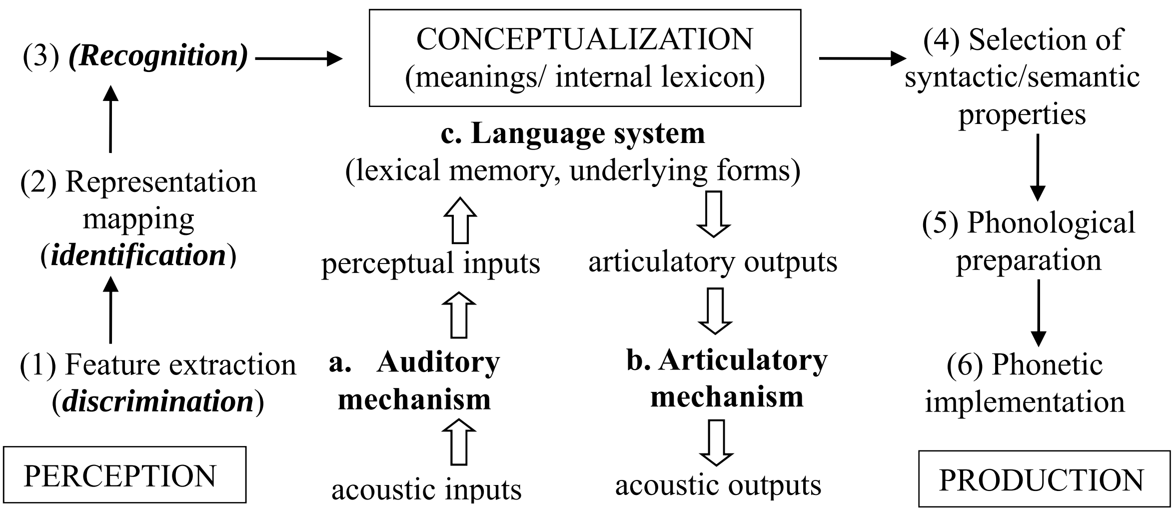

Figure 3.3 The three-component framework of speech processing: speech perception, conceptualization and speech production.

In addition to the levels of speech processes, three other issues are proposed to account for different phonetic and phonological processes. As shown in (21) below, the four fundamental issues are the mechanism issue, the level issue, the representation issue, and the strategy issue. First of all, the mechanism issue concerns speech components that govern each process, and these speech components include sensor-motor mechanisms and lexical systems. The former govern those phonetic processes in physical dimensions, and the latter govern those phonological and lexical ones. The mechanism issue is correlated to the levels of speech processes and the interface between phonetics and phonology, but it can be problematic to simply relate the sensor-motor mechanisms and phonetic processes to speech perception and production. Since speech perception and production not only contain phonetic processes, but also include phonological ones, as illustrated by different processing stages in Figure 3.3 above, it is less controversial to distinguish the mechanism issue from the level and the representation issue. Second, the level issue concerns each speech process that decodes and encodes acoustic signals. Each process level was argued to be responsible for different kinds of information, so the level issue and the representation issue were previously considered to be the same processing issue that relates to each level of linguistic derivations, i.e. phonetic, phonological, and lexical levels. The level issue is currently proposed to contrast the representation issue. That is, the level issue concerns how these processes work, i.e. in a serial or a simultaneous manner. The representation issue concerns how each kind of information is stored in memory, i.e. as perceptual abstractions, articulatory gestures, or lexical exemplars. Lastly, the strategy issue concerns what kinds of knowledge listeners apply to speech signals, current information, previous experiences or both. They apply a bottom-up strategy when targeting current information from acoustic signals, and a top-down strategy when targeting previous experiences from lexical memory. As indicated by Calabrese (2007), Poeppel & Monahan (2011), and Stevens & Halle (1967), listeners may apply both strategies at the same time, which refers to an analysis-by-synthesis approach.

(21) Four fundamental issues on speech processing

a. The mechanism issue: Speech components which are responsible for speech processes, i.e., sensor-motor mechanism and language system.
b. The level issue: Speech processes that decode and encode acoustic signals, i.e., phonetic and phonological level.
c. The representation issue: Kinds of information within speech signals, which were stored in memory from earlier experiences, and are triggered to process incoming signals, i.e., phonetic and phonological factors.
d. The strategy issue: A choice/availability of access to current information or previous experiences, i.e., a bottom-up strategy, a top-down strategy, and an analysis-by-synthesis approach.

Some of these processing issues are more fundamental to models of speech processing than the others. Based on previous processing models, such as the generative model (Fitzpatrick & Wheeldon 2000; Levelt 1999), the functional model (Boersma 1998), the TRACE model (McClelland & Elman 1986), the connectionist model (Dell 1988; Plaut 2003), the direct-realist model (Best 1995; Fowler 1986), the motor theory (Liberman & Mattingly 1985, 1989), and the exemplar model (Goldinger 1996, 1998; Johnson 2006, 2007; Pierrehumbert 2001, 2003), the level issue and the representation issue are more crucial to speech processing. The direct-realist model and the motor theory assumed that linguistic information/knowledge is stored and processed in form of articulatory gestures, whereas the exemplar theory argued for a lexically-based form. These different arguments make fundamental representation a controversial issue concerning speech processing. Similarly, the generative model and the functional model assumed that different psychological processes apply in a serial order, whereas the TRACE model and the connectionist model argued for some kind of simultaneous processes. The serial or simultaneous processes make controversial the level issue concerning whether different kinds of information/knowledge are encoded and decoded in a serial or simultaneous manner. In the following sections, we briefly discuss the two fundamental issues, introduce these processing models, and compare the exemplar-based models to others.

3.2.2 Two controversial issues

The level issue and the representation issue are more essential to processing models for the reason that they address the questions of how to deal with variations and to bridge a gap between variations and invariance. The level issue arises to deal with variations by different levels of processes, and the representation issue arises to deal with variations by different representations of signals/grammars.

3.2.2.1 The level issue

The level issue may include two scopes: (i) a difference between physical and psychological dimensions, and (ii) a series of psychological processes. The former is currently defined as the mechanism issue, and it seems less controversial than the latter. This following discussion focuses on the question of whether these process levels work in serial order or in tandem. As generalized from the previous processing models, there are four potential relations among each level: hierarchical, divisional, parallel, and network, as illustrated in Figure 3.4 below.

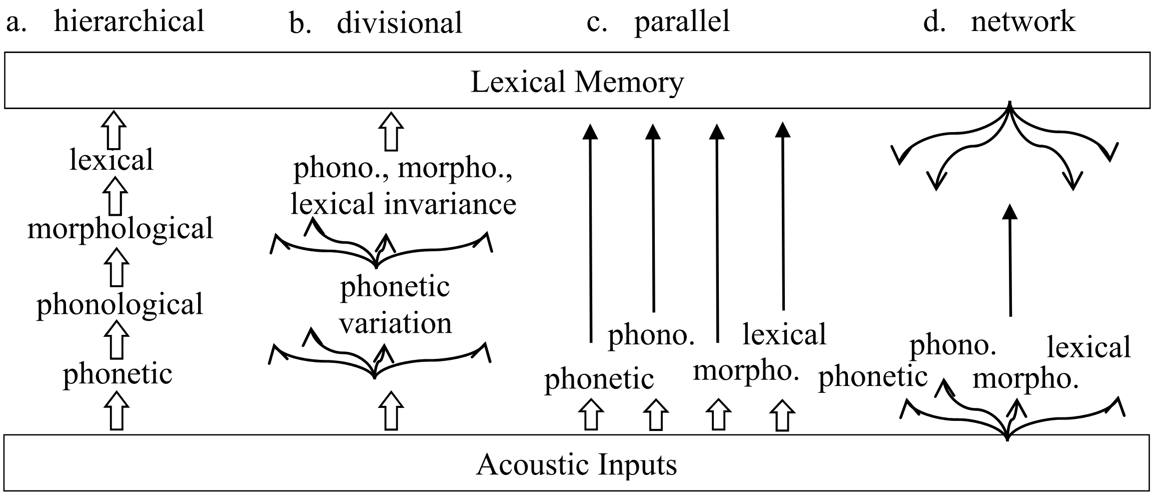

Figure 3.4 Four potential relations among each level of speech processes: a. hierarchical, b. divisional, c. parallel, and d. network.

As illustrated in Figure 3.4 above, the generative model and the functional model (Boersma 1998; Fitzpatrick & Wheeldon 2000; Levelt 1999) assumed a hierarchical relation; the TRACE model (McClelland & Elman 1986) assumed a divisional relation (TRACE I for variations, and TRACE II for invariance), and so did the motor theory and the direct-realist model (Best 1995; Fowler 1986); the connectionist model (Dell 1988) assumed a parallel relation; and the exemplar model (Johnson 2006, 2007; Pierrehumbert 2001, 2003) assumed a network relation. As to the hierarchical relation, each level of processes (corresponding to linguistic derivations) works one after another. As to the divisional relation, speech processes work simultaneously in two sessions: a variation session and an invariance session, and the two sessions include a network unit to activate processing information all together. As to the parallel relation, each level of processes works for a layer of information in tandem. As to the network relation, it is a combination of the divisional relation and the parallel relation. The network relation dispenses with the two simultaneous sessions and the multiple layers, and it activates all information simultaneously. The four relations of processing levels deal with variations in different manners: variations first and then invariance in the hierarchical relation; variations and invariance simultaneously, but separately in the divisional relation; variations and invariance simultaneously, and altogether in the parallel relation; and variations in and out altogether in the network relation.

The comparisons of the four relations suggest that there are three factors to evaluate different processing models: (1) serial or simultaneous: a temporal factor (to differentiate the hierarchical relation from the others), (2) invariance or not (to differentiate the hierarchical relation and the divisional relation from the others), and (3) processing cohorts or not (to differentiate the network relation from the others). First, as to the temporal factor, each level of speech processes was assumed to take place one after another as in linguistic derivations. The longer the timing, the more likely the lexical influence will be found. For instance, in experimental setup, a speeded format is usually adopted for a phonetic process (to elicit more phonetic information). In neuroscience, an event-related potential (ERP), or peak in electrical brain activity measured by electroencephalography (EEG) is conventionally characterized by a positive- or negative-going deflection that peaks around a certain temporal lapse (milliseconds) after the stimulus played to elicit it, such as N100 (negative deflection that peaks around 100 ms) for voice onset time, N200 for semantic and phonological information, N400 for sematic/lexical anomalies, and P600 for syntactic anomalies (Kutas & Federmeier 2000; Osterhout & Holcomb 1992; Schmitt et al 2000; Zouridakis et al 1998). Second, as to the invariance factor, the first two relations assume a transition from variations to invariance, whereas the last two relations do not assume such a transition. The parallel relation and the network relation assume that different factors may directly engage in speech processing. As to the processing cohort, the network relation assumes some specific units that integrate and process different factors altogether in speech processing, so speakers basically process these units rather than individual factors. The other relations do not assume such as a processing cohort.

3.2.2.2 The representation issue

The representation issue also includes two scopes: (i) what kinds of information have to be represented as knowledge, and (ii) in what way they are represented. The former concerns the effect of phonetic, phonological, and lexical factors, and it tends to be considered part of a level issue. The latter concerns whether the representations are abstract, no abstractions or both, as indicated by Pisoni & Levi (2007), in order to deal with variations, especially at a phonetic level. As generalized from the previous models, there are four kinds of representations: a. perceptual abstractions, b. articulatory gestures, c. lexical exemplars, and d. a hybrid. As shown in (22), perceptual abstractions refer to features, constraints, and other generalizations, and they are more abstract and less relevant to variations; articulatory gestures refer to articulators, gestural coordination, and gestural constriction, and they are less abstract and more applicable to variations; lexical exemplars refer to a lexically-based unit that contains all phonetic details and other factors, and they are also less abstract and more applicable to variations; and a hybrid is a combination of abstractions and lexical exemplars, or an integral of gestures and lexical memory. In general, the functional model and the generative model argued for perceptual abstractions; the motor theory and the direct-realist model argued for articulatory gestures or a hybrid of gestures and lexical memory; and the exemplar theory assumed a lexically-based unit, and so did the connectionist model and the TRACE model. The comparisons of the four representations suggest two factors to evaluate different processing models: (1) variations or not (to differentiate perceptual abstractions from the others), and (2) lexically-based or not (to differentiate lexical exemplars from the others).

(22) Four kinds of representations

a. Perceptual abstractions: Features, constraints, and other kinds of generalizations.

b. Articulatory gestures: Articulators, gestural coordination, and gestural constriction.

c. Lexical exemplars: Phonetic details and multiple factors in a lexical unit.

d. Hybrid: Abstractions and lexical exemplars, gestures and lexical memory.

Although the variations and the lexical influences seem to be potential factors to evaluate the representation issue, some additional issues on speech processing, such as the strategy issue and the stochastic approach, make it difficult to define what exert an influence on variations and lexically-based processes. For instance, Boersma (1998) introduced a stochastic approach to the functional model, which not only allows deriving a gradient pattern from phonological processes, but also makes abstract representations capable of dealing with phonetic variations. In addition, the top-down strategy and Calabrese's (2009) analysis-by-synthesis strategy allow a process from lexical memory to acoustic inputs, which make it difficult to tease apart lexically-based and non-lexically-based processes. These additional issues indicate that variations and lexical influences are no longer the crucial factors to differentiate the four kinds of representations, and there need to be some other criteria to evaluate those different processing models.

As mentioned above, those previous models were mostly proposed to deal with variations and to bridge a gap between variations and invariance. They approached variations by different levels of processes and different kinds of representations. However, variations seem to occur not only at the phonetic level, but also the phonological level. As shown in Hai-lu Hakka's tones and many other cases above, variations are common and extensive, and they were approached in different ways by those previous processing models. In other words, these processing models indicated that variations are extensive and common at each level of speech processes, including both phonetic and phonological processes. It is unclear how to differentiate each level of speech processes and each kind of representations by the occurrence of variations. It is more fundamental to define different kinds of variations in speech processing.

3.2.3 Comparisons of three processing models

The processing models discussed above can be classified into three general kinds: (i) derivational and psychoacoustic, such as the generative model and the functional model, (ii) direct and articulatory, such as the motor theory and the direct-realist model, and (iii) integrative and lexical, such as the TRACE model, the connectionist model, and the exemplar model. One of each kind is introduced and compared, and they are the functional model (Boersma 1998), the direct-realist (Best 1995, Fowler 1986), and the exemplar model (Pierrehumbert 2001, 2003). As shown in Table 3.2, the three models are basically similar in processing mechanism, grammars and effects, and processing strategies, and are more contrastive in processing levels, processing representations, relations between phonetics and phonology, and variations.

Table 3.2 Comparisons of the functional model, the direct-realist model, and the exemplar model.

	Functional model	Direct-realist model	Exemplar model
Proponents	Boersma (1998)	Best (1995), Fowler (1986)	Pierrehumbert (2001, 2003)
Processing mechanisms	sensor-motor and language systems	sensor-motor and language systems	language and sensor-motor systems
Grammars and effects	perceptual, articulatory, & lexical influences	articulatory, and some lexical influences	lexical, and some perceptual & articulatory influences
Processing levels	distinctive and hierarchical	less distinctive, parallel	less distinctive, network
Relations of phonetics and phonology	interface	trivial interface or no interface	trivial interface or no interface
	stochastic	algorithmic	probabilistic
Variations	trivial, phonological	crucial, phonetic	crucial, multiple kinds
Processing representations	abstract, perceptual generalizations	concrete, articulatory gestures	less abstract, phonetic and lexical details
	perception-driven	production-driven	lexically-based
Processing strategies	mostly bottom-up and some top-down	mostly bottom-up and some top-down	mostly top-down and some bottom-up

As to Boersma's (1998) functional model, phonological grammars constitute an integral of perceptual, articulatory, and lexical influences. These influences are represented by abstract perceptual generalizations, such as features and constraints, in a hierarchical manner. The hierarchical relation among each processing level tends to be analogized to distinctive levels of linguistic derivations, which indicates an interface between phonetics and phonology. Although both phonetic and phonological influences are involved in speech processing, they are not equally important. The model simply focuses on phonological variations in a stochastic manner, and barely attends to phonetic variations. In addition, since speech processing is considered to be perceptually-driven, it is more likely to rely on sensor-motor mechanism (rather than language system) and to apply a bottom-up processing strategy (from perception to grammars) to speech processing.

As to Best's (1995) direct-realist model, phonological grammars are mostly articulation-driven, and its latest revision also incorporated lexical influences into grammars. These influences are represented by less abstract articulatory gestures, and grammars fall out from gestural constellations, including gestural coordination and gestural constrictions, in an algorithmic manner. Phonetics refers to innate gestures, and phonology refers to selective settings of gestural constellations. These gestural representations directly engage in speech processing, which indicates a parallel relation between phonetic and phonological influences, and there seems to be a trivial or no interface between phonetics and phonology. In addition, since phonetic variations are common in speech production, they are crucial to the articulation-driven model, and they are arguably responsible for variations of other kinds. The articulation-driven model is also more likely to rely on sensor-motor mechanism (rather than language system) and to apply a bottom-up processing strategy (from production and acoustics to grammars) to speech processing.

As to Pierrehumbert's (2001, 2003) exemplar model, phonological grammars include a stochastic ladder of multiple generalizations: tokens < constraints < morpho-phonological alternations, in correspondence to distinctive levels of linguistic derivations. These phonological generalizations are stored and represented as lexical exemplars, a token of experiences, in a probabilistic manner, and are activated mutually as a network to process acoustic inputs. Phonetic and phonological influences engage in speech processing simultaneously, and the mutual activation indicates a trivial or no interface between phonetics and phonology. Since each level of generalizations has its own occurrence distribution, variations of different kinds are all crucial to the lexically-based model. These variations' influences are likely to be determined by their probabilistic distribution. In addition, the lexically-based model is more likely to rely on language system (rather than sensor-motor mechanism) and to apply a top-down processing strategy (from lexical grammars to perception and production) to speech processing.

In general, these processing models were previously argued to be contrastive in kinds of representations and grammars (Best 1995; Durvasula 2009; Levi & Pisoni 2007). As shown in Table 3.2, Boersma's (1998) functional model argued for abstract perceptual abstractions; Best's (1995) direct-realist model argued for articulatory gestures; and Pierrehumbert's (2001, 2003) exemplar model argued for multiple generalizations of lexical exemplars. These representations were also argued to account for variations in a different manner, i.e., a trivial perspective by perception-driven models, a crucial role of phonetic variations by production-driven models, and a crucial role of lexical variations by exemplar-based models. However, the kinds of representations and the approaches to variations seem no longer the contrastive factors to differentiate these models, as each model continued to incorporate additional proposals into its previous framework. For instance, Boersma's (1998) functional model as part of perception-based models considered articulatory and lexical influences to be part of phonological grammars, and Best's (1995) direct-realist model also tried to incorporate lexical influences into her production-based framework. In other words, these models seem to contrast one another crucially in degrees of accessibility to various kinds of representations and grammars. The accessibility to each representation may lead to a different pattern in speech processes to some extent. In addition, as discussed above, variations are no longer restricted to a phonetic level, and as this dissertation will show, they are common and extensive at various levels of tonal modifications in Hai-lu Hakka. A fitting model of speech processing is required to account for variations of different kinds. Since the exemplar model attends to variations at multiple levels, we consider it a fitting model for this dissertation's concerns and provide further discussion in the following section.

3.2.4 The exemplar-based models

As indicated by Johnson (2007), the exemplar-based models have been considered a crucial approach to human memory for at least a hundred years, and have gradually taken shape from Hintzman's (1986, 1988) MINERVA model: a simulation theory of human memory. They were applied to spoken word recognition by Goldinger (1996, 1998), and were later introduced to linguistic theory in recent decades. The exemplar-based models have developed from two common characteristics into some different proposals. The two common characteristics refer to multiple traces and exemplars, and the different proposals include (i) whether there are some kinds of linguistic generalizations other than exemplars, (ii) whether there are some kinds of probabilistic distribution, (iii) whether exemplars are represented by sounds or words, and (iv) how many dimensions exemplars are represented in.

3.2.4.1 The common characteristics: multiple traces and exemplars

The exemplar-based models have two common characteristics: multiple traces and exemplars. As generalized from Goldinger (1996) and Johnson (2007), exemplars are tokens of experiences (i.e., sounds or words), and traces are episodic details of tokens. The episodic details consist of various kinds of information, such as gender, voice quality, and other talker variations. The multiple episodic traces are stored in exemplars represented as a fundamental unit of lexical memory. Their detailed information makes it possible for variations of different kinds to be stored and represented accordingly, and therefore they are crucial to the exemplar-based models.

The multiple episodic traces and exemplars are different from an abstractionist view, since they do not require acoustic signals to be normalized and specified as canonical categories in speech processes. The difference involves two potential issues: the level issue and the representation issue. As to the level issue, the episodic traces and exemplars were considered evidence to argue against a hierarchical relation between speech processes and serial derivations. As discussed in section 3.2.2.1, they support simultaneous processes, such as parallel or network processes. As to the representation issue, they were arguably less abstract than features, constraints and other perceptual abstractions. In addition to the degree of abstractness, they are different from perceptual abstractions and articulatory gestures in two more senses. First, the exemplars and traces can be processed as a whole rather than as separate pieces. For instance, articulatory gestures were also argued to be less abstract than features and constraints, but they are still a separate piece of sounds or words. There is somehow a gap between gestures and words, and it is not clear how to represent sounds and words as articulators. Second, their episodic characteristics themselves carry lexical meanings. It is less likely for perceptual abstractions and articulators to carry meanings in the same sense. In other words, the multiple episodic traces and exemplars seem less abstract than two other representations in terms of structures and meanings.

3.2.4.2 The differences: other phonological generalizations or not?

As mentioned above, the exemplar-based models have gradually developed into four different proposals. The four proposals mostly concern the representation issue: (i) more phonological generalizations other than exemplars or not, (ii) probabilistic distribution or not, (iii) exemplars of sounds or words, and (iv) more information other than auditory dimensions, or not. For instance, Johnson (2007) indicated that exemplars should be represented by words (Johnson 2006, 2007), and others argued for sounds as representation of exemplars (Pierrehumbert 2001, 2003). Johnson (2007) also indicated that ideal exemplars not only carry auditory dimensions, but also include visual and articulatory information in some cases. The influences of visual information were supported by Good's (2008) findings on child's phonological acquisition of English intonation.

As shown in Figure 3.5 below, there are three different kinds of exemplar-based models that contrast in the proposals of phonological generalizations and probabilistic distribution, especially the question on additional phonological generalizations to exemplars. Approach A argues for no additional generalizations to exemplars, and seldom discusses the probabilistic effect (Goldinger 1996, 1998). Approach B also argues for no additional generalizations, but tries to incorporate probabilistic distribution into its framework (Port 2007). Approach C argues for additional phonological generalizations as well as probabilistic distribution to exemplars (Pierrehumbert 2001, 2003; Pisoni & Levi 2007). For instance, Pierrehumbert (2001, 2003) argued that exemplars consist of three probabilistic generalizations as phonological codes: phonetic tokens, phonological constraints, and morpho-phonological alternations. These phonological codes are defined by three levels of probabilistic distribution (chances: token frequency < type frequency < word frequency) that may exert a potential influence on lexical access. In other words, they seem to be less abstract than previously assumed, and they affect different kinds of frequency factors. As to Port (2007), exemplars only contain concrete and detailed auditory codes, and phonological generalizations are not useful for lexical access. Each exemplar carries its own frequency information automatically, which indicates a one-by-one correspondence between frequency of occurrence and exemplars. In other words, it seems to account for variations of different kinds by exemplars.

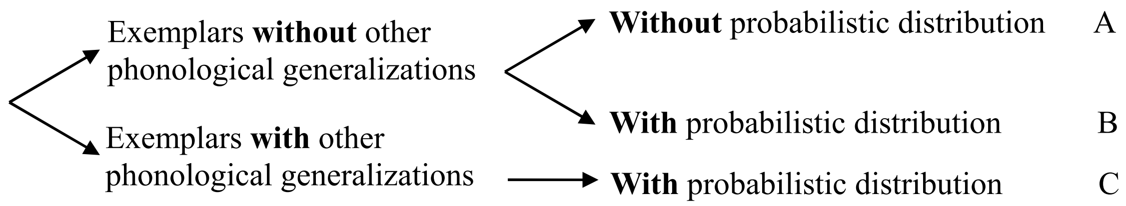

Figure 3.5 Three different kinds of exemplar-based models: a. exemplars without other generalizations and probabilities, b. exemplars with probabilities, but without other generalizations, c. exemplars with other generalizations and probabilities.

It is debatable whether it is necessary for episodic traces and exemplars to integrate other phonological generalizations, such as phonetic tokens, phonological constraints, and morpho-phonological alternations, proposed by Pierrehumbert (2001, 2003), in speech processing. As indicated by Johnson (2007), people might have misunderstood that exemplar-based models may not exhibit effects of prototypes or effects of other generalizations, but exemplar-based systems do exhibit some generalization characteristics and patterns. The question is whether the generalization-like patterns arise from exemplars themselves or other generalizations stored in each exemplar. It is likely to distinguish the effects of phonological generalizations from those of lexical exemplars by examining the phonetic/phonological effects on novel words. In general, Pisoni & Levi (2007) concluded that it is more likely that both exemplars and generalizations should be considered in speech processing.

3.2.4.3 The exemplar-based approach to speech processing

The exemplar-based approach to speech processing generally argues for three principles: (i) multiple episodic traces in various dimensions, (ii) exemplar-based processes, and (iii) simultaneous activation in a network relation, in contrast to other models. The multiple episodic traces refer to various kinds of information, such as auditory, articulatory, and visual, and their direct engagement spares a transition from variations to invariance. These traces are stored and represented altogether in a fundamental unit of memory, known as exemplars, and the exemplar-based processes make unnecessary serial derivations from acoustic inputs to lexical memory. In other words, the exemplar-based processes constitute simultaneous networks which activate similar traces and exemplars all at once for lexical access (Johnson 2007). The exemplar-based processes also tend to favor a processing strategy based on lexical memory, known as the top-down strategy. These exemplar-based principles are illustrated in Figure 3.6 below.

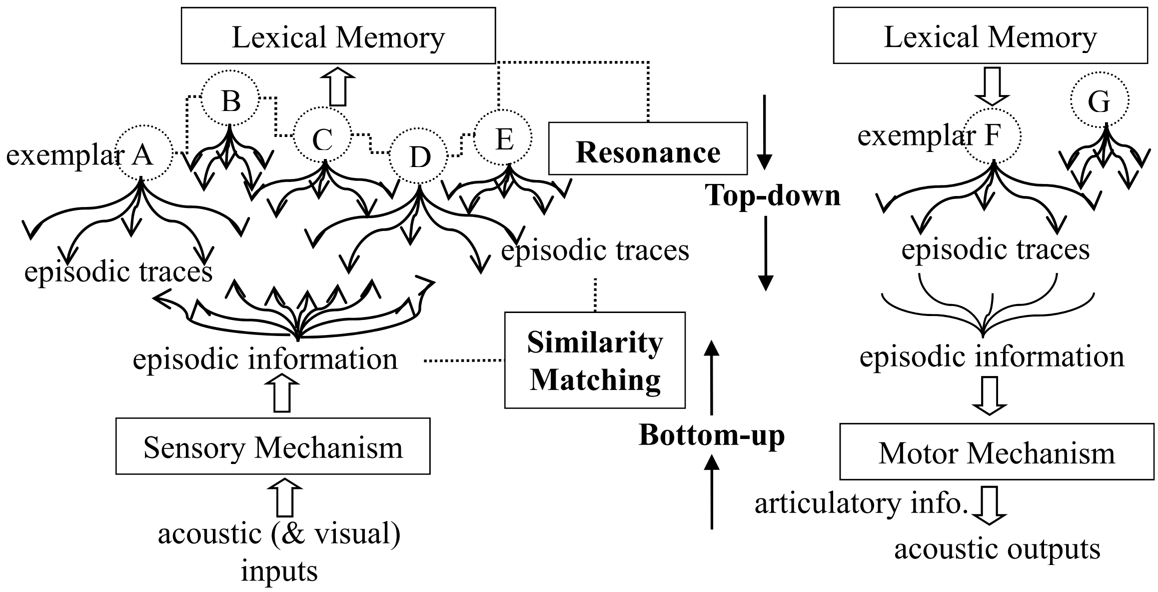

Figure 3.6 The exemplar-based framework of speech perception (left) and speech production (right).

As shown in Figure 3.6 above, the left side illustrates perceptual processes, and the right side illustrates speech production. In speech perception, speech signals are processed as acoustic and visual inputs from speakers to listeners by sensory mechanism (both auditory and visual systems). These speech inputs carry various kinds of episodic information from a specific context. As indicated by Johnson (2007), there is similarity matching between current information and previous experiences that are stored and represented as multiple traces in exemplar-based memory. The similarity matching is operated on the basis of exemplars in a probabilistic manner, and both the degrees of linguistic similarity and frequency of occurrence determine the result of lexical access. There is also an exemplar resonance mechanism that activates a set of similar exemplars (e.g., exemplar A, B, C, D, E, etc.) simultaneously to enhance similarity matching. Johnson (2007) indicated that the simultaneous activation spreads through a set of similar exemplars via non-phonetic properties, and it creates a resonance loop to exert a beneficiary effect from exemplars on lexical access. In other words, the resonance loop makes it likely to apply a top-down strategy.

Speech production tends to be considered the reversal of perceptual processes, as it starts from lexical memory to acoustic outputs. As shown in the left part of Figure 3.6, lexical memory is retrieved, and it activates some similar exemplars (e.g., exemplar F, G, etc.). The exemplar's multiple episodic traces are also activated simultaneously, and are sent to motor mechanism. Then the multiple traces are implemented into acoustic outputs accordingly. Most exemplar-based models argued that articulatory information may play a role in phonetic implementation, and it may account for a potential difference between perception and production processes.

3.3 Theoretical implications and research hypotheses

This chapter first discusses the previous assumptions on tonal contrasts and tone sandhi, and refers the two assumptions as the distinctiveness issue and the productivity issue. Some recent challenges indicated a potential role of variations in tonal processing, and raised the classification issue that relates different tonal variations/modifications to linguistic derivations/processes. In order to deal with the classification issue, this chapter compares different proposals of speech processing, and points out two crucial arguments that define phonetics and phonology by processing levels and processing representations. The two crucial issues differentiate the three processing models: the functional model, the direct-realist model, and the exemplar-based model. This dissertation's results may not only clarify the two previous assumptions, but also shed light on the classification issue by evaluating a fitting model to speech processing.

Based on the previous findings and the potential role of variations, this dissertation proposes three general hypotheses to answer the two research questions as to whether variations play a role in Hai-lu Hakka's contrast of falling tones and application of tone sandhi. As indicated in (23) below, the three hypotheses are: a. the lexical hypothesis, b. the phonetic/phonological hypothesis, and c. the interaction hypothesis. Each of these hypotheses has two subsets: (i) various effects on the contrast of two falling tones and (ii) various effects on the application of tone sandhi.

(23) The dissertation's three general hypotheses

a. The lexical hypothesis: Lexical factors exert an influence on tonal variations, and affect Hai-lu Hakka speakers' tonal processing.
   (i) The lexical factors affect the perception of the tonal contrast between high-falling tone and low-falling tone.
   (ii) The lexical factors affect the application of low-rising tone sandhi and high-checked tone sandhi.

b. The phonetic/phonological hypothesis: Phonetic and phonological factors exert an influence on tonal variations, and affect Hai-lu Hakka speakers' tonal processing.
   (i) The phonetic/phonological factors affect the perception of the tonal contrast between high-falling tone and low-falling tone.
   (ii) The phonetic/phonological factors affect the application of low-rising tone sandhi and high-checked tone sandhi.

c. The interaction hypothesis: Lexical and phonetic/phonological factors interact with each other to affect Hai-lu Hakka speakers' tonal processing.

(i) The interaction between lexical and phonetic/phonological factors affects the perception of the contrast between high-falling tone and low-falling tone.

(ii) The interaction between lexical and phonetic/phonological factors affects the application of low-rising tone sandhi and high-checked tone sandhi.

The lexical hypothesis (23a) indicates that lexical factors, such as word types and lexical frequency, exert an influence on the contrast of falling tones and the application of tone sandhi. They are likely to affect how Hai-lu Hakka speakers perceive and produce different tonal variations. Based on the exemplar-based model, tonal variations are stored and represented in detail as multiple episodic traces in exemplars. Tonal variations, from acoustic inputs to lexical memory and from lexical memory to acoustic outputs, are processed by similarity matching in a probabilistic manner. These processes are exemplar-based, and the exemplar-based processes make it likely for exemplars to exert an influence. Since lexical factors are crucial to exemplars, they are argued to play a role in similarity matching and other processes. Therefore, lexical factors are predicted to affect the contrast of falling tones and the application of tone sandhi.

The phonetic/phonological hypothesis (23b) indicates that phonetic and phonological factors, such as pitch height and prosodic types, exert an influence on the contrast of falling tones and the application of tone sandhi. They are likely to affect how Hai-lu Hakka speakers perceive and produce different tonal variations. Based on the exemplar-based model, various kinds of phonetic and phonological information are stored and represented as multiple episodic traces in exemplars. The exemplar-based processes (or other phonological generalizations per se) make it likely for these phonetic and phonological factors to exert an influence on speech processes. As a result, phonetic and phonological factors are hypothesized to exert an influence.

The interaction hypothesis (23c) indicates that lexical factors interact with phonetic and phonological factors to exert an additional influence, and their interaction is likely to affect how Hai-lu Hakka speakers perceive and produce different tonal variations. Based on the exemplar-based model, listeners may apply two different processing strategies to tonal variations: a bottom-up strategy and a top-down strategy. The two strategies work via different linguistic properties: phonetic information for the bottom-up process and non-phonetic knowledge for the top-down process, as indicated by Johnson (2007). The two strategies make it likely for listeners to deal with tonal variations by focusing on either kind of factors. When they focus on either kind of factors, they may reinforce this specific kind of effects. In other words, the processing strategies give rise to the interaction effect. As a result, the interaction effect is hypothesized.

In general, tonal variations are hypothesized to play a role in Hai-lu Hakka's contrast of falling tones and application of tone sandhi. They are argued to exert a lexical influence, a phonetic/phonological influence, and an interaction effect on Hai-lu Hakka speakers' perception and production results. Although it is not easy to compare the exemplar-based models to the functional model and the direct-realist model by the three hypotheses, it is likely to evaluate the three primary models by the level issue and the representation issue. The dissertation's results may point to a more reasonable relation of processing levels and a more crucial type of processing representations. Although the level and representation issues not hypothesized currently, they could be potential indicators of a fitting model to speech processing.

CHAPTER FOUR

THE CONTRAST OF TWO FALLING TONES

This dissertation examines how variations influence two Hai-lu Hakka's tonal patterns: the contrast of two falling tones and the application of two tone sandhi rules. Chapter 4 focuses on the role of three pitch variations (i.e. onset-pitch variations, offset-pitch variations, and overall-pitch variations) in the tonal contrast. The current methods include 30 Hai-lu Hakka participants and two perceptual tasks (i.e. a tonal identification task and a lexical recognition task). The results indicate that (i) both lexical and phonetic/phonological factors play a role in the tonal contrast and that (ii) the tonal contrast varies crucially with onset-pitch height rather than offset-pitch and overall-pitch height. In addition, these pitch variations are found to play a different role in tonal and lexical processing, indicating (iii) an interaction between phonetic and lexical factors. These findings suggest that variations induced by tonal co-articulation and other contextual factors affect the contrast of falling tones, giving rise to some tonal confusion. Therefore, this chapter indicates that some tonal contrasts are not as distinctive as assumed previously due to the effects of phonetic/phonological variations on tonal processing.

4.0 Introduction

This chapter investigates the role of pitch variations in Hai-lu Hakka's contrast of falling tones (Tone-53: high-falling tone vs. Tone-31: low-falling tone). Since Hai-lu Hakka's tonal patterns were less investigated previously, it is unclear whether the tonal contrast varies in different conditions and what may affect the tonal contrast. According to recent findings (Hsu 2009; Jiang 2003; Yeh & Lin 2011, 2012), the two falling tones may be confused as each other for three reasons. First of all, Lo (1990: 184) indicated that the falling tones have similar pitch contour, and they contrast crucially in pitch height. Second, Jiang (2003) indicated that high-falling tone tends to be co-articulated with neighboring tones, and the tonal co-articulation effect gives rise to many pitch variations. Third, they are found to be common in speech errors. The three reasons are further discussed as follows.

First, Hai-lu Hakka's falling tones (Tone-53 vs.Tone-31) are intrinsically similar in pitch contour, and contrast crucially in pitch height (high vs. low). As illustrated in Figure 4.1 below, they share several acoustic correlates: a. onset-pitch height, b. offset-pitch height, c. pitch drop, and d. pitch contour. The onset-pitch height refers to the peak *f0* of initial pitch height. The offset-pitch height refers to the valley *f0* of ending pitch height. The pitch drop refers to the difference between the peak *f0* and the valley *f0*. The peak and the valley rarely occur at the very beginning and the very end. The pitch contour refers to the shape of overall *f0* change. As to the four characteristics, the two falling tones are similar in offset pitch and pitch contour, while they are more contrastive in onset pitch and pitch drop. Lo (1990: 184) indicated that their phonetic similarity may cause Hakka speakers to confuse one with the other.

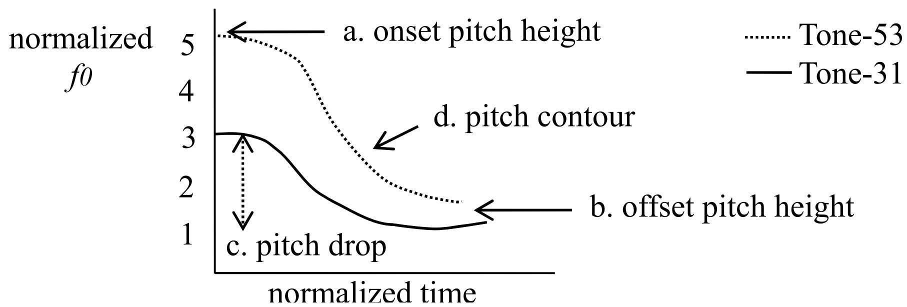

Figure 4.1 Acoustic correlates of Hai-lu Hakka's two falling tones: Tone-53 high-falling tone (dotted line) and Tone-31 low-falling tone (black line).

Second, Hai-lu Hakka's falling tones have many tonal variations induced by different factors, and these different variations may make more similar the two falling categories than their original dimensions. As discussed in section 2.1 and 2.3 above, the falling tones have at least two kinds of tonal variations: (i) phonetic variations derived from tonal co-articulation and (ii) morpho-phonological variations derived from derivational alternations. As to the phonetic variations, Jiang (2003) indicated that high-falling tone tends to be co-articulated with neighboring tones in connected speech. As indicated in (24a) below, high-falling tone's offset pitch tends to be assimilated to following tones' onset-pitch height. The higher the following tones' onset pitch, the higher the high-falling tone's offset pitch will be. This tonal co-articulation effect gives rise to variations such as Tone-5**4**[2] (cf. Tone-53). As indicated in (24b), high-falling tone's onset pitch also tends to be assimilated to preceding tones' offset-pitch height. The lower the preceding tones' offset pitch, the lower the high-falling tone's onset pitch will be. This tonal co-articulation effect gives rise to variations such as Tone-**4**3 (cf. Tone-53). As to the morpho-phonological variations, Lo (1990: 186-188) indicated that the two tones change one into the other as derivational devices in a few words. For instance, the low-falling word [tʂɔŋ**31**] 'to fit' becomes high-falling [tʂɔŋ**53**] as a noun in 'China'. These different variations may cause Hakka speakers to confuse one falling tone with the other.

(24) Two pitch variations of high-falling tone in Hai-lu Hakka

a. Higher offset-pitch height when preceding high tones, e.g. Tone-54.

b. Lower onset-pitch height when following low tones, e.g. Tone-43.

Third, although Hai-lu Hakka's speech errors were barely investigated by previous studies, the two falling tones tend to be mispronounced as each other, especially from low-falling tone to high-falling tone. For instance, some radio-station hosts consistently mispronounced the very frequent low-falling word [tʰaŋ**31**] 'to hear, to listen' as high-falling [tʰaŋ**53**]. Some extreme cases even show that such mispronunciations may lead to sound change in particular words. This specific sound change is called [va31-ʐim53] 'gliding sound' in Hai-lu Hakka.

[2] Although these high-falling-tone variants are illustrated as a category such as Tone-54 and Tone-43, they are derived from tonal co-articulation.

For instance, the low-falling word [hɪɛn**31**] ‘smell’ is consistently mispronounced as high-falling [hɪɛn**53**] in this particular compound [tʂʰju31-ɲjau22-hɪɛn**53**] ‘stinky-urine-smell,’ and remains unchanged in other words, such as [tʂʰju31- so53-hɪɛn**31**] ‘foul smell’. These cases indicate that some Hakka speakers may have difficulty in differentiating the two falling tones.

To sum up, these current findings indicate that Hai-lu Hakka’s two falling tones are intrinsically similar in pitch contour, and they are contrastive crucially in pitch height. They tend to be co-articulated with neighboring tones, and the co-articulation effect gives rise to many pitch variations. The tonal variations may distort the two tones’ crucial contrast in pitch height. In other words, the effects of phonetic similarity and tonal co-articulation may account for the two tones’ common occurrence in speech errors. They may also cause Hakka speakers to confuse one falling category with the other. Therefore, these findings motivate this dissertation to examine the potential role of pitch variations in the tonal contrast.

4.1 Tonal confusion between high-falling and low-falling tones

Previous studies (Garding et al 1986; Li 2012; Yeh 2009; Yeh & Lin 2011, 2012; Yeh & Tu 2012; Yeh et al 2013) found that tonal confusion between high-falling and low-falling tones occurs in Taiwan Mandarin, Taiwan Southern Min, and Zhengjiang dialects. For instance, Yeh (2009) and Yeh & Lin (2011) examined effects of three pitch variations such as onset-pitch variations, offset-pitch variations, and pitch-drop variations on 30 Taiwan Mandarin speakers’ contrast of T3 (low-falling tone) and T4 (high-falling tone). Their results indicated that onset-pitch variations and pitch-drop variations significantly affect the tonal contrast. Yeh & Lin (2012) and Yeh et al (2013) examined the same pitch variations in Taiwan Southern Min (Tone-51 vs. Tone-21) and Zhengjiang dialects (Tone-42 vs. Tone-31) respectively. Their results also indicated that onset-pitch variations and pitch-drop variations play a crucial role in the tonal contrast. In addition, they pointed out the potential role tone sandhi may play in distinguishing the two falling tones. These findings suggest that different pitch variations (both phonetic and phonological) play a role in the tonal contrast as they may result in tonal confusion between high-falling and low-falling tones in many Chinese languages.

Lo (1990:184) indicated that Hai-lu Hakka's Tone-53 and Tone-31 can be difficult for L1 speakers to identify accurately. Since the two tones both consist of a falling contour, their similar pitch contour may cause Hakka speakers to confuse one as the other. However, it is still unclear whether the similar pitch contour leads to tonal confusion between Tone-53 and Tone-31 in Hai-lu Hakka. One of the reasons is that Hai-lu Hakka's tonal patterns have been less investigated by previous studies, comparing to other Chinese languages, as summarized in Table 4.1 below.

Table 4.1 Summary of previous studies on tonal confusion between high-falling tone and low-falling tone.

Languages	Studies	Approaches	Potential factors
Hakka	Lo (1990)	descriptive analysis	similar pitch contour
Taiwan Mandarin	Li (2012)	perception	prosodic positions
	Garding et al (1986)	perception	onset pitch contour
	Miracle (1989)	production	pitch register errors
	Wang (2011)	production	tonal misperceptions
	Wang et al (2003)	production	pitch register errors
	Wong et al (2005)	production	phonetic similarity
	Yeh (2009)	perception	onset pitch & pitch drop
	Yeh & Lin (2011)	perception	onset pitch & pitch drop
Taiwan Southern Min	Liu & Wang (2008)	production	tone sandhi
	Yeh & Tu (2012)	production	similar pitch contour & tone sandhi
	Yeh & Lin (2012)	perception	onset pitch, pitch drop & tone sandhi
Zhengjiang	Yeh et al (2013)	perception	onset pitch & pitch drop

In order to examine the potential role of variations in Hai-lu Hakka's falling-tone contrast, this dissertation poses three research questions. As indicated in (25) below, the three research questions are: a. the lexical effect, b. the phonetic/phonological effect, and c. the interaction effect. As indicated in (25b), the second question concerning the phonetic/phonological factors consists of three subset questions: (i) the effect of onset-pitch variations, (ii) the effect of offset-pitch variations, and (iii) the effect of overall-pitch[3] variations, based on the previous findings (Yeh 2009; Yeh & Lin 2011, 2012; Yeh et al 2013).

(25) Three research questions on the contrast of falling tones

a. The lexical effect: Does the contrast of two falling tones vary with lexical factors, such as word types and lexical frequency, in Hai-lu Hakka?

b. The phonetic/phonological effect: Does the contrast of two falling tones vary with phonetic/phonological factors, such as pitch variations, in Hai-lu Hakka?

   (i) The onset-pitch effect: Does the contrast of two falling tones vary with onset-pitch variations in Hai-lu Hakka?

   (ii) The offset-pitch effect: Does the contrast of two falling tones vary with offset-pitch variations in Hai-lu Hakka?

   (iii) The overall-pitch effect: Does the contrast of two falling tones vary with overall-pitch variations in Hai-lu Hakka?

c. The interaction effect: Does the contrast of two falling tones vary with the interaction between lexical and phonetic/phonological factors in Hai-lu Hakka?

As indicated in (25a) above, the first question concerns the lexical effect on the tonal contrast in Hai-lu Hakka. According to the previous findings (Yeh 2009; Yeh & Lin 2011, 2012; Yeh et al 2013), word types and lexical frequency play a role in tonal perception. The previous findings indicated that the more frequent the lexical responses, the more likely the

[3] The term of overall-pitch variations is adopted to replace that of pitch-drop variations used by previous studies (Yeh 2009; Yeh & Lin 2011; Yeh & Lin 2012; Yeh et al 2013), as suggested by Dr. Daniel Hirst in the International Conference on Phonetics of the Languages in China (ICPLC2013). The three kinds of pitch variations involve both pitch-height and pitch-drop changes, and it is misleading to call one particular kind as ‘pitch-drop’ variations. In addition, the ‘pitch drop’ of pitch-drop variations is not controlled. Therefore, we use ‘pitch-drop’ variations for previous findings, and currently use ‘overall-pitch’ variations to avoid misunderstandings.

responses will be chosen. As to the word types, actual words (cf. non-words) were also found to enhance tonal perception. Hence, lexical factors may affect the contrast of falling tones in Hai-lu Hakka.

As indicated in (25b) above, the second question concerns the phonetic/phonological effect on the tonal contrast in Hai-lu Hakka. According to the previous findings (Yeh 2009; Yeh & Lin 2011, 2012; Yeh et al 2013), three kinds of pitch variations (i.e. onset-pitch variations, offset-pitch variations, and pitch-drop variations) affect the contrast of falling tones in Taiwan Mandarin, Taiwan Southern Min, and Zhengjiang dialects. Onset-pitch and pitch-drop variations are more crucial to the tonal contrast, but offset-pitch variations also play a role in some particular cases (e.g. in a sandhi condition). Since Hai-lu Hakka's two falling tones contrast crucially in pitch height, pitch variations may also play a role in the tonal contrast.

As indicated in (25c) above, the last question concerns the interaction effect on the tonal contrast in Hai-lu Hakka. According to Yeh & Lin (2012) and Yeh et al (2013), offset-pitch variations are less crucial to the contrast of falling tones, but they may play a more significant role in lexical recognition than in tonal identification. The finding indicates that lexical processing elicits an additional or enhanced influence of offset-pitch variations on the tonal contrast. The additional influence seems to result from the interaction between lexical and phonetic/phonological factors. Such an interaction may also exert an additional influence on the tonal contrast in Hai-lu Hakka.

4.2 Hai-lu Hakka's two falling tones

Hai-lu Hakka's falling tones are phonetically similar in pitch contour. As discussed above, the phonetic similarity may cause Hai-lu Hakka speakers to confuse one with the other. The two tones contrast crucially in pitch height, and the tonal contrast may decrease due to the influence from pitch-height variations. Those pitch variations may make more phonetically similar the two intrinsically resembling categories. In other words, they are more likely to result in tonal confusion between the two falling tones. In order to examine the role variations play in the tonal contrast, this section first introduces the two falling tones' potential variations in section 4.2.1, and then proposes three hypotheses regarding different effects of tonal variations in section 4.2.2.

4.2.1 Tonal variations of Hai-lu Hakka's falling tones

Hai-lu Hakka's falling tones may undergo two kinds of tonal modifications: (i) tonal co-articulation at the phonetic level and (ii) morpho-phonological alternations at the morphological level. The phonetic factors include neighboring tones (preceding tones, following tones, and both), prosodic positions (word-initial, word-medial, and word-final), and prosodic boundaries (word-level, phrase-level, and sentence-level). The morphological factors include derivational devices, adjectival reduplication, and focus intonation. The two tonal influences give rise to different tonal variations, and those potential variations are illustrated in Table 4.2 below. Although it is less understood whether the falling tones are involved in any sandhi process, it is worth noting that the emerging pattern of low-rising tone sandhi may result in a new sandhi form as low-falling tone (derived from low-rising tone or low-level tone), as discussed in section 2.2.1 above.

Table 4.2 Different tonal variations of Hai-lu Hakka's falling tones.

	Tone-53 (High-falling tone)	Tone-31 (Low-falling tone)
Phonetic variations	1. High-falling tone with lower onset pitch 2. High-falling tone with higher offset pitch 3. High-falling tone with lower overall pitch	1. Low-falling tone with higher onset pitch 2. Low-falling tone with higher overall pitch
Phonological variations	n.a.	n.a.
Morpho-phono. alternations	1. High-falling tone as low-falling 2. High-falling tone as low-rising 3. High-falling tone as high-level	1. Low-falling tone as high-falling 2. Low-falling tone as rising 3. Low-falling tone as high-level

As to the three phonetic factors, they may change two falling tones' onset pitch, offset pitch, and overall pitch height to different degrees. For instance, as found by Jiang (2003), (i) high-falling tone's offset pitch tends to be higher in non-final position, especially when followed by high tones. As generalized from other languages (Peng 1997; Xu 1997, 2004), (ii) high-falling tone's onset pitch can be lower in non-initial position, especially when preceded by low tones, and (iii) low-falling tone's onset pitch can be higher, when preceded by high tones. In addition, (iv) two falling tones' overall pitch height can be lower in sentence-final position. These variations of pitch height were mostly found under a specific condition restricted to each phonetic factor. In fact, these phonetic factors are not mutually independent. They may collaborate to change two falling tones' pitch height to a wider extent. In other words, they are very likely to make intrinsically similar tones more phonetically similar, and may cause mutual confusion between two falling tones.

As to the three morphological factors, they may change two falling tones' onset pitch, offset pitch, and overall pitch height in some specific words to a more perceptible extent. As discussed in section 2.3 above, (i) high-falling tone may change to a lower pitch register, and low-falling tone may change to a higher pitch register as derivational devices in some words. (ii) The tone change as derivational devices also turns low-falling tone to a high-level-tone-like variant and to a low-rising-tone-like variant. In addition, (iii) both falling tones may become rising or high-level for adjectival reduplication and focus intonation. These morphological factors may cause two falling tones to sound like a similar category in some specific words. In other words, the morphological factors are also very likely to cause mutual confusion between the two falling tones, but they are lexically bound.

4.2.2 Hypotheses on the contrast of falling tones

Based on the discussions in section 4.1 and 4.2 above, three hypotheses are proposed accordingly below. As shown in (26), the three hypotheses are (a) the lexical hypothesis, (b) the phonetic/phonological hypothesis, and (c) the interaction hypothesis. The phonetic/phonological hypothesis includes three subset hypotheses that consider (i) onset-pitch height, (ii) offset-pitch height, and (iii) overall-pitch height to be the acoustic correlates between high-falling tone and low-falling tone.

(26) Three hypotheses on the contrast of falling tones

a. The lexical hypothesis: Lexical factors affect the (perceptual) contrast of two falling tones.

b. The phonetic/phonological hypothesis: Phonetic/phonological factors affect the (perceptual) contrast of two falling tones.

   (i) Pitch perturbations of **onset-pitch height** affect the contrast of two falling tones.

   (ii) Pitch perturbations of **offset-pitch height** affect the contrast of two falling tones.

   (iii) Pitch perturbations of **overall-pitch height** affect the contrast of two falling tones.

c. The interaction hypothesis: Phonetic/phonological factors affect the contrast of two falling tones in a different manner between tonal identification and lexical recognition due to different degrees of lexical access.

As shown in (26a), the lexical hypothesis concerns the lexical effect on the contrast of two falling tones. The lexical effect refers to the influence of lexical access to different degrees, such as word types and lexical frequency. The lexical influence is hypothesized to exert a significant influence on the tonal contrast, based on both empirical findings and theoretical assumptions. For instance, lexical frequency was found to be correlated to actuation of sound change (Bybee 2002; Phillips 1984). The lexical influence was also found to enhance perceptual accuracy and tonal production (Yang 2012). In addition, lexical exemplars were argued to be a processing fundament by Johnson (2007) and Pierrehumbert (2001, 2003).

Since the contrast of falling tones is arguably processed on the lexical basis, the degree of lexical access (various kinds of lexical factors) is hypothesized to exert an influence on the tonal contrast.

As shown in (26b), the phonetic/phonological hypothesis concerns the phonetic/phonological effect on the contrast of two falling tones. As indicated by Miracle (1989) and Wang et al (2003), pitch height, including onset pitch, offset pitch, and overall pitch height, was found to be a crucial correlate between high-falling tone and low-falling tone. The crucial correlate is susceptible to various contextual factors that may cause pitch height to vary. The variations of pitch height are very likely to make two falling tones more phonetically similar than their intrinsic dimensions, and hence may cause mutual confusion between the two falling tones. As a result, these various phonetic and phonological factors are hypothesized to exert an influence on the tonal contrast.

As shown in (26c), the interaction hypothesis concerns the interaction effect between lexical and phonetic/phonological factors on the contrast of two falling tones. As mentioned above, the interaction effect is defined by different results (i.e., patterns) of phonetic/phonological effects with different degrees of lexical access; for instance, a more significant role of offset-pitch variations in lexical recognition than in tonal identification. The interaction effect is hypothesized to exert an influence on the tonal contrast, based on both empirical findings and theoretical assumptions. First, based on Pierrehumbert's (2003) exemplar-based approach to language acquisition, young learners may apply phonetic learning to speech signals, and their strategy may change to stochastic learning when more lexical knowledge is available. Likewise, adult speakers may rely on phonetic/phonological knowledge with a minimal degree of lexical access, which was confirmed by Zhang et al (2011) that found a more significant role of phonetic factors in novel words than actual words. Second, as discussed in section 4.2.1 above, morphological factors are restricted to some specific words, and hence are lexically bound. They may result in additional variations that affect lexical recognition, but not tonal identification. As a result, the interaction effect is hypothesized to exert an influence on the tonal contrast.

4.3 Method

In order to verify the three general hypotheses shown in (26) above, multiple linguistic factors were set up as independent variables in the following experiment. The lexical factors include word types and lexical frequency. The word types refer to non-words (tonal categories) and actual words, which were set up as task types: tonal identification and lexical recognition. Lexical frequency refers to frequent and less frequent words, which is an intrinsic variable in each lexical response (a high-falling or a low-falling word). The two lexical responses themselves do not constitute an independent variable, since they not only differ in frequency variables, but also contrast with each other in two falling tones' acoustic correlates. The phonetic/phonological factors include variations of pitch height and different kinds of tonal modifications. The variations of pitch height refer to tonal changes in onset pitch, offset pitch, and overall pitch height, which were set up as three continua of stimuli. The tonal modifications of different kinds refer to phonetic, phonological, and morphological factors of tonal changes.

4.3.1 Participants

30 Hai-lu Hakka participants were recruited in the Hsinchu area of Taiwan. They are all Hakka-Mandarin bilinguals who speak Hai-lu Hakka on a daily basis. Their demographic background is shown below. As shown in Table 4.3 below, Hai-lu Hakka participants are generally older (40.5 years-old in average), and female (F) participants are more than male (M) participants (24 females > 6 males). The choice of older participants can avoid a potential effect of language attrition on the tonal contrast. As indicated by Hsiao (2007) and Yeh & Lu (2012), most young Hai-lu Hakka speakers no longer use their mother tongue on a daily basis, and tend to exhibit some attrition symptoms, such as misperceptions and

non-native accents. The attrition symptoms were found to exert a destructive influence on non-daily users' linguistic knowledge as well as speech processing. In order to avoid the attrition effect, fluent daily users were chosen, and most of them were in their late thirties. In addition, about half of these participants are Hai-lu Hakka instructors, and all of these instructors happen to be female. The gender difference was simply random.

Table 4.3 Demographic background of 30 Hai-lu Hakka participants.

Languages	N	Age range	Mean age	Gender
Hai-lu Hakka	30	24- 60 yrs	40.5 yrs	M: 6; F: 24

4.3.2 Stimuli

30 stimuli were synthesized from natural variations of falling tones by the Pitch Synchronous Overlap Add (PSOLA) of PRAAT (Boersma & Weenink 2009). They were considered to be naturalistic but controlled tokens, and were chosen to balance real-world and laboratory methods. These hybrid stimuli's control and independent variables were set up in reference to Yeh's (2009) acoustic analyses of T3 and T4 in Mandarin. Yeh (2009) recruited 10 Taiwan Mandarin participants (mean age: 28.1 yrs; 5 males and 5 females) to read di3 底 'bottom' and di4 弟 'younger brother' in a carrier phrase: *wo3 shi4 shuo***1** ____ *zhe***4** *ge zi4* 我是說____這個字 'It is ____ that I said,' and analyzed seven acoustic parameters, including onset pitch, offset pitch, actual pitch drop, F1 formants, F2 formants, syllable duration, and degree of glottalization. Then a T-test analysis was conducted to examine acoustic correlates between T3 and T4, and the results were shown in Table 4.4 below.

Table 4.4 Results of acoustic analyses on two falling tones (T3: low-falling tone and T4: high-falling tone) in Taiwan Mandarin.

		Onset *f0* (Hz)	Offset *f0* (Hz)	P. Drop (Hz)	F1 (Hz)	F2 (Hz)	Duration (ms)	Glottal. (%)
T3	max	145	102	45	320	2387	393	78.0
	min	116	87	28	267	2298	357	37.9
	avg	130	93	37	289	2346	369	58.7
T4	max	223	106	122	288	2535	399	57.1
	min	191	89	95	263	2399	361	14.8
	avg	207	97	110	276	2465	378	27.9
T-test		P< ***	p> 0.05	P< ***	P< *	P< ***	p> 0.05	P< ***

As shown in Table 4.4, T4 (as high-falling tone) has significantly (i) higher onset pitch, (ii) larger actual pitch drop, (iii) lower F1, (iv) higher F2, and (v) smaller degrees of glottalization than T3 (as low-falling tone). The five acoustic parameters seem to distinguish T3 and T4 in production, but not necessarily so in perception. For instance, Garding et al (1986) and Bent (2005: 139) found that glottalization is a concomitant of low tones, but the degrees of glottalization are not used to distinguish T3 from T4 in Mandarin. Since *f0* is the main cue for tonal perception (Yip 2002: 291), pitch-related parameters were synthesized as independent variables and non-*f0* parameters were set up as control variables.

4.3.2.1 Control variables

The 30 stimuli were made up by a constant [ti] syllable for two reasons. First, a simple syllable with an unaspirated voiceless onset and a high vowel makes it more likely to avoid potential effects of aspiration and vowel height on pitch height, as found by Lai (2004) and Lai & Su (2011). Second, the syllable rarely uses two falling tones as derivational devices in the Hai-lu Hakka, as demonstrated by Hsu (2009) and Lo (1990: 186-188), and it makes it more likely to avoid effects of morphological alternations on the tonal contrast so as to focus on phonetic and phonological factors. In addition to the syllable type, five other parameters, including intensity, syllable duration, F1 formants, F2 formants, and degrees of glottalization, were set up as control variables in 30 hybrid stimuli. As shown in Table 4.5 below, the 30 stimuli were made up by 80 dB in intensity, 380 ms in syllable duration, 270 Hz in F1 formants, 2450 Hz in F2 formants, and about 25% of glottalization.

Table 4.5 Control variables.

Variables	Intensity	Duration[4]	F1	F2	Glottalization
	80 (dB)	380 (ms)	270 (Hz)	2450 (Hz)	25 (%)

4.3.2.2 Independent variables

The 30 hybrid stimuli were made up by 10 10-Hz pitch variations in three independent variables: onset pitch, offset pitch, and overall pitch (i.e. 30= 10x 3). The 10 onset-pitch stimuli contrast one another in a 10-Hz pitch variation of onset pitch, with all the other variables being equal. That is, the 10 onset-pitch stimuli keep offset pitch constant at 90 Hz, and change in onset pitch from 100 Hz to 190 Hz, Similarly, the 10 offset pitch stimuli contrast one another in a 10-Hz pitch variation of offset pitch, and the 10 overall pitch stimuli contrast one another in a 10-Hz pitch variation of overall pitch. The 10-Hz pitch difference was determined by a maximum value of just noticeable difference found by previous studies (Li 2004; Yip 2002: 290-291).

The three independent variables were manipulated by a 10-Hz pitch difference to simulate each potential kind of tonal variations modified by various factors in a given context. These stimuli change in a 10-Hz actual difference as *f0* perturbations of onset pitch, offset pitch, and overall pitch in each tonal variation. The 10-Hz actual difference is constant in a physical dimension, but not in a perceptual manner. According to the Weber-Fechner Law, the perceived difference is promotional to the logarithm of the physical difference. In order to

[4] Although two anonymous reviewers from the 17th International Congress of Phonetics Sciences pointed out that high-falling tone is inherently short in syllable duration, the duration setup (380 ms) in this experiment did not disfavor or lower frequency rates of high-falling responses. In addition, as shown in Table 4.5, the syllable duration of high-falling tone was not found to be significantly shorter than that of low-falling tone in Mandarin.

indicate the logarithmic relation between actual and perceived 10-Hz differences, the three independent variables were translated into a conventional five-point scale by Bent's (2005: 126) equation in (27) below, and were further interpreted as musical notes in reference to Rasch & Plomp (1999).

(27) Equation for pitch normalizations

$$T=\frac{\log X-\log L}{\log H-\log H}\ x\ 5$$

As shown in (27) above, X is a given pitch value measured from a speaker; L is the lowest pitch measured from the same speaker; H is the highest pitch measured from the same one; and T refers to a log value which ranges from 0 to 5, and then the T value can be directly transformed into Chao's (1968) five-point scale: with 1 indicating the lowest pitch, and 5 the highest. For instance, the 30 stimuli's highest pitch is 210 Hz, and the lowest is 60 Hz. As these pitch values were put in the equation, a log value was derived accordingly. As shown in Table 4.6 below, the pitch values 60 and 70 Hz correspond to log values 0.00 and 0.62 respectively, and the T values from 0.00 to 0.99 correspond to 1 as the pitch scale, which indicates that the pitch values 60 and 70 Hz constitute a low pitch register among the 30 stimuli. Similarly, the pitch values 100, 110, and 120 Hz correspond to log values 2.04, 2.42, and 2.77 respectively, and the T values from 2.00 to 2.99 correspond to 3 as the pitch scale, indicating that the pitch values 100, 110, and 120 Hz constitute a middle pitch register. In addition, the table shows the pitch values in musical notes. According to Rasch & Plomp (1999), one octave includes eight musical notes, i.e., C, D, E, F, G, A, B, C_{+1}, which corresponds to 12 semitones, and one semitone corresponds to 100 cents, i.e., 1 octave= 8 notes= 12 semitones= 1200 cents. For instance, the pitch value 60 Hz corresponds to B_1-49 cents in the first octave, and the pitch value 110 Hz corresponds to A_2 in the second octave. The physical *f0* difference and perceived pitch difference is closely related in that the low pitch register almost corresponds to the first octave (except for 70 Hz), the mid-low and the middle pitch register correspond to the second octave, and the mid-high and the high pitch register correspond to the third octave.

Table 4.6 The logarithmic relation between *f0* and perceived pitch difference.

Actual *f0* (Hz)		Pitch scale & log value	In musical notes	
210	H	5 (5.00)	$G_3^{\#}$ +19 cents	3rd Octave
200		5 (4.81)	G_3 +35 cents	
190		5 (4.60)	$F_3^{\#}$ +46 cents	
180		5 (4.38)	$F_3^{\#}$ -47 cents	
170		5 (4.16)	F_3 -46 cents	
160	MH	4 (3.91)	$D_3^{\#}$ +49 cents	
150		4 (3.66)	D_3 +37 cents	
140		4 (3.38)	$C_3^{\#}$ +18 cents	
130		4 (3.09)	C_3 -11 cents	
120	M	3 (2.77)	B_2 -49 cents	2nd Octave
110		3 (2.42)	A_2	
100		3 (2.04)	G_2 +35 cents	
90	ML	2 (1.62)	$F_2^{\#}$ -47 cents	
80		2 (1.15)	$D_2^{\#}$ +49 cents	
70	L	1 (0.62)	$C_2^{\#}$ +48 cents	
60		1 (0.00)	B_1 -49 cents	1st Octave

The logarithmic relation between *f0* and perceived pitch difference indicates a strong pattern of fewer 10-Hz variations in a lower pitch register, and more 10-Hz variations in a higher pitch register. For instance, as shown in Table 4.6 above, there are two 10-Hz variations in the low and the mid-low pitch register (i.e., 60 and 70 Hz, 80 and 90 Hz), three in the mid pitch register (i.e., 100, 110, and 120 Hz), four in the mid-high pitch register (i.e., 130, 140, 150, and 160 Hz), and five in the high pitch register (i.e., 170, 180, 190, 200, and 210 Hz). The uneven pattern confirms the typical tendency of pitch perception: the same amount of pitch difference is more significant in a low pitch register, and less significant in a high pitch register. As shown in Figure 4.2 below, the same 10-Hz variations exhibit a wider distribution in a lower pitch register and in the first octave, and a narrower distribution in a higher pitch register and the third octave. The wider distribution means more perceptually different, and the narrower distribution means less different.

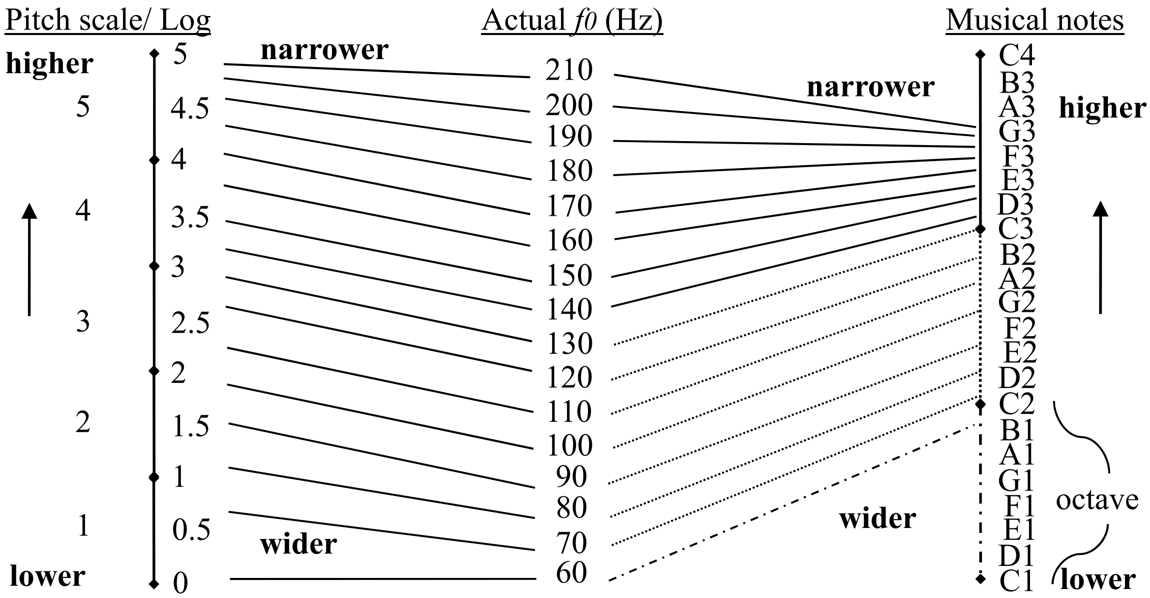

Figure 4.2 The logarithmic relation between *f0* and perceived pitch difference: (left) on a conventional five-point scale, and (right) in musical notes.

4.3.2.3 Three pitch-height continua

The 30 stimuli were classified into three continua by the three independent variables: onset pitch, offset pitch, and overall pitch. In the onset-pitch continuum, the 10 onset-pitch stimuli's initial pitch was manipulated by a 10-Hz variation, increasing from 100 Hz to 190 Hz as in stimulus#1 to stimulus#10, and their offset pitch stays constant at 90 Hz (a transition from a low pitch register to a mid-low level), as shown in Table 4.7 below.

Table 4.7 10 onset-pitch stimuli's pitch values, log values, and corresponding pitch scales.

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Onset p. (Hz)	100	110	120	130	140	150	160	170	180	190
Log value	2.04	2.42	2.77	3.09	3.38	3.66	3.91	4.16	4.38	4.60
Offset p. (Hz)	90	90	90	90	90	90	90	90	90	90
Log value	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
P. drop (Hz)	10	20	30	40	50	60	70	80	90	100
P. scale	32	32	32	42	42	42	42	52	52	52
P. register	ML	ML	ML	HML	HML	HML	HML	HL	HL	HL

As the onset pitch increases and the offset pitch remains the same, the pitch drop increases along with a 10-Hz variation of onset pitch. That is, the 10 onset-pitch stimuli are stimulus#1:

100-90 Hz with a 10-Hz drop, stimulus#2: 110-90 Hz with a 20-Hz drop, stimulus#3: 120-90 Hz with a 30-Hz drop, etc. As illustrated in Figure 4.3 below, the 10 onset-pitch stimuli increase in a 10-Hz variation of both onset pitch and pitch drop, from stimulus #n to stimulus #n+1. Then they were translated into a five-point scale. As shown in the last two row of Table 4.7 above, the first three onset-pitch stimuli were categorized as Tone-32; the four middle stimuli were categorized as Tone-42; and the last three stimuli were categorized as Tone-52. Based on these stimuli's pitch scale, the 10 onset-pitch stimuli were classified into three subsets: the lower onset-pitch group, the ambiguous onset-pitch group, and the higher onset-pitch group.

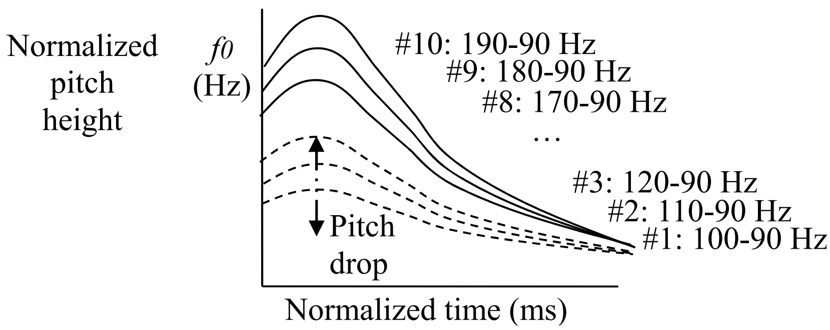

Figure 4.3 10 onset-pitch stimuli's pitch contour and other pitch variables in simulation.

In the offset-pitch continuum, the 10 offset-pitch stimuli's ending pitch was manipulated by a 10-Hz variation, increasing from 60 Hz to 160 Hz as in stimulus#1 to stimulus#10, and their onset pitch stays constant at 160 Hz (a transition from a mid-high pitch register to a high level), as shown in Table 4.8 below.

Table 4.8 10 offset-pitch stimuli's pitch values, log values, and corresponding pitch scales.

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Onset p. (Hz)	160	160	160	160	160	160	160	160	160	160
Log value	3.91	3.91	3.91	3.91	3.91	3.91	3.91	3.91	3.91	3.91
Offset p. (Hz)	60	70	80	90	100	110	120	130	140	150
Log value	0.00	0.62	1.15	1.62	2.04	2.42	2.77	3.09	3.38	3.66
P. drop (Hz)	100	90	80	70	60	50	40	30	20	10
P. scale	41	41	42	42	43	43	43	44	44	44
P. register	HL	HL	HML	HML	HM	HM	HM	HH	HH	HH

As the offset pitch increases and the onset pitch remains the same, the pitch drop decreases along with a 10-Hz variation of offset pitch. That is, the 10 offset-pitch stimuli are stimulus#1: 160-60 Hz with a 100-Hz drop, stimulus#2: 160-70 Hz with a 90-Hz drop, stimulus#3: 160-80 Hz with an 80-Hz drop, etc. As illustrated in Figure 4.4 below, the 10 offset-pitch stimuli increase in a 10-Hz variation of offset pitch, and decrease in a 10-Hz variation of pitch drop, from stimulus #n to stimulus #n+1. Then they were translated into a five-point scale. As shown in the last two row of Table 4.8 above, the first four offset-pitch stimuli were categorized as Tone-41 and Tone-42; the three middle stimuli were categorized as Tone-43; and the last three stimuli were categorized as Tone-44. Based on these stimuli's pitch scale, the 10 offset-pitch stimuli were classified into three subsets: the lower offset-pitch group, the ambiguous offset-pitch group, and the higher offset-pitch group.

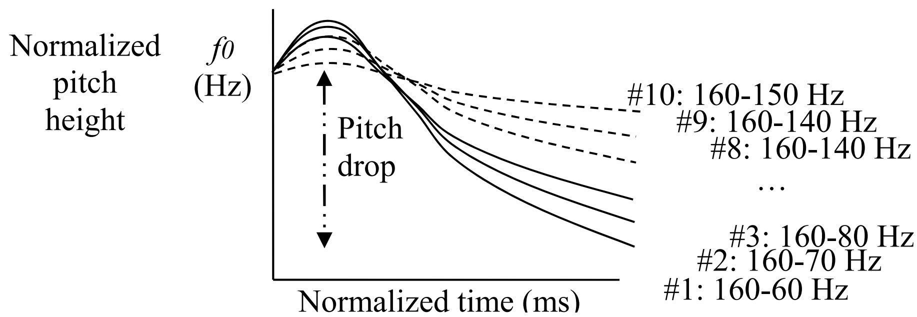

Figure 4.4 10 offset-pitch stimuli's pitch contour and other pitch variables in simulation.

In the overall-pitch continuum, the 10 overall-pitch stimuli's general pitch was manipulated by a 10-Hz variation, increasing from 120-60 Hz to 210-150 Hz as in stimulus#1 to stimulus#10, and their *f0* difference between onset pitch and offset pitch is the same as 60 Hz (an ambiguous difference based on the acoustic analysis in Table 4.4 above), as shown in Table 4.9 below.

Table 4.9 10 overall-pitch stimuli's pitch values, log values, and corresponding pitch scales.

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Onset p. (Hz)	120	130	140	150	160	170	180	190	200	210
Log value	2.77	3.09	3.38	3.66	3.91	4.16	4.38	4.60	4.81	5.00
Offset p. (Hz)	60	70	80	90	100	110	120	130	140	150
Log value	0.00	0.62	1.15	1.62	2.04	2.42	2.77	3.09	3.38	3.66
P. diff. (Hz)	60	60	60	60	60	60	60	60	60	60
P. scale	31	41	42	42	43	53	53	54	54	54
P. register	ML	HL	HML	HML	HM	HM	HM	HH	HH	HH

As the overall pitch increases with a 10-Hz variation, both the onset pitch and the offset pitch increases with the same amount of pitch variations, and the difference is the same as 60 Hz. That is, the 10 overall-pitch stimuli are stimulus#1: 120-60 Hz with a 60-Hz drop, stimulus#2: 130-70 Hz with a 60-Hz drop, stimulus#3: 140-80 Hz with a 60-Hz drop, etc. As illustrated in Figure 4.5 below, the 10 overall-pitch stimuli increase in a 10-Hz variation of both onset pitch and offset pitch, from stimulus #n to stimulus #n+1. Then they were translated into a five-point scale. As shown in the last two row of Table 4.9 above, stimulus#1 was categorized as Tone-31; stimulus#2 was categorized as Tone-41; the third and the fourth stimuli were categorized as Tone-42; stimulus#5 was categorized as Tone-43; the sixth and the seventh stimuli were categorized as Tone-53; and the last three stimuli were categorized as Tone-54. The 10 overall-pitch stimuli are more different in their pitch scale, and they were also classified into three subsets: the lower overall-pitch group, the ambiguous overall-pitch group, and the higher overall-pitch group.

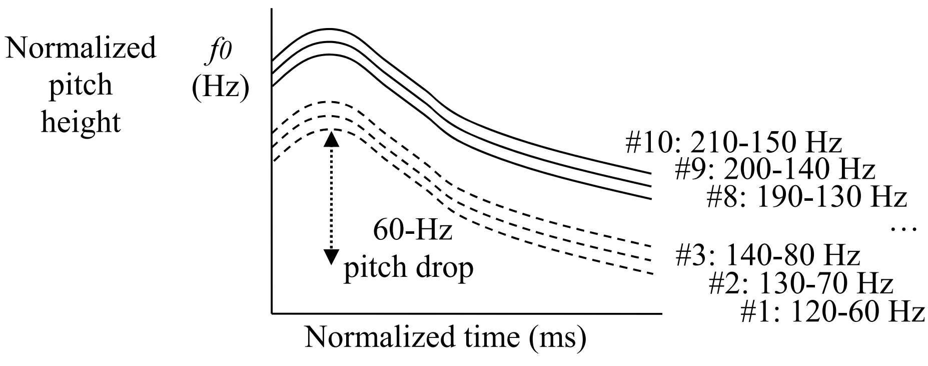

Figure 4.5 10 overall-pitch stimuli's pitch contour and other pitch variables in simulation.

4.3.3 Types of tasks

The experiment includes two perceptual tasks: a tonal identification task and a lexical recognition task. The tonal identification task requires participants to judge stimuli's pitch variations by tonal categories, whereas the lexical recognition task requires participants to judge stimuli's pitch variations by actual words. The two tasks were set up as lexical factors to contrast two word types: non-words and actual words. As mentioned above, the frequency variables were also considered, since token frequency and lexical frequency are intrinsic to the two tasks' tonal responses and lexical responses.

4.3.3.1 Tonal identification task

In the tonal identification task, 30 hybrid stimuli were presented at random, and each stimulus was repeated for four times, which makes 120 trials total (30 stimuli x 4 repetitions). Before the tonal identification task, there was a five-minute training session on Hai-lu Hakka's two falling categories: Tone-53 (high-falling tone) and Tone-31 (low-falling tone). The tonal training is indispensable, since Hai-lu Hakka participants had never learned any Hai-lu Hakka's tonal labels before. In order to avoid a potential training effect, the two falling tones were explicitly compared to Mandarin's falling categories T3 and T4. Based on the official teaching materials issued by the Council of Hakka Affairs in Taiwan (i.e., Chung et al 2008), Tone-53 was compared to T4 (Tone-51), and Tone-31 was compared to T3 (Tone-21). The tonal categories were instructed in three Hai-lu Hakka's minimal pairs: 夫 [fu53] 'husband' vs. 褲 [fu31] 'pants'; 知 [ti53] 'to know' vs. 帝 [ti31] 'emperor'; and 禿 [t^{h}u53] 'bald' vs. 兔 [t^{h}u31] 'rabbit'. After the training, all participants were given five practice trials in the [fu] minimal pair, i.e. [fu53] vs. [fu31], and they were permitted to proceed to the test trials only if they got the five practice trials correct.

In each identification trial, participants just heard one monosyllabic stimulus in isolation. They were explicitly told that all trials are forced-choice questions that require them to respond to either Tone-53 or Tone-31. After hearing each trial, they were asked to repeat the stimulus first, and then to answer orally whether they heard a high-falling category as T4, or a low-falling category as T3. After answering the trial orally, they were asked to click either ‘Tone-53 as T4’ or ‘Tone-31 as T3’ on the laptop screen. After clicking the response, they would hear the next trial in 500 ms. The tonal identification task is self-paced, with an optional one-minute break in the middle, and it takes about10 minutes.

4.3.3.2 Lexical recognition task

In the lexical recognition task, there are also 120 trials total, and the 120 trials are exactly the same as in the tonal recognition task. The trials were also presented at random. The only difference between the two tasks is the type of responses: tonal categories vs. actual words. Before the lexical recognition task, the two lexical responses, i.e., a low-falling word [ti31] in [fɔŋ55-ti31] ‘superior-emperor: emperor’ and a high-falling word [ti53] in [mï55-ti53] ‘not-know: don’t know,’ were explicitly instructed in Hai-lu Hakka to guarantee an equal access to lexical knowledge among all participants.

In each lexical recognition trail, participants just heard one monosyllabic stimulus in isolation. They were explicitly told that all trials are forced-choice questions that require them to respond to either [ti53] ‘to know’ or [ti31] ‘emperor’. After hearing each trial, they were asked to repeat the stimulus first, and then to answer orally whether they heard a high-falling word [ti53] ‘to know’ in [mï55-**ti53**], or a low-falling word [ti31] ‘emperor’ in [fɔŋ55-**ti31**]. It is worth mentioning that about five participants mispronounced [ti31] ‘emperor’ as [t^hi31] ‘to shave’. After answering the trial orally, they were asked to click either 不知的知 [ti53] of [mï55-**ti53**] ‘to know’ or 皇帝的帝 [ti31] of [fɔŋ55-**ti31**] ‘emperor’ on the laptop screen. After clicking the response, they would hear the next trial in 500 ms. The lexical recognition task is also self-paced, with an optional one-minute break in the middle, and it takes less than10 minutes.

4.3.4 Procedure

The experiment was conducted with Praat (Boersma & Weenink 2009) either in a computer lab or in a noise-free conference room otherwise. All participants were tested with a headphone (Sennheiser CX300ii) on a laptop (HP 6530b), and their responses were recorded digitally by the Praat scripts on the laptop. The two tasks were conducted in no specific order: half of 30 participants had the identification task first, and the others had the lexical task first. The two tasks take approximately 20 minutes total.

After the two perceptual tasks, participants were instructed to evaluate the two lexical responses' degrees of lexical familiarity by their own Hai-lu Hakka experience on a five-point scale, with 5 indicating the most familiar and 1 the least familiar. The degrees of lexical familiarity (also known as subjective lexical frequency) were considered to be lexical factors, in addition to objective lexical frequency, for two reasons. First, there have been no known corpus studies on Hai-lu Hakka. The only corpus study on Hakka languages was conducted by Chui & Lai (2009). However, the corpus includes very limited tokens (six recordings, and about 30 minutes for each), and its statistical analysis fails to distinguish Hai-lu Hakka from other Hakka varieties. The methodological difficulties make it somehow problematic to judge the objective lexical frequency of the two lexical responses based on Chui & Lai (2009). Second, previous studies on lexical access, such as Janssen et al (2008), Kreuz (1987), McDonald & Shillcock (2001), and Stadthagen-Gonzalez & Davis (2006), demonstrated that subjective familiarity ratings are usually highly correlated with objective frequency measures. Gernsbacher (1984) and Gelfand (2009: 254) even found that the subjective familiarity ratings may predict both percent accuracy and response time of lexical access in a better way than the actual word counts in a given corpus. As a result, both the subjective familiarity ratings and the actual word counts were considered to be frequency factors in this experiment. The current results show that the two lexical responses' subjective familiarity ratings are consistent with the actual word counts. The high-falling word [ti53] 'to know' is found to be significantly more frequent and more familiar than the low-falling word [ti31] ‘emperor’ to all Hai-lu Hakka participants.

4.3.5 Coding

30 participants’ tonal and lexical responses to 120 trials (30 stimuli x 4 repetitions) were analyzed in terms of 30 stimuli (10 variations x 3 independent variables). The 120 tonal responses were encoded as frequency rates (%) of Tone-31 (low-falling tone) in the tonal identification results, and the 120 lexical responses were encoded as frequency rates (%) of [ti31] ‘emperor’ (low-falling word) or [ti53] ‘to know’ (high-falling word) in the lexical identification results. Each participant’s frequency rates of each stimulus have only five possible values: 0%, 25%, 50%, 75%, and 100%. The value 0% refers to zero out of four repetitions, and it means that a participant never identifies a given stimulus as low-falling tone (or high-falling tone), or never recognizes that stimulus as [ti31] ‘emperor’ (or [ti53]). Similarly, the value 25% refers to one out of four repetitions, and it means that a participant identifies a given stimulus as low-falling tone, or recognizes that stimulus as [ti31] ‘emperor’ for one out of four times. Since all these trials are forced-choice questions, the two tonal responses are in complementary distribution, and so are the two lexical responses. For instance, three repetitions as Tone-31 indicate one repetition as Tone-53, and four repetitions as [ti31] ‘emperor’ indicate no repetition as [ti53] ‘to know’. Each participant’s frequency rates of each stimulus were calculated in average, and then the mean values were presented as the 10-variation continua of three independent factors in the following sections.

4.3.6 Detailed predictions

Based on the hypotheses in (26) above, the results of Hai-lu Hakka’s falling tones are predicted in detail as follows. The detailed predictions are summarized in Table 4.10 below.

Table 4.10 Detailed predictions for results of Hai-lu Hakka's falling tones.

Hypothesis	The contrast of two falling tones in Hai-lu Hakka
Lexical Hypothesis	(i) Frequency rates of tonal responses are significantly different from frequency rates of lexical responses (**an effect of word types**). (ii) Lexical responses to a high-falling word [ti53] 'to know' are more frequent than responses to a low-falling word [ti31] 'emperor' (**an effect of lexical frequency**).
Phonetic and Phonological Hypothesis	(i) There is a perceptual boundary in the onset-pitch continuum (**an effect of onset pitch**). (ii) There is **no** perceptual boundary in the offset-pitch continuum (**no effect of onset pitch**). (iii) There is a perceptual boundary in the overall-pitch continuum (**an effect of overall pitch**).
Interaction Hypothesis	(i) The phonetic/phonological effects are more significant in tonal identification results than in lexical recognition results, and/or… (ii) The phonetic/phonological effects exhibit a different pattern between tonal identification and lexical recognition results.

As to the lexical hypothesis, the effects of word types (tonal categories vs. actual words) and lexical frequency (frequent vs. less frequent) are hypothesized, and predict two particular results. First, the effect of word types predicts that frequency rates of lexical responses are significantly different from frequency rates of tonal responses, since the two types of responses provide participants with different kinds of knowledge to process tonal variations. In addition, the two tonal categories and the two actual words have different levels of frequency factors: token frequency vs. lexical frequency. Hsu (2009:48) indicated that Tone-53's token frequency is slightly higher than Tone-31's, i.e. 1032 (22.54%): 772 (16.86%), whereas Chui & Lai (2009) indicated that [ti53]'s lexical frequency is significantly higher than [ti31]'s. The frequency factors may also result in the difference between lexical responses and tonal responses. Second, lexical frequency is an intrinsic factor of lexical responses, and it may also exhibit an influence on lexical results. The effect of lexical frequency indicates that the more frequent the lexical item, the more likely it will be chosen from lexical access (as responses to a given stimulus). In other words, it predicts that the more frequent high-falling word [ti53] 'to know' is more likely to be chosen as lexical responses than the less frequent low-falling word [ti31] 'emperor'.

As to the phonetic/phonological hypothesis, the effects of onset pitch and overall pitch are hypothesized, but the effect of offset pitch is not. The effects of onset pitch and overall pitch are hypothesized, since the two pitch variables were found to contrast Hai-lu Hakka's two falling tones. The higher the onset-pitch variations, the more likely they will be perceived as high-falling categories. The lower the onset-pitch variations, the more likely they will be perceived as low-falling categories. Similarly, the higher the overall-pitch variations, the more likely they will be perceived as high-falling categories. The lower the overall-pitch variations, the more likely they will be perceived as low-falling categories. As a result, the effects of onset pitch and overall pitch predict a perceptual boundary in the onset-pitch continuum and the overall-pitch continuum. As to the offset pitch, it usually stays in the lower pitch register in both falling tones. It is unclear how offset pitch is perceived in a higher pitch register. Since offset pitch is not a crucial correlate, it is not hypothesized to exert an effect. As a result, no perceptual boundary in the offset-pitch continuum is predicted.

As to the interaction hypothesis, the phonetic/phonological factors are hypothesized to exert a more significant effect on tonal identification results, in which a minimal level of lexical access is required. In addition, as mentioned above, the two types of responses (tonal categories and actual words) may provide participants with different kinds of knowledge to process tonal variations, and the access to different knowledge is hypothesized to exhibit different patterns between tonal identification and lexical recognition results. The interaction effect is demonstrated basically in a qualitative manner, since there is no interaction variable to be analyzed statistically. It is not entirely clear what predications the interaction effect makes, but it is more likely to occur in the offset-pitch continuum in which many pitch variables are ambiguous intrinsically, for instance, the ambiguous role of offset pitch and an ambiguous onset pitch at 160 Hz. Similarly, the overall-pitch variations also have some ambiguous variables. As a result, a different pattern of offset-pitch and overall-pitch effects is more likely to occur.

4.4 Results and analyses

This section first presents the frequency rates of both tasks in terms of three continua (onset-pitch continuum, offset-pitch continuum, and overall-pitch continuum) as preliminary results in section 4.4.1, and then demonstrates the analyses of three hypotheses (lexical effects, phonetic/phonological effects, and interaction effects) in the following three sections.

4.4.1 Preliminary results

The preliminary results include the frequency rates of tonal responses as tonal results in section 4.4.1.1 and the frequency rates of lexical responses as lexical results in section 4.4.1.2. In addition, the subjective familiarity ratings and the actual word counts of two lexical responses ([ti53] ‘to know’ and [ti31] ‘emperor’) are reported in section 4.4.1.3.

4.4.1.1 Tonal results

The tonal results are presented in terms of three continua as follows. Figure 4.6 shows the frequency rates of 10 onset-pitch stimuli in the onset-pitch continuum. Figure 4.7 shows the frequency rates of 10 offset-pitch stimuli in the offset-pitch continuum. Figure 4.8 shows the frequency rates of 10 overall-pitch stimuli in the overall-pitch continuum. As shown in these figures, the blue dots represent the frequency rates of all stimuli as Tone-31 (low-falling tone) responses, and the orange dots represent the frequency rates of all stimuli as Tone-53 (high-falling tone). As mentioned earlier, since these tonal trials are forced-choice questions, the frequency rates of both Tone-31 and Tone-53 are in complementary distribution.

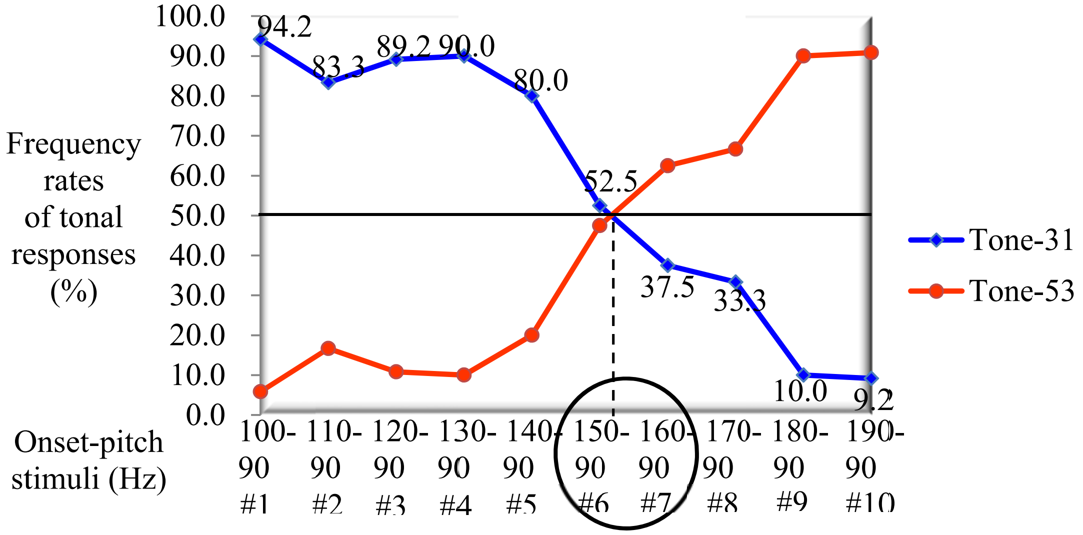

Figure 4.6 Hai-lu Hakka's tonal results of 10 onset-pitch stimuli (the onset-pitch continuum).

As shown in Figure 4.6 above, Hai-lu Hakka participants responded 94.2% of stimulus#1-like onset-pitch variations to Tone-31, and only 5.8% to Tone-53; they responded 83.3% of stimulus#2-like onset-pitch variations to Tone-31, and only 16.7% to Tone-53; and they responded only 9.2% of stimulus#10-like onset-pitch variations to Tone-31, and 90.8% to Tone-53. The tonal results indicate that Hai-lu Hakka participants tend to identify those onset-pitch variations with lower onset pitch (i.e., stimulus#1: 100-90 Hz, stimulus#2: 110-90 Hz, and stimulus#3: 120-90 Hz) as low-falling tone, and tend to identify those with higher onset pitch (i.e., stimulus#9: 180-90 Hz, and stimulus#10: 190-90 Hz) as high-falling tone. Based on a 75% standard of tonal acquisition (So & Dodd 1995; Zhu & Dodd 2000), the first five onset-pitch stimuli (stimulus#1 to stimulus#5) tend to be identified as low-falling tone; the three middle stimuli (stimulus#6 to stimulus#8) are ambiguous variations; and the last two stimuli (stimulus#9 and stimulus#10) tend to be identified as high-falling tone.

In addition, the two tendency lines (blue and orange) intersect between stimulus#6: 150-90 Hz and stimulus#7: 160-90 Hz. The intersection indicates a perceptual boundary between low-falling tone and high-falling tone. The perceptual boundary indicates that pitch variations of onset pitch may cause Hai-lu Hakka participants to feel confused with the tonal contrast of two falling tones, especially when onset pitch varies to a 150-160 Hz range.

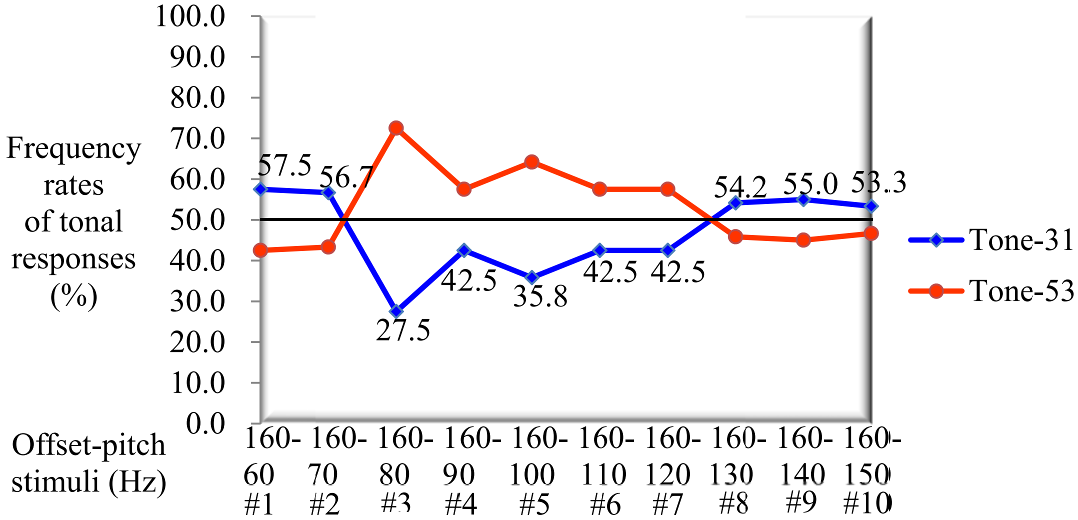

Figure 4.7 Hai-lu Hakka's tonal results of 10 offset-pitch stimuli (the offset-pitch continuum).

As shown in Figure 4.7 above, Hai-lu Hakka participants responded 57.5% of stimulus#1-like offset-pitch variations to Tone-31, and 42.5% to Tone-53; they responded 56.7% of stimulus#2-like offset-pitch variations to Tone-31, and 43.3% to Tone-53; and they responded 53.3% of stimulus#10-like offset-pitch variations to Tone-31, and 46.7% to Tone-53. The tonal results indicate that the frequency rates of 10 offset-pitch stimuli are mostly at a chance level (50%), and that Hai-lu Hakka participants can hardly identify those offset-pitch variations as either low-falling tone or high-falling tone. Based on the 75% standard of tonal acquisition, all these offset-pitch stimuli are ambiguous variations.

In addition, the tonal results indicate no clear tendency line in the offset-pitch continuum. The blue and orange lines intersect twice by stimulus#3 and stimulus#7, which indicates no clear perceptual boundary between low-falling tone and high-falling tone. Since there is no perceptual boundary in the offset-pitch continuum, offset-pitch variations are less likely to contrast Hai-lu Hakka's two falling tones. When falling tones are implemented with MH pitch onset (i.e. 160 Hz), they are more likely to be identified as ambiguous variations, regardless of offset-pitch changes.

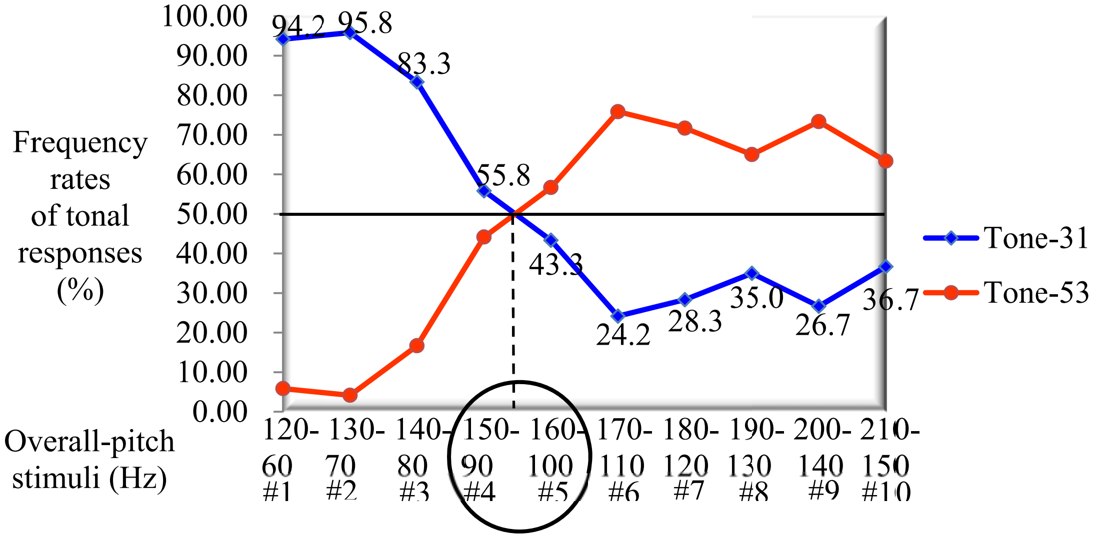

Figure 4.8 Hai-lu Hakka's tonal results of 10 overall-pitch stimuli (the overall-pitch continuum).

As shown in Figure 4.8 above, Hai-lu Hakka participants responded 94.2% of stimulus#1-like overall-pitch variations to Tone-31, and only 5.8% to Tone-53; they responded 95.8% of stimulus#2-like overall-pitch variations to Tone-31, and only 4.2% to Tone-53; and they responded only 36.7% of stimulus#10-like overall-pitch variations to Tone-31, and 63.3% to Tone-53. The tonal results indicate that Hai-lu Hakka participants tend to identify those overall-pitch variations with lower overall pitch (i.e., stimulus#1: 120-60 Hz, stimulus#2: 130-70 Hz, and stimulus#3: 140-80 Hz) as low-falling tone, and tend to identify those with higher overall pitch (i.e., stimulus#6: 170-110 Hz, and stimulus#7: 180-120 Hz) as high-falling tone. Based on the 75% standard of tonal acquisition, the first three overall-pitch stimuli (stimulus#1 to stimulus#3) tend to be identified as low-falling tone; and the rest (stimulus#4 to stimulus#10) are ambiguous variations, except for stimulus#6: 170-110 Hz. The sixth overall-pitch stimulus tends to be identified as high-falling tone.

In addition, the two tendency lines (blue and orange) intersect between stimulus#4: 150-90 Hz and stimulus#5: 160-100 Hz. The intersection indicates a perceptual boundary between low-falling tone and high-falling tone. The perceptual boundary indicates that pitch variations of overall-pitch height cause Hai-lu Hakka participants to get confused with the contrast of two falling tones, especially when onset pitch varies to the 150-160 Hz range, and offset pitch varies to the 90-100 Hz range. It is intriguing that the perceptual boundary is found to be similar in the onset-pitch continuum and in the overall-pitch continuum, i.e. between onset-pitch stimulus#6: 150-90 Hz (Tone-42) and onset-pitch stimulus#7: 160-90 Hz (Tone-42), and between overall-pitch stimulus#4: 150-90 Hz (Tone-42) and overall-pitch stimulus#5: 160-100 Hz (Tone-43). The similar loci of perceptual boundaries indicate that onset-pitch height (150 to 160 Hz) is slightly more crucial to the contrast of two falling tones than degrees of pitch drop (Tone-42 or Tone-43).

4.4.1.2 Lexical results

The lexical results are also demonstrated in terms of three continua as follows. Figure 4.9 shows the frequency rates of 10 onset-pitch stimuli in the onset-pitch continuum. Figure 4.10 shows the frequency rates of 10 offset-pitch stimuli in the offset-pitch continuum. Figure 4.11 shows the frequency rates of 10 overall-pitch stimuli in the overall-pitch continuum. As shown in these figures, the sky-blue dots represent the frequency rates of 10 onset-pitch stimuli as [ti31] responses (a low-falling word ‘emperor’), and the bronze dots represent the frequency rates as [ti53] responses (a high-falling word ‘to know’). As mentioned earlier, since these lexical trials are also forced-choice questions, the frequency rates of both [ti31] and [ti53] words are in complementary distribution.

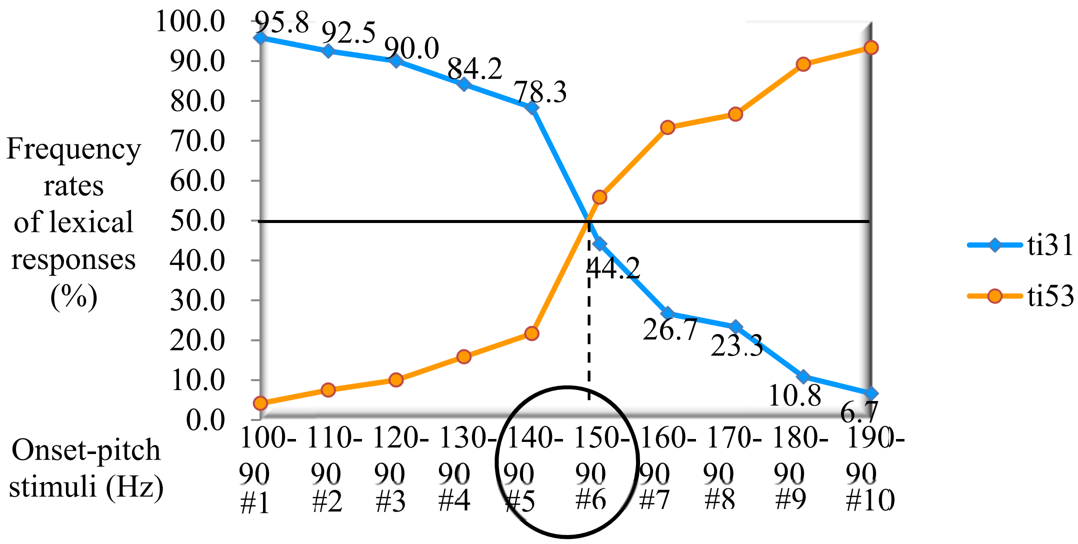

Figure 4.9 Hai-lu Hakka's lexical results of 10 onset-pitch stimuli (the onset-pitch continuum).

As shown in Figure 4.9 above, Hai-lu Hakka participants responded 95.8% of stimulus#1-like onset-pitch variations to [ti31] 'emperor,' and only 5.8% to [ti53] 'to know'; they responded 92.5% of stimulus#2-like onset-pitch variations to [ti31] 'emperor,' and only 7.5% to [ti53] 'to know'; and they responded only 6.7% of stimulus#10-like onset-pitch variations to [ti31] 'emperor,' and 93.3% to [ti53] 'to know'. The lexical results indicate that Hai-lu Hakka participants tend to recognize those onset-pitch variations with lower onset pitch (i.e., stimulus#1: 100-90 Hz, stimulus#2: 110-90 Hz, and stimulus#3: 120-90 Hz) as low-falling words, and tend to recognize those with higher onset pitch (i.e., stimulus#9: 180-90 Hz, and stimulus#10: 190-90 Hz) as high-falling words. Based on the 75% standard of tonal acquisition, the first five onset-pitch stimuli (stimulus#1 to stimulus#5) tend to be recognized as [ti31] 'emperor'; the two middle stimuli (stimulus#6 and stimulus#7) are ambiguous variations; and the last three stimuli (stimulus#8 to stimulus#10) tend to be recognized as [ti53] 'to know'.

In addition, the two tendency lines (sky-blue and bronze) intersect between stimulus#5: 140-90 Hz and stimulus#6: 150-90 Hz. The intersection indicates a perceptual boundary between low-falling words and high-falling words. The perceptual boundary indicates that pitch variations of onset pitch may cause Hai-lu Hakka participants to feel confused with the lexical contrast of two falling words, especially when onset pitch varies to the 140-150 Hz range. The loci of perceptual boundaries are different in the tonal results and the lexical results, i.e. between stimulus#6: 150-90 Hz and stimulus#7: 160-90 Hz in the tonal results, and between stimulus#5: 140-90 Hz and stimulus#6: 150-90 Hz in the lexical results. The difference indicates that there are more lexical responses to high-falling categories than tonal responses to high-falling categories. In other words, Hai-lu Hakka participants are more likely to respond to high-falling words [ti53] ‘to know’ than to low-falling words [ti31] ‘emperor’ in lexical recognition.

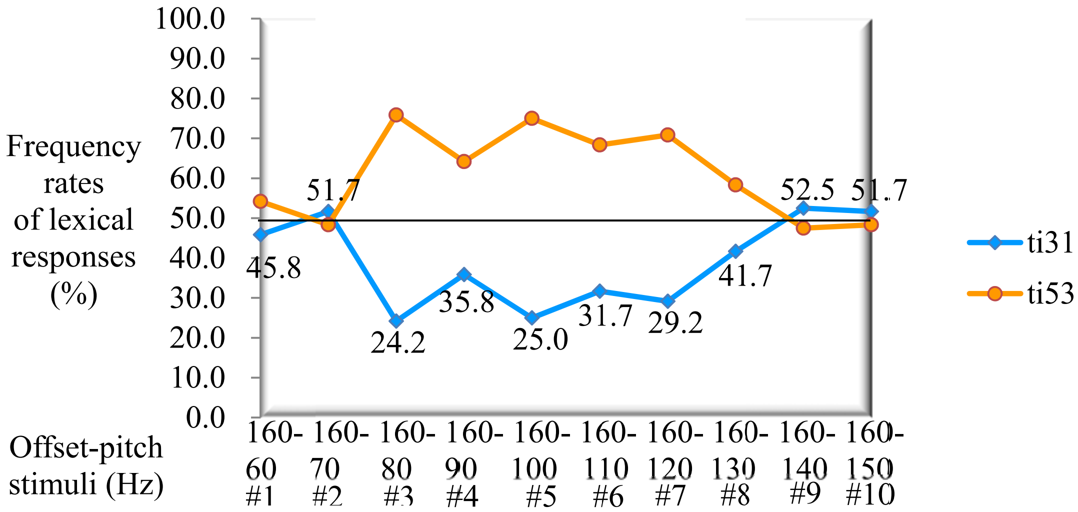

Figure 4.10 Hai-lu Hakka’s lexical results of 10 offset-pitch stimuli (the offset-pitch continuum).

As shown in Figure 4.10 above, Hai-lu Hakka participants responded 45.8% of stimulus#1-like offset-pitch variations to [ti31] ‘emperor,’ and 54.2% to [ti53] ‘to know’; they responded 51.7% of stimulus#2-like offset-pitch variations to [ti31] ‘emperor,’ and 48.3% to [ti53] ‘to know’; and they responded 51.7% of stimulus#10-like offset-pitch variations to [ti31] ‘emperor,’ and 48.3% to [ti53] ‘to know’. The lexical results indicate that the frequency rates of 10 offset-pitch stimuli are usually at a chance level (50%), and that Hai-lu Hakka participants have difficulty recognizing those offset-pitch variations as either low-falling words or high-falling words. Based on the 75% standard of tonal acquisition, most of these offset-pitch stimuli are ambiguous variations, except for stimulus#3: 160-80 Hz and stimulus#5: 160-100 Hz. The third and the fifth offset-pitch stimuli tend to be recognized as high-falling words [ti53] 'to know'.

In addition, the lexical results indicate no clear tendency line in the offset-pitch continuum. The sky-blue and bronze lines intersect twice by stimulus#2 and stimulus#9, which indicates no clear perceptual boundary between low-falling words and high-falling words. Since there is no perceptual boundary in the offset-pitch continuum, offset-pitch variations seem less likely to contrast Hai-lu Hakka's two falling words [ti31] 'emperor' and [ti53] 'to know'. When falling words are implemented with MH pitch onset (i.e. 160 Hz), they are more likely to be recognized as ambiguous variations, regardless of offset-pitch changes.

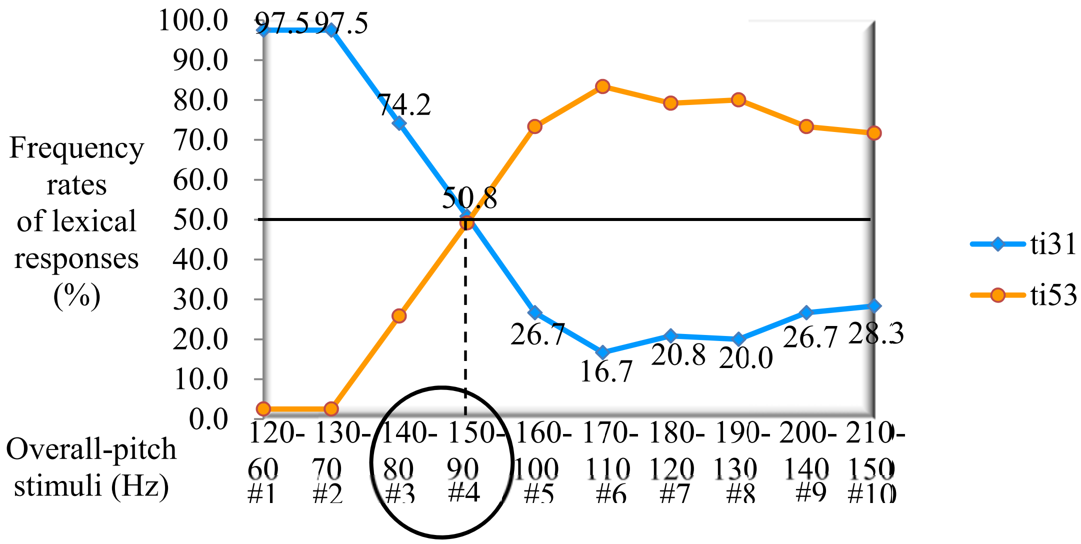

Figure 4.11 Hai-lu Hakka's lexical results of 10 overall-pitch stimuli (the overall-pitch continuum).

As shown in Figure 4.11 above, Hai-lu Hakka participants responded 97.5% of stimulus#1-like overall-pitch variations to [ti31] 'emperor', and only 2.5% to [ti53] 'to know'; they responded 97.5% of stimulus#2-like overall-pitch variations to [ti31] 'emperor', and only 2.5% to [ti53] ‘to know’; and they responded only 28.3% of stimulus#10-like overall-pitch variations to [ti31] ‘emperor,’ and 71.7% to [ti53] ‘to know’. The lexical results indicate that Hai-lu Hakka participants tend to recognize those overall-pitch variations with lower overall pitch (i.e., stimulus#1: 120-60 Hz, stimulus#2: 130-70 Hz, and stimulus#3: 140-80 Hz) as low-falling words, and tend to recognize those with higher overall pitch (i.e., stimulus#6: 170-110 Hz, stimulus#7: 180-120 Hz, and stimulus#8: 190-130 Hz) as high-falling words. Based on the 75% standard of tonal acquisition, the first two overall-pitch stimuli (stimulus#1 to stimulus#2) tend to be recognized as [ti31] ‘emperor’; the three middle stimuli (stimulus#6 to stimulus#8) tend to be recognized as [ti53] ‘to know’; and the rest (stimulus#3 to stimulus#5, stimulus#9, and stimulus#10) are ambiguous variations.

In addition, the two tendency lines (sky-blue and bronze) intersect between stimulus#3: 140-80 Hz and stimulus#4: 150-90 Hz. The intersection indicates a perceptual boundary between low-falling tone and high-falling words. The perceptual boundary indicates that pitch variations of overall pitch may cause Hai-lu Hakka participants to feel confused with the lexical contrast of two falling words, especially when onset pitch varies to the 140-150 Hz range, and offset pitch varies to the 80-90 Hz range. The perceptual boundary was also found to be pretty close in the onset-pitch continuum and in the overall-pitch continuum, i.e. between onset-pitch stimulus#5: 140-90 Hz (Tone-42) and onset-pitch stimulus#6: 150-90 Hz (Tone-42), and between overall-pitch stimulus#3: 140-80 Hz (Tone-42) and overall-pitch stimulus#4: 150-90 Hz (Tone-42). The loci of perceptual boundaries are different in the tonal results and the lexical results, i.e. between stimulus#4: 150-90 Hz and stimulus#5: 160-100 Hz in the tonal results, and between stimulus#3: 140-80 Hz and stimulus#4: 150-90 Hz in the lexical results. The difference indicates that there are more lexical responses to high-falling categories than tonal responses to high-falling categories. In other words, Hai-lu Hakka participants are more likely to respond to high-falling words [ti53] ‘to know’ than to low-falling words [ti31] ‘emperor’ in lexical recognition.

4.4.1.3 Results of subjective familiarity ratings and actual word counts

Both the results of subjective familiarity ratings and actual word counts indicate that the high-falling response [ti53] ‘to know’ is a more frequent and more familiar word than the low-falling response [ti31] ‘emperor’. According to Chui & Lai (2009), the ratio of actual word counts between [ti53] ‘to know’ and [ti31] ‘emperor’ is 114: 0, and it indicates that the actual word counts of [ti53] ‘to know’ is (significantly) higher than the counts of [ti31] ‘emperor’. In other words, the high-falling word [ti53] ‘to know’ is more frequent than the low-falling word [ti31] ‘emperor’. According to the subjective familiarity ratings collected from 30 Hai-lu Hakka participants, the mean ratings of [ti53] ‘to know’ are 4.9 out of 5.0 (on a five-point scale), and those of [ti31] ‘emperor’ are 1.4 out of 5.0. These ratings were analyzed by a two-sample T-test. As shown in Table 4.11 below, the ratings of the high-falling word are significantly higher than those of the low-falling word. In addition, as mentioned in section 4.3.3.2 above, the low-falling word [ti31] ‘emperor’ was found to be mispronounced as [t^{h}i31] ‘to shave’ occasionally by about five participants. The finding indicates that the high-falling word [ti53] ‘to know’ is more familiar to 30 Hai-lu Hakka participants than the low-falling word [ti31] ‘emperor’.

Table 4.11 Hai-lu Hakka’s results of subjective familiarity ratings.

		Rating scores	Score range	T-test result
Hai-lu Hakka	[ti53] ‘to know’	4.9 (sd: 0.25)	Max:5; Min:4	t(30)= 30.8016 p< 0.001***
	[ti31] ’emperor’	1.4 (sd: 0.57)	Max:3; Min:1	

4.4.2 Lexical analyses

In order to evaluate the lexical hypothesis, the two lexical factors (word types and lexical frequency) are analyzed. In order to analyze the lexical factor of word types (tonal categories vs. actual words), the tonal results and the lexical results are compared in terms of three continua. In order to compare both the tonal and the lexical results in a single figure, only the frequency rates of low-falling responses (Tone-31 or [ti31] 'emperor') are shown as follows. Since both low-falling and high-falling responses are in complementary distribution, it makes no difference whether low-falling or high-falling responses are compared in the lexical analysis. The comparison between tonal and lexical results is analyzed by a two-sample T-test. As to the frequency factors, they are intrinsic variables to two lexical responses [ti53] 'to know' and [ti31] 'emperor'. The intrinsic variables mean that they are not independent variables in the experiment. The frequency variables are simply analyzed in a descriptive manner.

The comparison between tonal and lexical results is demonstrated in terms of three continua below. Figure 4.12 shows the lexical analysis on 10 onset-pitch stimuli in the onset-pitch continuum. Figure 4.13 shows the lexical analysis on 10 offset-pitch stimuli in the offset-pitch continuum. Figure 4.14 shows the lexical analysis on 10 overall-pitch stimuli in the overall-pitch continuum. As shown in these figures, the navy dotted line represents the frequency rates of Tone-31 as tonal results, and the sky-blue line represents the frequency rates of [ti31] 'emperor' as lexical results.

4.4.2.1 Lexical analysis on onset-pitch stimuli

As shown in Figure 4.12 below, the 10 onset-pitch stimuli were classified into three groups: a group of onset-pitch variations in the low pitch register, a group of onset-pitch variations in the ambiguous pitch register, and a group of onset-pitch variations in the high pitch register, in terms of these stimuli's pitch values shown in Table 4.7 above. The four low onset-pitch variations are Tone-32, except for stimulus#4: 130-90 Hz. The fourth stimulus' pitch value is slightly close to Tone-42. Since it was found to be a typical low-falling variant by Yeh's (2009) production results shown in Table 4.4 above, it was considered to have a low pitch register. The three ambiguous onset-pitch variations are all Tone-42. The three high onset-pitch variations are all Tone-52.

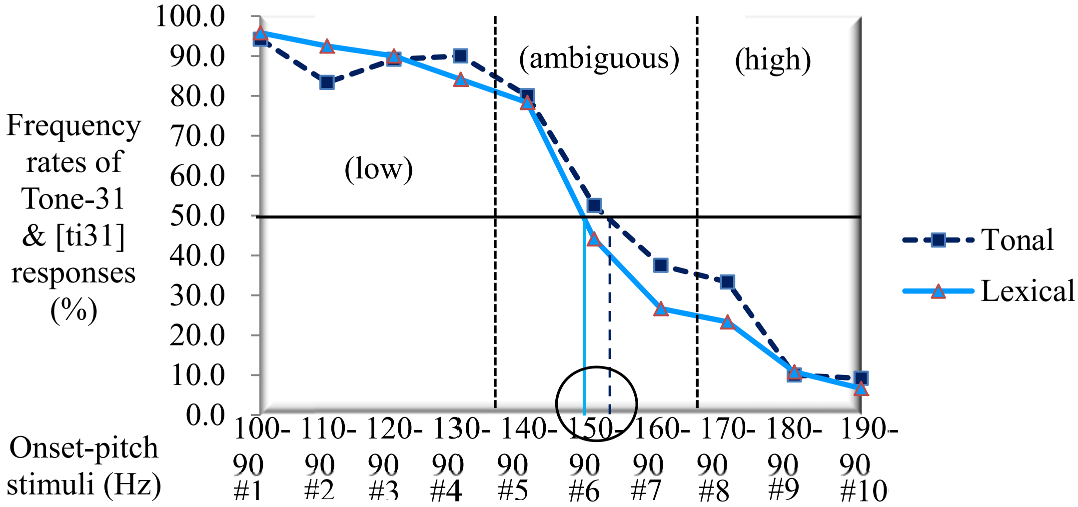

Figure 4.12 Hai-lu Hakka's lexical analysis on 10 onset-pitch stimuli (the onset-pitch continuum).

As shown in Figure 4.12 above, the comparison generally indicates two different patterns between tonal and lexical results. First, the frequency rates of Tone-31 (as the navy dotted line) are higher than those of [ti31] 'emperor' (as the sky-blue line). The difference indicates that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] 'to know' over [ti31] 'emperor' than to choose Tone-53 over Tone-31. This tendency is also demonstrated by the different cross-points between the navy and the sky-blue lines and the perceptual boundary (50%). The navy dotted line (tonal results) intersect the boundary between stimulus#6: 150-90 Hz and stimulus #7: 160-90 Hz, whereas the sky-blue line (lexical results) intersect the boundary between stimulus#5: 140-90 Hz and stimulus#6: 150-90 Hz. The navy line intersects the boundary at higher frequency rates of Tone-31, and the sky-blue line does so at lower frequency rates of [ti31] 'emperor'. The different cross-points indicate that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] 'to know' over [ti31] 'emperor' than to choose Tone-53 over Tone-31. The results support an effect of frequency variables, which indicates that Hai-lu Hakka participants are more likely to respond to the more frequent/familiar word [ti53] 'to know'. Second, the difference between tonal and lexical results seems to be more distinct in the ambiguous group of onset-pitch variations.

In order to further compare the difference, a Two-sample T-test analysis was conducted. The T-test analysis shows that the 10 onset-pitch stimuli's frequency rates of Tone-31 are slightly higher than those of [ti31] 'emperor', $t(30)= 1.2957$, $p> 0.05$. The analysis indicates that Hai-lu Hakka participants are more likely to respond to low-falling categories in tonal identification than in lexical recognition, but not in a significant way. The results slightly support the effect of word types, which predicts that frequency rates of tonal responses are different from frequency rates of lexical responses, but the analysis indicates that the difference is not quite significant. In addition, the intra-group analysis was conducted to compare the difference in the three groups of onset-pitch stimuli. The intra-group analysis also indicates that although the difference seems to be more distinct in the ambiguous group, it is not significant in the three groups, i.e., the low group: $t(30)= -0.5340$, $p> 0.0167$[5], the ambiguous group: $t(30)= 1.1406$, $p> 0.0167$, the high group: $t(30)= 1.0569$, $p> 0.0167$.

4.4.2.2 Lexical analysis on offset-pitch stimuli

As shown in Figure 4.13 below, the 10 offset-pitch stimuli were also classified into three groups: a group of offset-pitch variations in the low pitch register, a group of offset-pitch variations in the ambiguous pitch register, and a group of offset-pitch variations in the high pitch register, in terms of these stimuli's pitch values shown in Table 4.8. The three low offset-pitch variations are Tone-41, except for stimulus#3: 160-80 Hz. The third stimulus' pitch value is Tone-42, but it is closer to Tone-41 than to Tone-43. The fourth stimulus' pitch value is Tone-42, but it is closer to Tone-43 than to Tone-41. The four ambiguous offset-pitch

[5] The p value of significant levels is adjusted by the Bonferroni Correction (0.1/3= 0.0333+, 0.05/3= 0.0167*, 0.01/3= 0.0033**, 0.001/3= 0.0003***) because the intra-group analysis involves three multiple comparisons.

variations are Tone-43, except for stimulus#4: 160-90 Hz. The three high offset-pitch variations are all Tone-44.

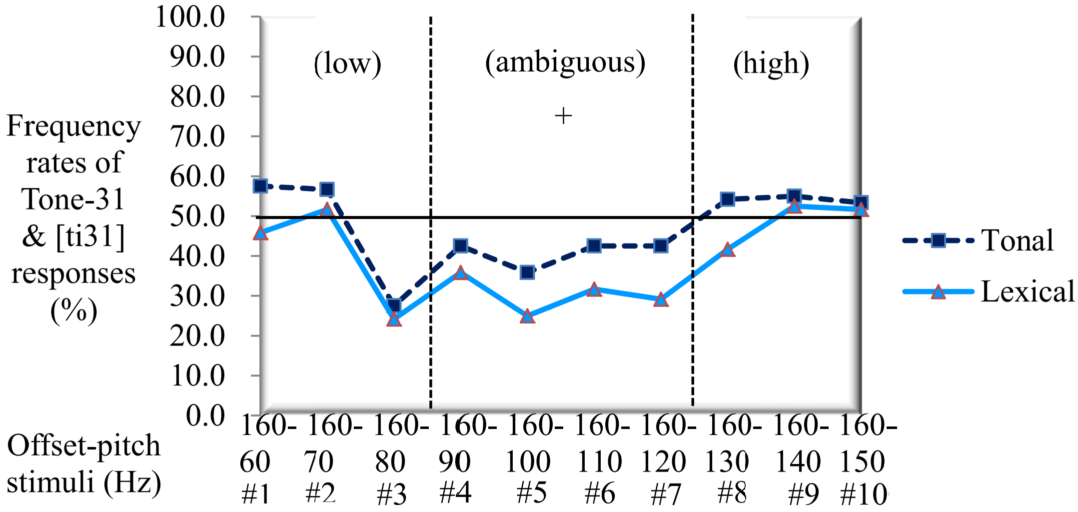

Figure 4.13 Hai-lu Hakka's lexical analysis on 10 offset-pitch stimuli (the offset-pitch continuum).

As shown in Figure 4.13 above, the comparison generally indicates two different patterns between tonal and lexical results. First, the frequency rates of Tone-31 (as the navy dotted line) are consistently higher than those of [ti31] 'emperor' (as the sky-blue line). The difference indicates that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] 'to know' over [ti31] 'emperor' than to choose Tone-53 over Tone-31. Second, the difference between tonal and lexical results seems to be more distinct in the ambiguous group of offset-pitch variations.

In order to further compare the difference, a Two-sample T-test analysis was conducted. The T-test analysis shows that the 10 offset-pitch stimuli's frequency rates of Tone-31 are significantly higher than those of [ti31] 'emperor', $t(30)= 2.3447$, $p< 0.05$*. The analysis indicates that Hai-lu Hakka participants are more likely to respond to low-falling categories in tonal identification than in lexical recognition, and suggests that they respond to tonal categories and actual words in different manners. The analysis supports an effect of word types, which predicts that frequency rates of tonal responses are significantly different from frequency rates of lexical responses. In addition, the intra-group analysis was conducted to compare the difference in the three groups of offset-pitch stimuli. The intra-group analysis also indicates that the difference is slightly significant in the ambiguous group: $t(30)= 2.1022$, $p= 0.0399+$, but not in the low group: $t(30)= 0.8889$, $p> 0.0167$, not in the high group: $t(30)= 0.6679$, $p> 0.0167$.

4.4.2.3 Lexical analysis on overall-pitch stimuli

As shown in Figure 4.14 below, the 10 overall-pitch stimuli were also classified into three groups: a group of overall-pitch variations in a low pitch register, a group of overall-pitch variations in an ambiguous pitch register, and a group of overall-pitch variations in a high pitch register, in terms of these stimuli's pitch values shown in Table 4.9. The three low overall-pitch variations are Tone-31, Tone-41, and Tone-42, whose onset pitch register is ambiguous and offset pitch is low. The four ambiguous overall-pitch variations are Tone-42, Tone-43, and Tone-53, whose offset pitch is ambiguous. The three high overall-pitch variations are all Tone-54, whose onset pitch and offset pitch are both high.

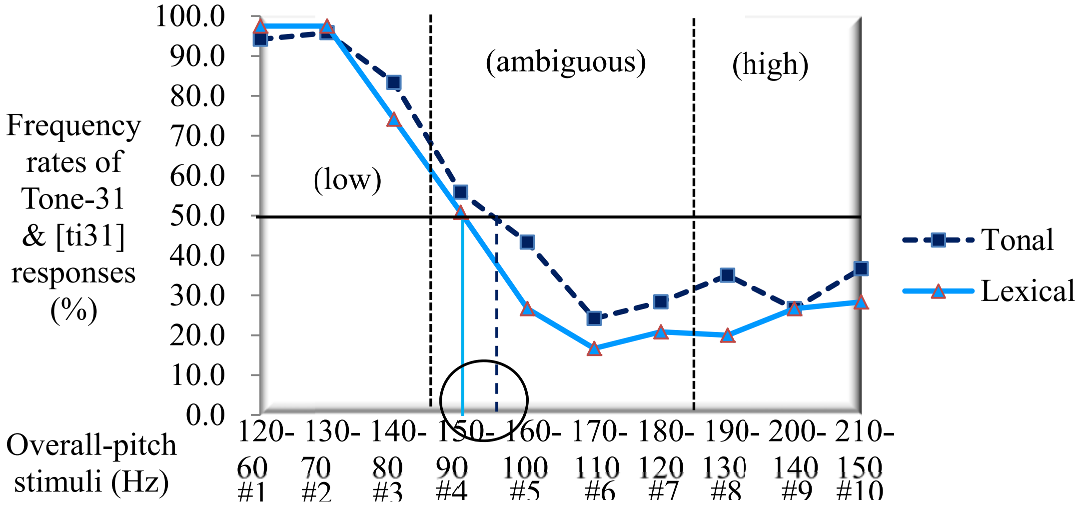

Figure 4.14 Hai-lu Hakka's lexical analysis on 10 overall-pitch stimuli (the overall-pitch continuum).

As shown in Figure 4.14 above, the comparison generally indicates two different patterns between tonal and lexical results. First, the frequency rates of Tone-31 (as the navy dotted line) are higher than those of [ti31] 'emperor' (as the sky-blue line). The difference indicates that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] 'to know' over [ti31] 'emperor' than to choose Tone-53 over Tone-31. This tendency is also demonstrated by the different cross-points between the navy and the sky-blue lines and the perceptual boundary (50%). The navy dotted line (tonal results) intersect the boundary between stimulus#4: 150-90 Hz and stimulus #5: 160-100 Hz, whereas the sky-blue line (lexical results) intersect the boundary between stimulus#3: 140-80 Hz and stimulus#4: 150-90 Hz. The navy line intersects the boundary at higher frequency rates of Tone-31, and the sky-blue line does so at lower frequency rates of [ti31] 'emperor'. The different cross-points indicate that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] 'to know' over [ti31] 'emperor' than to choose Tone-53 over Tone-31. The results support an effect of frequency variables, which predicts that Hai-lu Hakka participants are more likely to respond to the more frequent/familiar word [ti53] ‘to know’. Second, the difference between tonal and lexical results seems to be more significant in the ambiguous group of overall-pitch variations.

In order to further compare the difference, a Two-sample T-test analysis was conducted. The T-test analysis shows that the 10 overall-pitch stimuli’s frequency rates of Tone-31 are significantly higher than those of [ti31] ‘emperor’, $t(30)= 2.1466$, $p< 0.05$*. The analysis indicates that Hai-lu Hakka participants are more likely to respond to low-falling categories in tonal identification than in lexical recognition, and suggests that they respond to tonal categories and actual words in different manners. The analysis supports an effect of word types, which predicts that frequency rates of tonal responses are significantly different from frequency rates of lexical responses. In addition, the intra-group analysis was conducted to compare the difference in the three groups of overall-pitch stimuli. However, the intra-group analysis indicates that the difference is not significant, i.e., the low group: $t(30)= 0.5437$, $p> 0.0167$, the ambiguous group: $t(30)= 1.6949$, $p> 0.0167$, the high group: $t(30)= 1.1741$, $p> 0.0167$.

4.4.2.4 Summary of lexical analyses

The results of T-test analyses and three intra-group analyses are summarized in Table 4.12 below. In general, the comparisons between tonal and lexical results show a difference in the processing of tonal identification and lexical recognition, which indicates that Hai-lu Hakka participants are more likely to choose [ti53] ‘to know’ over [ti31] ‘emperor’ than to choose Tone-53 over Tone-31. The finding supports the frequency effect predicting that Hai-lu Hakka participants are more likely to respond to the more frequent/familiar word [ti53] ‘to know’. In addition, the difference is found to be significant in 10 offset-pitch stimuli and 10 overall-pitch stimuli, but not in 10 onset-pitch stimuli. The findings generally support the word-type effect predicting that frequency rates of tonal responses are significantly different from those of lexical responses, although the difference is less significant in 10 onset-pitch stimuli. In other words, Hai-lu Hakka's lexical analyses generally confirm the predictions, and therefore verify the lexical hypothesis.

Table 4.12 Summary of lexical analyses and three intra-group analyses in the three continua.

		Onset-pitch stimuli	Offset-pitch stimuli	Overall-pitch stimuli
Across groups		$p > 0.05$	$p < 0.05$*	$p < 0.05$*
Intra-group	Low	$p > 0.0167$	$p > 0.0167$	$p > 0.0167$
	Ambiguous	$p > 0.0167$	$p \fallingdotseq 0.0333$+	$p > 0.0167$
	High	$p > 0.0167$	$p > 0.0167$	$p > 0.0167$

As shown in Table 4.12 above, the analyses also show that the lexical effect tends to be more significant in ambiguous stimuli, such as (i) three ambiguous groups of stimuli, (ii) offset-pitch stimuli, and (iii) overall-pitch stimuli. As to the three ambiguous groups of stimuli, they are phonetically ambiguous, since they were set up by ambiguous variations of pitch height (onset pitch, offset pitch, or overall pitch). As to the offset-pitch stimuli and the overall-pitch stimuli, they are more phonetically ambiguous than onset-pitch stimuli. The offset-pitch stimuli were all set up with constant 160-Hz onset pitch which is in the MH pitch register. As shown in Figure 4.12, the 160-Hz onset-pitch variation was found to be phonetically ambiguous to most Hai-lu Hakka participants. Similarly, the overall-pitch stimuli were all set up with constant overall pitch (60-Hz difference between onset pitch and offset pitch). The overall-pitch stimuli were also found to be phonetically ambiguous, especially in the ambiguous group and the high group. In other words, lexical factors (word types and lexical frequency as different degrees of lexical access) seem to exert a more significant influence on phonetically ambiguous tonal variations.

4.4.3 Phonetic/phonological analyses

The preliminary results shown in section 4.4.1 indicate that there is a perceptual boundary in the onset-pitch stimuli and the overall-pitch stimuli, but no clear boundary in the offset-pitch stimuli. The findings suggest that onset-pitch and overall-pitch variations exert an influence on the contrast of two falling tones, but not offset-pitch variations. In order to further analyze the phonetic/phonological effects, a Two-sample T-test analysis was conducted to compare frequency rates of two consecutive groups of stimuli, for instance, low vs. ambiguous, and ambiguous vs. high. Similar analyses were also conducted to compare frequency rates of two consecutive stimuli in each group, for instance: stimulus#1 vs. stimulus#2, stimulus#2 vs. stimulus#3, and the like. The former is an inter-group comparison, and the latter is an intra-group comparison. The two comparisons were conducted to analyze how pitch variations of three kinds affect frequency rates in tonal identification and lexical recognition respectively in section 4.4.3.1 and section 4.4.3.2 below.

4.4.3.1 Phonetic/phonological analysis on tonal results

As summarized in Table 4.13 below, the T-test analyses of both inter-group and intra-group comparisons on tonal results are demonstrated in terms of three pitch variations. In general, the analyses indicate that onset-pitch variations play a more significant role in tonal identification of two falling tones than overall-pitch variations and offset-pitch variations, and the effect of offset-pitch variations is the least significant. The analyses confirm the preliminary findings of perceptual boundaries.

Table 4.13 Phonetic/phonological analyses on tonal identification results.

Tonal results		Onset-pitch var.	Offset-pitch var.	Overall-pitch var.
Inter-group	Low vs. ambiguous	t(30)= 7.8028, p< 0.0005[6]***	t(30)= 1.0225, p> 0.025	t(30)= 12.9801, p< 0.0005***
	Ambiguous vs. high	t(30)= 8.5078, p< 0.0005***	t(30)= -1.9265, p= 0.0589	t(30)= 0.9635, p> 0.025
Intra-group	Low	1vs2: p= 0.0116 2vs3: p> 0.0056[7] 3vs4: p> 0.0056	1vs2: p> 0.0056 2vs3: p< 0.0011	1vs2: p> 0.0056 2vs3: p< 0.0056
	Ambiguous	4vs5: p> 0.0056 5vs6: p< 0.0001 6vs7: p> 0.0056	3vs4: p> 0.0056 4vs5: p> 0.0056 5vs6: p> 0.0056 6vs7: p> 0.0056	3vs4: p< 0.0011 4vs5: p> 0.0056 5vs6: p= 0.0124+ 6vs7: p> 0.0056
	High	7vs8: p> 0.0056 8vs9: p< 0.0011 9vs10: p> 0.0056	7vs8: p> 0.0056 8vs9: p> 0.0056 9vs10: p> 0.0056	7vs8: p> 0.0056 8vs9: p> 0.0056 9vs10: p> 0.0056

As to the inter-group comparison, the analyses show different patterns in the three kinds of pitch variations. First, the analyses show that the frequency rates are significantly different between the low-pitch group and the ambiguous-pitch group of onset-pitch stimuli: t(30)= 7.8028, p< 0.0005***, and between the ambiguous-pitch group and the high-pitch group of onset-pitch stimuli: t(30)= 8.5078, p< 0.0005***. The differences indicate that onset-pitch variations from the low-pitch register, i.e. Tone-32, to a high-pitch register, i.e. Tone-52, play a significant role in tonal identification of two falling tones. Second, the analyses show that the frequency rates are less significantly different between the low-pitch group and the ambiguous-pitch group of offset-pitch stimuli: t(30)= 1.0225, p> 0.025, and not between the ambiguous-pitch group and the high-pitch group of offset-pitch stimuli: t(30)= -1.9265, p> 0.025. The less-significant differences indicate that offset-pitch variations from the low-pitch register, i.e. Tone-41, to the high-pitch register, i.e. Tone-44, play a less significant role in tonal identification of two falling tones. Third, the analyses show that the frequency rates are

6 The p value of significant levels is adjusted by the Bonferroni Correction (0.1/2= 0.05+, 0.05/2= 0.025*, 0.01/2= 0.005**, 0.001/2= 0.0005***) because the inter-group analysis involves two multiple comparisons.

7 The p value of significant levels is adjusted by Bonferroni Correction (0.1/9= 0.0111+, 0.05/ 9= 0.0056*, 0.01/9= 0.0011**, 0.001/9= 0.0001***) because the intra-group analysis involves nine multiple comparisons.

significantly different between the low-pitch group and the ambiguous-pitch group of overall-pitch stimuli: $t(30)= 12.9801$, $p< 0.0005$***, but not between the ambiguous-pitch group and the high-pitch group of overall-pitch stimuli: $t(30)= 0.9635$, $p> 0.025$. The difference and the less-significant difference indicate that overall-pitch variations from the low-pitch register, i.e. Tone-31, to the ambiguous-pitch register, i.e. Tone-53, play a significant role in tonal identification of two falling tones, but overall-pitch variations from the ambiguous-pitch register, i.e. Tone-53, to the high-pitch register, i.e. Tone-54, play a less significant role in tonal identification of two falling tones. The different patterns suggest the effect of onset pitch and overall-pitch variations on the tonal contrast, but not the effect of offset-pitch variations, which generally verify the phonetic/phonological hypothesis.

As to the intra-group comparison, the analyses also show different patterns in the three kinds of pitch variations. First, as to the onset-pitch variations, the difference tends to be found in the ambiguous-pitch group and the high-pitch group. Second, as to the offset-pitch variations, there is a difference to be found in the low-pitch group. Third, as to the overall-pitch variations, the difference tends to be found in the low-pitch group and the ambiguous-pitch group. The intra-group comparison basically indicates similar patterns to the inter-group comparison, except for the offset-pitch variations. The inter-group analyses show that the variations of offset pitch were not found to play a significant role, but the intra-group analyses show that the low-pitch group of offset-pitch variations may play a role to some extent, especially when offset-pitch varies from 70 Hz to 80 Hz.

4.4.3.2 Phonetic/phonological analysis on lexical results

As summarized in Table 4.14 below, the T-test analyses of both inter-group and intra-group comparisons on lexical results are demonstrated in terms of three pitch variations. In general, the analyses indicate that onset-pitch variations play a more significant role in lexical recognition of two falling tones than overall-pitch variations and offset-pitch variations. The analyses seem to confirm the preliminary findings of perceptual boundaries, except for the effect of offset-pitch variations. As shown in Figure 4.13 above, there is no clear perceptual boundary in the offset-pitch continuum, but the analyses show that variations of offset pitch, from the ambiguous pitch register to the high pitch register, seem to play a significant role in lexical recognition of two falling words. The effect of offset-pitch variations suggests a potential difference between tonal processing and lexical processing, which is further discussed below.

Table 4.14 Phonetic/phonological analyses on lexical recognition results.

Lexical results		Onset-pitch var.	Offset-pitch var.	Overall-pitch var.
Inter-group	Low vs. ambiguous	t(30)= 7.9493, p< 0.0005***	t(30)= 1.5356, p> 0.025	t(30)= 13.8575, p< 0.0005***
	Ambiguous vs. high	t(30)= 6.7560, p< 0.0005***	t(30)= -2.7196, p< 0.025*	t(30)= 0.5604, p> 0.025
Intra-group	Low	1vs2: p> 0.0056 2vs3: p> 0.0056 3vs4: p> 0.0056	1vs2: p> 0.0056 2vs3: p< 0.0056	1vs2: p> 0.0056 2vs3: p< 0.0011
	Ambiguous	4vs5: p> 0.0056 5vs6: p< 0.0001 6vs7: p> 0.0056	3vs4: p> 0.0056 4vs5: p> 0.0056 5vs6: p> 0.0056 6vs7: p> 0.0056	3vs4: p< 0.0056 4vs5: p< 0.0056 5vs6: p> 0.0056 6vs7: p> 0.0056
	High	7vs8: p> 0.0056 8vs9: p> 0.0056 9vs10: p> 0.0056	7vs8: p> 0.0056 8vs9: p> 0.0056 9vs10: p> 0.0056	7vs8: p> 0.0056 8vs9: p> 0.0056 9vs10: p> 0.0056

As to the inter-group comparison, the analyses show different patterns in the three kinds of pitch variations. First, the analyses show that the frequency rates are significantly different between the low-pitch group and the ambiguous-pitch group of onset-pitch stimuli: t(30)= 7.9493, p< 0.0005***, and between the ambiguous-pitch group and the high-pitch group of onset-pitch stimuli: t(30)= 6.7560, p< 0.0005***. The differences indicate that onset-pitch variations from the low-pitch register, i.e. Tone-32, to the high-pitch register, i.e. Tone-52, play a significant role in lexical recognition of two falling words. Second, the analyses show that the frequency rates are significantly different between the ambiguous-pitch group and the high-pitch group of offset-pitch stimuli: t(30)= -2.7196, p< 0.025*, but not between the low-pitch group and the ambiguous-pitch group of offset-pitch stimuli. The difference and less-significant difference indicate that offset-pitch variations from the ambiguous-pitch register, i.e. Tone-43, to the high-pitch register, i.e. Tone-44, play a significant role in lexical recognition of two falling words, but offset-pitch variations from the low-pitch register, i.e. Tone-41, to the ambiguous-pitch register, i.e. Tone-43, play a less significant role in lexical recognition of two falling words. Third, the analyses show that the frequency rates are significantly different between the low-pitch group and the ambiguous-pitch group of overall-pitch stimuli: $t(30)= 13.8575$, $p< 0.0005$***, but not between the ambiguous-pitch group and the high-pitch group of overall-pitch stimuli. The difference and the less-significant difference indicate that overall-pitch variations from the low-pitch register, i.e. Tone-31, to the ambiguous-pitch register, i.e. Tone-53, play a significant role in lexical recognition of two falling words, but overall-pitch variations from an ambiguous-pitch register, i.e. Tone-53, to an ambiguous-pitch register, i.e. Tone-54, play a less significant role in lexical recognition of two falling words. The different patterns suggest the effect of onset pitch, offset-pitch, and overall-pitch variations on the lexical contrast of two falling words. Although the findings are somehow different from the predictions shown in Table 4.10 above, the analyses support the phonetic/phonological hypothesis.

As to the intra-group comparison, the analyses also show different patterns in the three kinds of pitch variations. First, as to the onset-pitch variations, the difference tends to be found in the ambiguous-pitch group. Second, as to the offset-pitch variations, there is a difference to be found in the low-pitch group. Third, as to the overall-pitch variations, the difference tends to be found in the low-pitch group and the ambiguous-pitch group. The intra-group comparison basically indicates similar patterns to the inter-group comparison, except for the offset-pitch variations. The inter-group analyses show that the variations of offset pitch (from an ambiguous pitch register to a high pitch register) were found to play a significant role, whereas the intra-group analyses show that the offset-pitch variations in a low pitch register may play a role to some extent, especially when offset-pitch varies from 70 Hz to 80 Hz.

4.4.3.3 Summary of phonetic/phonological analyses

The phonetic/phonological analyses on tonal and lexical results are summarized in Table 4.15 below. In general, the analyses indicate three kinds of phonetic/phonological effects on the contrast of falling categories. First, variations of onset pitch exert a significant influence on the contrast, especially in the ambiguous pitch register and the high pitch register. Second, although there is no clear perceptual boundary in the offset-pitch continuum, variations of offset pitch may exert an influence in some cases, for instance, from 70 Hz to 80 Hz in both tonal identification and lexical recognition, and from the ambiguous pitch register to the high pitch register in lexical processing. Third, variations of overall pitch also exert a significant influence on the contrast, but not so in the high pitch register. The findings are generally consistent with the predictions, except for the effect of offset-pitch variations. Although there are some exceptions, i.e. a potential effect of offset-pitch variations in lexical processing, and a less significant role of overall-pitch variations in the high pitch register, the findings generally verify the phonetic/phonological hypothesis.

Table 4.15 Summary of phonetic/phonological analyses in terms of the three continua.

		Onset-pitch var.	Offset-pitch var.	Overall-pitch var.
Tonal results	L vs. Am.	$p < 0.0005$***	$p > 0.025$	$p < 0.0005$***
	Am. vs. H	$p < 0.0005$***	$p > 0.025$	$p > 0.025$
Lexical results	L vs. Am.	$p < 0.0005$***	$p > 0.025$	$p < 0.0005$***
	Am. vs. H	$p < 0.0005$***	$p < 0.025$*	$p > 0.025$

In addition, the summary shown in Table 4.15 above indicates different effects of offset-pitch variations in tonal identification and lexical recognition. In the tonal results, variations of offset pitch, from the ambiguous pitch register to a high pitch register, barely contrast two falling tones, whereas they are more likely to contrast the high-falling word [ti53] ‘to know’ and non-high-falling words (i.e., ambiguous words or [ti31] ‘emperor’) in the lexical results. The difference indicates that Hai-lu Hakka participants are more likely to recognize those offset-pitch variations in the ambiguous pitch register, i.e. Tone-42 and Tone-43, as high-falling words [ti53] ‘to know’. The difference may result from Hai-lu Hakka participants’ access to different knowledge in tonal processing and lexical processing (different degrees of lexical access), and/or from the influence of lexical frequency: the more frequent the words, the more likely they will be chosen as lexical responses, i.e. [ti53] ‘to know’.

4.4.4 Interaction analyses

The lexical and the phonetic/phonological analyses indicate three particular findings to argue for a potential interaction between lexical and phonetic/phonological factors in the contrast. First, as indicated in the summary of lexical analyses (section 4.4.2.4) above, frequency rates of tonal responses and lexical responses are more significantly different in phonetically ambiguous stimuli, including ambiguous groups of stimuli, offset-pitch stimuli, and overall-pitch stimuli. The difference indicates that variables of word types seem to exert a more significant influence on phonetically ambiguous tonal variations. In other words, Hai-lu Hakka participants seem to rely more on lexical knowledge to process tonal variations with ambiguous phonetic/phonological characteristics.

Second, the phonetic/phonological analyses indicate that offset-pitch variations from the ambiguous pitch register to the high pitch register exert a more significant influence on lexical results than on tonal results. The differences indicate that Hai-lu Hakka participants are more likely to recognize the ambiguous group of offset-pitch variations as [ti53] ‘to know’ than to identify them as Tone-53. As indicated in the summary of phonetic/phonological analyses (section 4.4.3.3) above, the differences may result from the access to different knowledge in tonal processing and lexical processing (different degrees of lexical access), and/or from a more significant influence of lexical frequency. In other words, phonetic/phonological factors seem to play a different role in tonal identification and in lexical recognition.

Third, the intra-group comparisons indicate that frequency rates of two consecutive stimuli are more significantly different in tonal results than in lexical results. As shown by the phonetic/phonological analyses in section 4.4.3 above, there are three intra-group differences in onset-pitch stimuli (stimulus#1 vs. stimulus#2, #5 vs. #6, and #8vs. #9), one in offset-pitch stimuli (stimulus#2 vs. stumulus#3), and three in overall-pitch stimuli (stimulus#2 vs. stimulus#3, #3 vs. #4, and #5 vs. #6) in the tonal results of Table 3.13, whereas there are one intra-group difference in onset-pitch stimuli (stimulus#5 vs. stimulus#6), one in offset-pitch stimuli (stimulus#2 vs. stumulus#3), and three in overall-pitch stimuli (stimulus#2 vs. stimulus#3, #3 vs. #4, and #4 vs. #5) in the lexical results of Table 4.14 above. The differences indicate that there are more intra-group differences in tonal results than in lexical ones. In other words, phonetic/phonological factors seem to play a different role in tonal identification and in lexical recognition. They can be more significant in tonal processing than in lexical processing.

In general, the findings indicate that lexical effects vary with different kinds of phonetic/phonological factors quantitatively, and phonetic/phonological effects also vary with different degrees of lexical access quantitatively and qualitatively. They confirm the interaction hypothesis predicting that phonetic/phonological effects exhibit a different pattern in tonal and lexical results, and suggest that lexical factors interact with phonetic/phonological factors to some extent in the contrast of two falling tones. As a result, these findings support the interaction hypothesis.

4.5 Discussion

As summarized in Table 4.16 below, Hai-lu Hakka's results generally support the lexical hypothesis, the phonetic/phonological hypothesis, and the interaction hypothesis on Hai-lu Hakka's contrast of two falling tones. These findings are further discussed in the following section.

Table 4.16 Comparisons between the predictions and the results.

Hypotheses	Predictions and Hai-lu Hakka's results
The Lexical Hypothesis	(i) Frequency rates of tonal responses are significantly different from those of lexical responses. (ii) Lexical responses to a high-falling word [ti53] 'to know' are more frequent than those to a low-falling word [ti31] 'emperor'.
Results	**Yes,** (i) frequency rates of tonal responses are significantly different from those of lexical responses, <u>except for onset-pitch stimuli</u>. **Yes**, (ii) frequency rates of [ti53] 'to know' are higher than those of [ti31] 'emperor'.
The Phonetic-Phonological Hypothesis	(i) There is a perceptual boundary in the onset-pitch continuum. (ii) There is **no** perceptual boundary in the offset-pitch continuum. (iii) There is a perceptual boundary in the overall-pitch continuum.
Results	**Yes**, (i) there is a perceptual boundary in the onset-pitch continuum. **Yes**, (ii) there is **no** perceptual boundary in the offset-pitch continuum, <u>**but** there is a difference between the ambiguous group and the high group of offset-pitch stimuli in the lexical results</u>. **Yes**, (iii) There is a perceptual boundary in the overall-pitch continuum, **but** the difference is less significant between <u>the ambiguous group and the high group of overall-pitch variations.</u>
The Interaction Hypothesis	(i) The phonetic/phonological effects are more significant in tonal identification results than in lexical recognition results, and/or… (ii) The phonetic/phonological effects exhibit a different pattern between tonal identification and lexical recognition results.
Results	**Yes**, (i) there are more intra-group differences in phonetic/ phonological analyses of tonal results than those of lexical results. **Yes**, (ii) offset-pitch variations from the ambiguous to the high register exert an influence on lexical results, but not on tonal results. ➢ In addition, (iii) <u>the lexical effect is more significant in phonetically ambiguous stimuli</u>.

4.5.1 The lexical hypothesis

The lexical hypothesis predicts two kinds of lexical effects: the effect of word types and the effect of lexical frequency. The former predicts that frequency rates of tonal responses are significantly different from those of lexical responses, and the latter predicts that frequency rates of frequent words [ti53] 'to know' are higher than those of less frequent words [ti31] ‘emperor’. As shown in the top rows of Table 4.16, the two predictions are generally confirmed by the current results, which hence support the lexical hypothesis.

4.5.1.1 The effect of word types

The effect of word types demonstrates the difference between tonal results and lexical results. As shown in Figure 4.12, Figure 4.13, and Figure 4.14 in section 4.4.2.1 above, the frequency rates of low-falling tone (Tone-31) are consistently higher than those of low-falling words [ti31] ‘emperor,’ except for a few stimuli, such as onset-pitch stimulus#2: 110-90 Hz and overall-pitch stimulus#1: 120-60 Hz. As indicated by the T-test analyses and the intra-group comparisons, the difference is more significant (i) in the offset-pitch continuum and the overall-pitch continuum than in the onset-pitch continuum, and is also more significant (ii) in the ambiguous group of stimuli than in the low and the high group of stimuli. Although the difference is found to be less significant in the onset-pitch continuum and in the non-ambiguous group of stimuli, the less-significant findings do not undermine the effect of word types for two reasons. First, although the difference is less significant in the analyses, the preliminary results show a nearly-consistent pattern that frequency rates of low-falling tone are higher than those of [ti31] ‘emperor,’ across the three continua and the three groups of stimuli. Second, the monosyllabic setup of all stimuli may restrict all participants to a lower degree of lexical access, and it seems to have a negative effect on the lexical effect. As a result, the difference between tonal and lexical results supports the effect of word types, and the less-significant findings do not undermine the lexical effect.

4.5.1.2 The effect of lexical frequency/familiarity

The effect of lexical frequency/familiarity demonstrates the difference between responses to [ti53] ‘to know’ and responses to [ti31] ‘emperor’. The frequency factors, contrasting frequent and less frequent tokens/words, are intrinsic to two tonal/lexical responses, as mentioned earlier in the methodological section. As shown in Figure 4.12 and Figure 4.14 in section 4.4.2.1 above, the navy line (tonal results) intersects the boundary (50%) at higher frequency rates of Tone-31, and the sky-blue line (lexical results) does so at lower frequency rates of [ti31] ‘emperor’. The different cross-points indicate that Hai-lu Hakka participants tend to respond to low-falling categories in tonal identification than in lexical recognition. In other words, they are more likely to choose [ti53] ‘to know’ over [ti31] ‘emperor’ than to choose Tone-53 over Tone-31. Such preferences are predictable, since the high-falling word [ti53] ‘to know’ is found to be more frequent/familiar than the low-falling word [ti31] ‘emperor’ in section 4.4.1.3 above, and high-falling tone Tone-53 was also found to be more frequent than low-falling tone Tone-31 (Hsu 2009: 48). The preference of [ti53] ‘to know’ over [ti31] ‘emperor’ supports the effect of lexical frequency. It is worth noting that lexical frequency/familiarity is an inherent factor of two lexical responses. Since lexical frequency/familiarity was not originally set up as an independent factor, the effect of lexical frequency needs to be carefully interpreted and further examined. In general, the effects of word types and lexical frequency/familiarity verify the lexical hypothesis predicting that lexical factors play a role in the contrast of two falling tones in Hai-lu Hakka.

4.5.2 The phonetic/phonological hypothesis

The phonetic/phonological hypothesis predicts two kinds of phonetic/phonological effects: the effect of onset-pitch variations and the effect of overall-pitch variations, but no effect of offset-pitch variations. The effects of onset-pitch variations and overall-pitch variations predict a perceptual boundary between two tonal/lexical responses in the onset-pitch continuum and the overall-pitch continuum, but no perceptual boundary in the offset-pitch continuum. As shown in the middle rows of Table 4.16 above, the three predictions are generally confirmed by the current results, which hence support the phonetic/phonological hypothesis.

4.5.2.1 The effect of onset-pitch variations

The effect of onset-pitch variations demonstrates a perceptual boundary in the onset-pitch continuum, and a significant difference between the low group of onset-pitch stimuli and the ambiguous group, and between the ambiguous group and the high group. As shown in Figure 4.12 above, the perceptual boundary occurs between stimulus#6: 150-90 Hz and stimulus#7: 160-90 Hz in the tonal results, and it occurs between stimulus#5: 140-90 Hz and stimulus#6: 150-90 Hz in the lexical results. The different loci of perceptual boundaries indicate the lexical effect, as argued above. The perceptual boundaries indicate that variations of onset pitch play a crucial role in the contrast of two tonal/lexical responses. In general, the lower the onset-pitch variations, the more likely they will be perceived as low-falling responses. The higher the onset-pitch variations, the more likely they will be perceived as high-falling responses. The boundary between the two responses occurs around 150 Hz, i.e. a mid-high pitch register. The descriptive tendencies are supported by the phonetic/phonological analyses indicating that the frequency rates of low onset-pitch stimuli and ambiguous onset-pitch stimuli are significantly different from those of ambiguous onset-pitch stimuli and high onset-pitch stimuli respectively. In addition, the phonetic/phonological analyses indicate that there are three intra-group differences in tonal results, and only one difference in lexical results. The differences indicate that onset-pitch variations are more likely to affect Hai-lu Hakka participants' judgments of tonal responses than their lexical judgments. To sum up, these findings consistently confirm the effect of onset-pitch variations, and hence support the phonetic/phonological hypothesis.

4.5.2.2 No effect of offset-pitch variations

Offset-pitch variations predictably demonstrate no perceptual boundary in the offset-pitch continuum, but unexpectedly lead to a significant difference between the ambiguous group and the high group of offset-pitch stimuli in the lexical results. As shown in Figure 4.13

above, there is no clear perceptual boundary in the offset-pitch continuum for two reasons. First, the navy and the sky-blue lines (tonal and lexical results respectively) intersect the 50% boundary twice, around stimulus#2: 160-70 Hz and stimulus#3: 160-80 Hz in a low pitch register, and around stimulus#7: 160-120 Hz and stimulus#9: 160-140 Hz in a high pitch register. Second, the frequency rates of offset-pitch stimuli are consistently at a chance level (lower than 70% and higher than 25%, about 50%). In other words, variations of offset pitch do not favor either kind of tonal/lexical responses. The descriptive patterns are partially supported by the phonetic/phonological analyses indicating that the frequency rates of low offset-pitch stimuli and ambiguous offset-pitch stimuli are not significantly different from those of ambiguous offset-pitch stimuli and high offset-pitch stimuli respectively in tonal identification.

However, the analyses indicate an exception in which the frequency rates of ambiguous offset-pitch stimuli are significantly different from those of high offset-pitch stimuli in lexical recognition. The findings indicate that although variations of offset pitch are less likely to affect the contrast of two falling tones, they seem able to contrast two falling words, particularly from the ambiguous pitch register to the high level. As shown in Figure 4.13 above, the significant difference indicates that there are more high-falling responses to the ambiguous group of offset-pitch stimuli in lexical results than in tonal results. In addition, the phonetic/phonological analyses indicate that there is an intra-group difference in the tonal and the lexical results, between stimulus#2: 160-70 Hz and stimulus#3: 160-80 Hz. The intra-group differences indicate that although variations of offset pitch, from the low pitch register to an ambiguous level, are less likely to affect the contrast of two falling categories (both tonal and lexical responses), there seems an effect of offset pitch, from 70 Hz to 80 Hz. As indicated by Titze (1994: 188), the *f0* range of male adults is between 80 and 180 Hz, and that of female is between 160 and 260 Hz. As to young speakers, the *f0* range can be even higher than 400 Hz. In other words, it is atypical to produce or to perceive a sound with *f0* lower than 80 Hz. The very low pitch register, as in stimulus#1: 160-60 Hz and stimulus#2: 160-70 Hz, is atypical to high-falling tone, and seems to cause Hai-lu Hakka speakers to perceive the very low pitch, such as 60 and 70 Hz, as low-falling categories.

To sum up, these findings mostly confirm the prediction on no effect of offset-pitch variations, but variations of offset pitch may exert an influence on the tonal contrast in some atypical cases, such as in a very low pitch register and a very high pitch register. Therefore, these findings generally support the phonetic/phonological hypothesis that predicts a phonetic/phonological effect of the contrast of two falling tones.

4.5.2.3 The effect of overall-pitch variations

The effect of overall-pitch variations demonstrates a perceptual boundary in the overall-pitch continuum and a significant difference between the low group and the ambiguous group of overall-pitch stimuli (but not between the ambiguous group and the high group). As shown in Figure 4.14 above, the perceptual boundary occurs between stimulus#4: 150-90 Hz and stimulus#5: 160-100 Hz in tonal results, and it occurs near stimulus#4: 150-90 Hz in lexical results. The different loci of perceptual boundaries indicate the lexical effect, as argued above. The perceptual boundaries indicate that overall-pitch variations play a crucial role in the contrast of two tonal/lexical responses. In general, the lower the overall-pitch variations, the more likely they will be perceived as low-falling responses. The higher the overall-pitch variations, the more likely they will be perceived as high-falling responses. The boundary between the two responses occurs around 150 Hz, i.e. a mid-high pitch register. The descriptive tendencies are supported by the phonetic/phonological analyses indicating that the frequency rates of low overall-pitch stimuli are significantly different from those of ambiguous overall-pitch stimuli (but not between the ambiguous group and the high group).

In addition, the intra-group comparisons are consistent with inter-group comparisons indicating that there are two to three intra-group differences in tonal and lexical results, and all of the differences occur in the low group and the ambiguous group of overall-pitch stimuli. The intra-group differences indicate that overall-pitch variations from the low pitch register to the ambiguous level are more likely to affect Hai-lu Hakka participants' contrast of two falling tones. To sum up, these findings generally confirm the effect of overall-pitch variations with a less-significant influence on the high group of overall-pitch stimuli, supporting the phonetic/phonological hypothesis.

In general, the results and analyses support the phonetic/phonological hypothesis. These findings suggest that variations of onset pitch exert a more significant influence on the contrast of two falling tones than variations of offset pitch and overall pitch, and variations of offset pitch are the least crucial. Although these phonetic/phonological factors were found to play a different role (some are more crucial than the others), they exert an influence on speech processing of the two falling tones more or less under different conditions, such as the low versus high pitch register. In other words, it seems problematic to define these factors as either phonetic or phonological features in accessing their roles in speech processing. Their influences may exhibit a continuous or a categorical pattern, and the patterns are correlated with various phonetic details. In addition, variations of pitch height seem more crucial than degrees of pitch drop, as suggested by the similar loci of perceptual boundaries in the onset-pitch continuum and the overall-pitch continuum. As shown in Figure 4.12 and 4.14 above, the perceptual boundaries occur consistently in the mid-high pitch register (i.e. 4 on the 5-point scale), from 140 Hz to 160 Hz, especially near 150 Hz, but the degrees of pitch drop are more tolerable (Tone-42 or Tone-43).

4.5.3 The interaction hypothesis

The interaction hypothesis predicts two kinds of interaction effects. First, the phonetic/phonological factors play a more significant role in tonal identification than in lexical recognition. Second, the phonetic/phonological effects exhibit a different pattern between tonal identification and lexical recognition results. The first kind of interaction effects demonstrates that there are more intra-group differences in tonal results than in lexical results. The second kind of interaction effects demonstrates that variations of offset pitch, especially from the ambiguous pitch register to the high pitch register, are more likely to exert an influence on the tonal contrast in lexical recognition than in tonal identification. In addition, the lexical analyses indicate that the lexical factors exert a more significant influence on phonetically ambiguous stimuli than less ambiguous stimuli. As shown in the bottom rows of Table 4.16 above, the two predictions are generally confirmed by the current results. The two findings, as well as the additional findings of more significant lexical effects on phonetically ambiguous stimuli, hence support the interaction hypothesis.

4.5.3.1 More intra-group differences

The results of more significant phonetic/phonological effects on tonal identification demonstrate more intra-group differences in tonal results than in lexical results, especially among onset-pitch stimuli and overall-pitch stimuli. Descriptively speaking, there are seven intra-group differences in tonal results (three in onset-pitch stimuli, one in offset-pitch stimuli, and three in overall-pitch stimuli), whereas there are only five intra-group differences in lexical results (one in onset-pitch stimuli, one in offset-pitch stimuli, and three in overall-pitch stimuli). Such an interaction effect indicates that variations of pitch height, particularly onset pitch, are more likely to cause the contrast of two falling tones to be confusing in tonal processing than in lexical processing. The finding suggests that pitch variations modified by multiple phonetic/phonological factors play a more significant role in tonal processing than in lexical processing. Hai-lu Hakka speakers rely on more phonetic/phonological knowledge in speech processing of two falling tones (Tone-31 and Tone-53) than in speech processing of two falling words ([ti31] 'emperor' and [ti53] 'to know'). In other words, they are less susceptible to tonal variations in lexical recognition than in tonal identification.

4.5.3.2 Different roles of offset-pitch variations

The results of phonetic/phonological effects' different patterns demonstrate that offset-pitch variations from the ambiguous pitch register to the high level are more likely to exert an influence on the tonal contrast in lexical recognition than in tonal identification. The differences indicate that there are more lexical responses to [ti53] 'to know' in the ambiguous group of offset-pitch stimuli. As discussed in section 4.4.4 above, the differences may result from accessing different knowledge in tonal processing and lexical processing (different degrees of lexical access), and/or from a more significant influence of lexical frequency. Regardless of the reasons, the results indicate an interaction between lexical and phonetic/phonological factors. Such an interaction effect indicates that although pitch variables of offset-pitch stimuli seem to be ambiguous, regardless of offset-pitch variations from the low pitch register to the high level, they are more contrastive to the two falling categories in lexical recognition than in tonal identification, especially from the ambiguous pitch register to the high level. The offset-pitch variations in the ambiguous pitch register are arguably more contrastive, since they are more likely to be recognized as [ti53] 'to know' than as ambiguous words. The different roles of offset-pitch variations suggest that Hai-lu Hakka participants are less likely to confuse the ambiguous group of offset-pitch variations in lexical processing than in tonal processing. In other words, they are less susceptible to offset-pitch variations in the ambiguous pitch register in lexical recognition than in tonal identification.

4.5.3.3 More significant lexical effects

The results of more significant lexical effects on phonetically ambiguous stimuli demonstrate that lexical factors exert a more significant influence on offset-pitch and overall-pitch stimuli than onset-pitch stimuli, and a more significant influence on the ambiguous group of variations than two other groups. The more significant lexical effects indicate that frequency rates of tonal and lexical responses are more different in phonetically ambiguous stimuli. Such an interaction effect indicates that Hai-lu Hakka participants access more lexical knowledge to process ambiguous tonal variations. The findings suggest that lexical factors play a more significant role in phonetically ambiguous cases than in less phonetically ambiguous ones. In other words, lexical factors serve the remedy the process of various kinds of tonal variations in connected speech, and they seem to be more reliable and efficient cues for Hai-lu Hakka participants to process different variations of falling tones.

In general, Hai-lu Hakka's results indicate three findings in support of interactions between lexical and phonetic/phonological factors. First, the more intra-group differences suggest that Hai-lu Hakka participants are more susceptible to pitch variations in tonal processing than in lexical processing. Second, the different roles of offset-pitch variations suggest that Hai-lu Hakka participants are less susceptible to offset-pitch variations in the ambiguous pitch register in lexical recognition than in tonal identification. Third, the more significant lexical effects suggest that Hai-lu Hakka participants access more lexical knowledge to process ambiguous tonal variations. These interaction effects suggest a crucial implication for speech processing of Hai-lu Hakka's falling tones: Hai-lu Hakka participants are more susceptible to different kinds of tonal variations in tonal processing, and less susceptible to phonetically ambiguous variations in lexical processing. These tonal variations defined by pitch perturbations seem to be less ambiguous due to a significant influence of lexical access. In other words, lexical influences seem to determine whether or not variations of two falling tones are ambiguous to Hai-lu Hakka speakers.

4.6 Conclusion: general discussion, research questions, and implications

The current results generally support the three hypotheses: the lexical hypothesis, the phonetic/phonological hypothesis, and the interaction hypothesis, as summarized in Table

4.16 above. They indicate that both lexical and phonetic/phonological factors play a role in speech processing of falling tones, and the two kinds also interact with each other to some extent. These findings are further discussed in section 4.6.1 below, and then are used to answer three research questions in section 4.6.2. These findings indicate that pitch variations modified by phonetic factors may distort the contrast of two falling tones, and induce perceptual confusion between the two falling categories. Moreover, these findings suggest two crucial implications for a model of speech processing. First, lexical effects seem to be more consistent than phonetic/phonological effects. Second, lexical effects seem better able to reduce deviations and other differences derived from pitch variations. The two implications suggest that lexical factors play a more crucial role in speech processing. Therefore, the current results are more likely to favor a lexically-based model, i.e. the exemplar-based theory.

4.6.1 General discussion on three hypotheses

The current results generally support the three hypotheses, except for a few different findings. For instance, (i) as to the lexical hypothesis, there is a less significant lexical effect on onset-pitch stimuli in Hai-lu Hakka. (ii) As to the phonetic/phonological hypothesis, offset-pitch variations play a different role in the tonal and lexical results. These different findings generally do not contradict the hypotheses. The three hypotheses and different findings are discussed below. In general, the results indicate that both lexical and phonetic/phonological factors exert a significant influence on speech processing of two falling tones. As the two kinds of factors interact, lexical factors seem to exhibit a more consistent effect than phonetic/phonological factors. Phonetic/phonological factors are likely to exert a different pattern in tonal processing and in lexical processing.

4.6.1.1 More consistent patterns of lexical factors

The lexical hypothesis predicts an influence of word types and frequency variables on speech processing of two falling tones. Hai-lu Hakka's results confirm the lexical effects, except for less significant results of onset-pitch stimuli. The results indicate that frequency rates of tonal and lexical responses are significantly different in offset-pitch and overall-pitch continua, especially those stimuli in the ambiguous pitch register. Although the difference is less significant in onset-pitch stimuli and in non-ambiguous groups of stimuli, the pattern is generally consistent across 30 stimuli, which indicates that Hai-lu Hakka participants are more likely to respond to [ti53] 'to know' than to Tone-53, except for two stimuli, i.e. onset-pitch stimulus#2 and overall-pitch stimulus#1. These results confirm the two predictions that frequency rates of tonal and lexical responses are significantly different, and participants are more likely to respond to frequent/familiar words than to less frequent/familiar words. As a result, they support the lexical effects on speech processing of two falling tones in Hai-lu Hakka. The lexical effects tend to be more significant in ambiguous tonal variations, and exhibit a consistent pattern across three pitch continua.

4.6.1.2 More variable patterns of phonetic/phonological factors

The phonetic/phonological hypothesis predicts an influence of onset-pitch and overall-pitch variations on speech processing of two falling tones, but no effect of offset-pitch variations. The current results confirm the phonetic/phonological effects, except for some different patterns in offset-pitch and overall-pitch variations.

The results indicate that (i) frequency rates of low and ambiguous onset-pitch variations are significantly different from those of ambiguous and high onset-pitch variations respectively in both tonal and lexical results. (ii) Frequency rates of low and ambiguous offset-pitch variations are not significantly different from those of ambiguous and high offset-pitch variations respectively in both tonal and lexical results, except for a significant difference between frequency rates of ambiguous and high offset-pitch variations in lexical results. (iii) Frequency rates of low overall-pitch variations are significantly different from those of ambiguous overall-pitch variations, but frequency rates of ambiguous overall-pitch variations are not significantly different from those of high overall-pitch variations in both tonal and lexical results. Although offset-pitch and overall-pitch variations show a somewhat different pattern from the predictions, the results indicate that all these pitch variations cause Hai-lu Hakka participants to respond to different falling tones and words.

The results generally confirm the three predictions that perceptual boundaries occur in both onset-pitch and overall-pitch continua, but not in an offset-pitch continuum. Although offset-pitch and overall-pitch variations play a different role in speech processing of two falling tones, they still indicate some kinds of phonetic/phonological effects. Therefore, these results support the phonetic/phonological effects on speech processing of two falling tones in Hai-lu Hakka. The phonetic/phonological effects tend to be more significant in onset-pitch variations than offset-pitch and overall pitch variations. They also tend to play a different role in tonal and lexical processing and exhibit a different pattern in Hai-lu Hakka. In other words, the phonetic/phonological effects vary with (i) different groups of pitch variations and (ii) different levels of processing. These differences suggest that the phonetic/phonological effects exhibit a less consistent pattern across tonal variations and processing levels.

4.6.1.3 Two interaction patterns

As to the interaction hypothesis, it generally predicts a different role of tonal variations in tonal and lexical processing, and the difference indicates an interaction between lexical and phonetic/phonological factors. The current results indicate some different findings between tonal identification and lexical recognition, and these findings confirm the interaction hypothesis. These different findings include (i) more intra-group differences between two consecutive tonal variations in tonal results than in lexical results, (ii) different roles of offset-pitch variations in tonal and lexical results, and (iii) more significant lexical effects on phonetically ambiguous tonal variations.

The first findings indicate that Hai-lu Hakka participants are more susceptible to pitch variations in tonal processing than in lexical processing. The second and the third findings indicate that Hai-lu Hakka participants are more likely to process ambiguous offset-pitch variations as non-ambiguous responses (i.e. [ti53] 'to know') in lexical results than in tonal results. The ambiguous offset-pitch variations, the low offset-pitch variations, and the ambiguous overall-pitch variations are more likely to be perceived as ambiguous falling tones in tonal results. In other words, these findings suggest two crucial interaction patterns in Hai-lu Hakka, as shown in (28) below. First of all, as shown in (28a), pitch variations of three continua play a less significant role in lexical processing than in tonal processing. Since Hakka participants are more susceptible to pitch variations in tonal processing than in lexical processing, pitch variations are less likely to affect these participants' lexical decision than their tonal classification. Second, as shown in (28b), tonal variations are less ambiguous in lexical processing than in tonal processing. Since Hakka participants are more likely to process ambiguous tonal variations as non-ambiguous responses in lexical processing than in tonal processing, these ambiguous tonal variations are less ambiguous in lexical processing than in tonal processing. The two interaction patterns not only confirm that tonal variations play a different role in tonal and lexical processing, but also suggest a crucial role of lexical factors in processing the two falling tones. As a result, they support the interaction between lexical and phonetic/phonological factors in speech processing of Hai-lu Hakka's falling tones.

(28) Two interaction patterns in the contrast of two falling tones

a. Pitch variations play a less significant role in lexical processing than in tonal processing.

b. Ambiguous tonal variations are less ambiguous in lexical processing than in tonal processing.

4.6.2 Three research questions on the contrast of falling tones

As discussed above, these results verify the three hypotheses, and provide positive answers to three research questions concerning the effects of lexical and phonetic/phonological factors and the interaction between the two kinds of factors. As to the first research question on lexical effects, the results indicate that lexical factors, including word types and lexical frequency/familiarity, cause Hai-lu Hakka speakers to process two falling tones in different manners. For instance, as to the ambiguous tonal variations, Hai-lu Hakka participants are more likely to respond to a frequent/familiar word [ti53] 'to know' than to a less frequent/familiar word [ti31] 'emperor'. As to the second research question on phonetic/phonological effects, the results indicate that phonetic/phonological factors, including onset-pitch variations, offset-pitch variations, offset-pitch variation, and pitch registers of two falling tones, cause Hai-lu Hakka speakers to process two falling tones in different manners. For instance, Hai-lu Hakka participants tend to process the low group of onset-pitch variations as low-falling responses, the ambiguous group of onset-pitch variations as ambiguous responses, and the high group of onset-pitch variations as high-falling responses. As to the third research question on the interaction between lexical and phonetic/phonological factors, the results indicate that the two kinds of factors interact with each other to cause Hai-lu Hakka speakers to process two falling tones in different manners. For instance, Hai-lu Hakka participants are more likely to process an ambiguous group of offset-pitch variations as high-falling responses in lexical processing than in tonal processing.

4.6.3 Implications

Hai-lu Hakka participants' responses to 30 hybrid stimuli are summarized below in terms of three continua. Their tonal responses are classified into three kinds: low-falling tone, ambiguous falling tones, and high-falling tone, and their lexical responses are also classified into three kinds accordingly: a low-falling word, an ambiguous word, and a high-falling word.

Their responses to 10 onset-pitch stimuli are shown in Table 4.17 below; their responses to 10 offset-pitch stimuli are shown in Table 4.18; and their responses to 10 overall-pitch stimuli are shown in Table 4.19. In general, these responses to the three continua indicate that Hai-lu Hakka participants tend to process one third of these falling-tone variations, especially offset-pitch and overall-pitch variations, as ambiguous responses. The tendency for ambiguous responses indicates that tonal confusion between two falling tones is very likely to result from the influence from various lexical and phonetic/phonological factors in Hai-lu Hakka.

Table 4.17 Hai-lu Hakka participants' responses to 10 onset-pitch stimuli (x: ambiguous responses on a 75% basis).

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
P. scales	32	32	32	42	42	42	42	52	52	52
Tonal	31	31	31	31	31	x	x	x	53	53
Lexical	ti31	ti31	ti31	ti31	ti31	x	x	ti53	ti53	ti53

As shown in Table 4.17 above, Hai-lu Hakka participants' responses to 10 onset-pitch stimuli show a consistent pattern. The consistent patterns indicate that participants tend to process onset-pitch stimuli with a low onset-pitch register (lower than 150 Hz) as low-falling responses, those with a high onset-pitch register (higher than 170 Hz) as high-falling responses, and those in between as ambiguous responses. Although these responses show a categorical pattern in each set of results (i.e. tonal and lexical), they also demonstrate a gradient pattern between the two sets, especially to high-falling responses. The gradient pattern indicates that participants tend to choose high-falling responses in lexical processing more than in tonal processing. In other words, there are fewer ambiguous responses in lexical processing than in tonal processing.

Table 4.18 Hai-lu Hakka participants' responses to 10 offset-pitch stimuli (x: ambiguous responses on a 75% basis).

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
P. scales	41	41	42	42	43	43	43	44	44	44
Tonal	x	x	x	x	x	x	x	x	x	x
Lexical	x	x	ti53	x	ti53	x	x	x	x	x

As shown in Table 4.18 above, Hai-lu Hakka participants' responses to 10 offset-pitch stimuli show a less consistent pattern. The patterns indicate that participants tend to process offset-pitch stimuli with a MH onset-pitch register (160 Hz) as ambiguous responses, regardless of offset-pitch variations, except for a few offset-pitch variations with a low offset-pitch register (i.e. 80 Hz). Although these responses generally show a gradient pattern in each set of results (i.e. tonal and lexical), they also demonstrate a nearly-categorical pattern in some parts of lexical results, for instance, between the ambiguous group and the high group of offset-pitch stimuli in the lexical results. The nearly-categorical pattern indicates that Hai-lu Hakka participants tend to process the ambiguous group of offset-pitch stimuli as less ambiguous responses in lexical processing, but still process them as ambiguous responses in tonal processing. In other words, there are fewer ambiguous responses in lexical processing than in tonal processing.

Table 4.19 Hai-lu Hakka participants' responses to 10 overall-pitch stimuli (x: ambiguous responses on a 75% basis).

Stimuli	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
P. scales	31	41	42	42	43	53	53	54	54	54
Tonal	31	31	31	x	x	53	x	x	x	x
Lexical	ti31	ti31	x	x	x	ti53	ti53	ti53	x	x

As shown in Table 4.19 above, Hai-lu Hakka participants' responses to 10 overall-pitch stimuli also show a less consistent pattern. The less consistent patterns include both categorical and gradient patterns. The categorical part indicates that participants tend to process overall-pitch stimuli in the low pitch register (lower than 150 Hz) as low-falling responses, and those in a non-low pitch register (higher than 150 Hz) as non-low-falling responses. The gradient part indicates that they tend to process overall-pitch stimuli in the ambiguous or the high pitch register (higher than 150 Hz) as ambiguous or high-falling responses, regardless of overall-pitch variations. The gradient pattern is also demonstrated by the comparison between tonal and lexical results, which indicates that participants tend to choose high-falling responses in lexical processing more than in tonal processing. In other words, there are fewer ambiguous responses in lexical processing than in tonal processing.

In general, these responses suggest three implications for tonal variations, Hai-lu Hakka's falling tones, and speech processing. First, they exhibit both continuous and categorical patterns in phonetically-induced tonal variations. It seems contradictory to classify phonetically-induced variations as continuous/gradient and phonologically-driven variations as categorical/distinct as in a conventional/generative approach. Second, they demonstrate some tonal confusion in Hai-lu Hakka. It seems indispensable to investigate Hai-lu Hakka's own tonal patterns, although most previous studies and teaching materials tend to relate Hai-lu Hakka's tones to other languages'. Third, participants tend to process ambiguous tonal variations as less ambiguous responses in lexical results than in tonal results, suggesting that lexical factors play a more consistent and efficient role than phonetic/phonological factors in speech processing of Hai-lu Hakka's two falling tones. As a result, a lexically-based model seems to be a more favorable approach to speech processing in general.

CHAPTER FIVE

PERCEPTIBILITY AND PRODUCTIVITY OF TONE SANDHI RULES

This dissertation examines how variations influence Hai-lu Hakka's two tonal patterns: the contrast of two falling tones and the application of two tone sandhi rules. Chapter 5 focuses on the role of various factors (i.e. lexical factors, phonetic/phonological factors, and processing factors) in the tone-sandhi application. The current methods include 31 Hai-lu Hakka participants and four processing tasks (i.e. a tonal discrimination task, a tonal identification task, a lexical recognition task, and a production task). The results indicate that (i) both lexical and the phonetic/phonological factors play a role in the application of tone sandhi, and that (ii) the two kinds of factors may interact with each other to exert an additional influence. In addition, the phonetic/phonological effects are found to exhibit different patterns across different tasks (currently defined as processing factors), which indicates (iii) an influence from different degrees of lexical access and an asymmetry between perception and production processes. These findings demonstrate that variations derived from different lexical and phonetic/phonological factors affect the application of tone sandhi to various degrees, and suggest that Hai-lu Hakka's tone sandhi rules are less productive than assumed previously.

5.0 Introduction

This chapter examines lexical and phonetic/phonological effects on speech processing of two phonological variations derived from tone sandhi in Hai-lu Hakka. As shown earlier and repeated in (29) below, Hai-lu Hakka includes two tone sandhi patterns: low-rising tone sandhi and high-checked tone sandhi. The former rule changes low-rising tone into low-level tone in non-final position, as shown in (29a), and the latter changes high-checked tone into low-checked tone in the same context, as shown in (29b). As discussed in section 2.2 above, the two phonological rules exhibit some specific patterns and issues, such as exceptions to many different words (e.g. numerals, classifiers, and demonstratives) and new patterns emerging from an influence of ongoing tonal mergers. For instance, the numeral [ljɔk$\underline{5}$] ‘six’ and the classifier [pun13] do not undergo high-checked tone sandhi and low-rising tone sandhi respectively in the noun phrase [ljɔk$\underline{5}$-pun13-ʂu53] ‘six-classifier-book: six books’. These variations may play a role in speech processing of Hai-lu Hakka tone sandhi.

(29) Hai-lu Hakka’s tone sandhi rules

a. Low-rising tone sandhi: Tone-13 (low-rising tone)→ Tone-22 (low-level tone)/ ____ in non-final position

b. High-checked tone sandhi: Tone-$\underline{5}$ (high-checked tone)→ Tone-$\underline{2}$ (low-checked tone)/ ____ in non-final position

This chapter examines both perception and production processes of Hai-lu Hakka tone sandhi for three reasons. First of all, previous studies (Chen et al 2010; Chuang et al 2011; Hsieh 1970, 1976; Wang 1995; Zhang & Lai 2010; Zhang et al 2011) mostly focused on the productivity issue that evaluates the psychological reality of tone sandhi by application rates of tone sandhi in Mandarin and Taiwan Southern Min. The higher the application rates in novel words, the more likely the tone sandhi’ psychological reality will be confirmed. This dissertation intends to add to the literature a new case study with rather different tone sandhi patterns from those in Mandarin and Taiwan Southern Min. Second, some of these studies also focused on the phonetic-naturalness issue that evaluates the role of phonetic/phonological factors in the application of tone sandhi, but they simply attended to the effect of sandhi types (i.e. more phonetically natural rule vs. less phonetically natural rule). This dissertation examines whether or not sandhi types and other phonetic/phonological factors play a role in the application of Hai-lu Hakka’s tone sandhi. Third, these previous studies predominantly adopted a production approach to examining the psychological-reality issue and the phonetic-naturalness issue. It is unclear how the two issues can be interpreted in terms of perception, and this dissertation explores the issues both in speech perception and production.

This chapter is organized as follows. Section 5.1 introduces previous studies on the productivity of tone sandhi, and discusses their implications for tone sandhi. The next section focuses on potential effects on Hai-lu Hakka tone sandhi, and proposes specific research questions and hypotheses on the potential lexical and phonetic/phonological effects. In section 5.3, the methodology part includes several experimental setups (e.g. participants, stimuli, and task types) and detailed predictions. Section 5.4 presents both preliminary results and statistical analyses, and section 5.5 analyzes the data regarding the psychological-reality issue and the phonetic-naturalness issue in particular. The results and analyses are discussed in section 5.6. In section 5.7, the concluding section summarizes the findings and suggests the implications for speech processing of Hai-lu Hakka tone sandhi.

5.1 Productivity of tone sandhi and implications for psychological reality

Previous studies (Chen et al 2010; Chen et al 2012; Chuang et al 2011; Hsieh 1970, 1976; Wang 1995; Wang 2011; Zhang & Lai 2010; Zhang et al 2011; Zhang & Meng 2012; and many others) examined the productivity of tone sandhi mostly by addressing two crucial issues: psychological reality and phonetic naturalness. The psychological-reality issue concerns whether or not tone sandhi is lexically bound, and the phonetic-naturalness issue concerns whether phonetic factors exert an influence on the productivity of tone sandhi. The former focuses on lexical effects, and the latter focuses on phonetic/phonological effects. These studies suggest that application rates of tone sandhi are correlated to multiple linguistic factors. In other words, many different variations play a crucial role in the application of tone sandhi, which challenges the previous assumption that considers tone sandhi to be fully productive. This section reviews Wang's (2011) acquisition study on T3 sandhi and other productivity studies on adult L1 speakers in section 5.1.1. Section 5.1.2 discusses these studies' implications for tone sandhi, and section 5.1.3 summarizes these studies' findings and their theoretical implications. In general, the previous studies indicated that tone sandhi rules are less productive than assumed previously, which casts doubt on tone sandhi's psychological reality and challenges the previous assumption on tone sandhi.

5.1.1 Three kinds of productivity studies on tone sandhi

These productivity studies (Chen et al 2010; Chen et al 2012; Chuang et al 2011; Hsieh 1970, 1976; Wang 1995; Wang 2011; Zhang & Lai 2010; Zhang et al 2011) basically include three kinds of approaches: (i) tonal acquisition, (ii) phonetic and priming analyses, and (iii) multiple lexical and phonetic/phonological factors. Those studies on Mandarin tone sandhi adopted the first two approaches, whereas those on Southern Min tone sandhi adopted the third approach. The different approaches seem to be correlated to the two languages' sandhi patterns. As deduced from Zhang & Lai (2010) and Zhang et al (2011), Mandarin's sandhi patterns are considered more phonologically transparent than Southern Min's. Southern Min's tone sandhi was argued to be more opaque phonologically by Zhang et al (2011), since it demonstrates a circle-like chain shift. Regardless which approach was adopted, these studies indicated a difference between tone sandhi processes of actual words and novel words.

5.1.1.1 The first kind: acquisition of Mandarin T3 sandhi by young L1 speakers

Studies adopting the first approach through the lens of tonal acquisition include Wang (2011) and Zhu & Dodd (2000), especially Wang (2011). Wang (2011) examined effects on processing strategies on the application of Mandarin T3 sandhi based on children's acquisition of T3 sandhi. As mentioned earlier and repeated in (30) below, T3 sandhi changes T3 into T2 before another T3. Wang (2011) recruited tens of Mandarin-speaking children at the age of three to six to perform five different tasks that require participants to apply T3 sandhi accordingly. The five tasks include spontaneous speech, flat structures, nominal phrases, natural speech repetition, and synthetic speech repetition. For instance, Mandarin-speaking children were instructed to read wu3 'five' for three or five times continuously in a flat-structure task which requires them to apply T3 sandhi for multiple times in a flat structure without syntactic branching or hierarchy, whereas they were instructed to produce innovated nominal compounds, such as duan3-tui3-ma3 'short-leg-horse,' in a nominal-phrase task which requires the participants to apply T3 sandhi for a couple times in a hierarchical structure.

(30) Mandarin T3 sandhi and half T3 sandhi

a. T3 sandhi: T3 (214)→ T2 (35)/ ___ T3 (214)

b. Half T3 sandhi: T3 (214)→ 21/ ___ any other tone (i.e. T1, T2, and T4)

The results showed that both young and adult L1 speakers demonstrated variations of T3 sandhi in each task, and these variations may result from different processing strategies applied by the two groups of participants. For instance, in the nominal-phrase task, children were able to apply T3 sandhi cyclically in the same way as adults, but they may resort to the non-cyclic strategy in more complex compounds. The findings indicated that although young speakers know to change T3 to T2 before another T3, it takes time for them to acquire adult-like strategies to set up prosodic domains for applying T3 sandhi. That is, these young participants, even the six-year-olds in the oldest group of young speakers, did not yet acquire how to apply T3 sandhi fully to an adult level,.

Wang's (2011) findings question the previous claim made by Zhu & Dodd (2000) that T3 sandhi is acquired earlier than the age of two. The different findings are very likely to result from methodological differences in task types and word types, which require participants to perform T3 sandhi in different manners. For instance, Wang's (2011) tasks mostly require participants to apply T3 sandhi for multiple times in innovated words, whereas a conventional format of picture-naming adopted by Zhu & Dodd (2000) simply requires them to 'recall' T3 sandhi in some learned words. In addition to the effect of processing strategies (as factors of task types), their different findings also indicate the effect of word types (novel words vs. actual words) on young speakers' application rates of T3 sandhi. In other words, there seems to be a productivity issue in tonal acquisition of T3 sandhi, which suggests T3 sandhi may be lexicalized in young speakers' grammars.

5.1.1.2 The second kind: T3 sandhi and half T3 sandhi by adult L1 speakers

The second approach that adopted phonetic and priming analyses includes Chen et al (2012) and Zhang & Lai (2010). Both studies focused on the application of Mandarin T3 sandhi. They are more interested in spectrographic analyses on pitch contour than degrees of application rates.

First of all, Zhang & Lai (2010) compared application accuracy of Mandarin T3 sandhi and half T3 sandhi in terms of pitch contour and syllable duration. As indicated in (30) above, T3 sandhi changes T3 into T2 before another T3, while half T3 sandhi changes T3 into a low-falling variant Tone-21 before any tones other than T3 (i.e. T1, T2, and T4). Half T3 sandhi was argued to be more phonetically motivated, and hence was predicted to be more accurate in production. They recruited about 20 and 30 adult speakers for a production task that requires participants to combine two separate monosyllabic words of two word types (actual words and novel words) into a disyllabic compound. When a T3 word occurs in non-final position, T3 sandhi and half T3 sandhi may apply. For instance, they were instructed to combine lao3 'old' and hu3 'tiger' as a compound lao**2**hu3 'tiger,' in which T3 sandhi changes lao3 'old' to lao2. The results showed that pitch contour is significantly different between actual words and novel words in T3 sandhi application, but the difference is not significant in the application of half T3 sandhi. Syllable duration was also found to be not significantly different between actual words and novel words in the application of two sandhi rules. The findings supported the prediction that the more phonetically-motivated rule is more accurate in production than the less phonetically-motivated one. They suggested that phonetic factors play a role in tone sandhi application, and T3 sandhi is less productive in the phonetic implementation of pitch contour.

Second, Chen et al (2012) compared the production of homophonous disyllabic sequences with and without T3 sandhi in terms of response time. They recruited 48 adult speakers for a production task that requires participants to produce four kinds of stimuli: (i) disyllabic sequences after application of T3 sandhi that have homophonous first syllables (ex: 起舞 **qi3**-wu3 'to start dancing', 乞討 **qi3**-tao3 'to beg' vs. 奇險 qi2-xian3 'adventure', 祈禱 qi2-dao3 'prayer'), (ii) homophonous disyllabic sequences before application of T3 sandhi that have homophonous first syllables (ex: 導演 **dao3**-yan3 'director', 搗鬼 **dao3**-gui3 'to do mischief' vs. 倒楣 dao3-mei2 'bad luck', 島國 dao3-guo2 'island nation'), (iii) T2-T3 or T3-T2 disyllabic sequences without tone sandhi application (ex: 執法 zhi2-fa3 'law enforcement', 直尺 zhi2-chi3 'straightedge' vs. 紙錢 zhi3-qian2 'spirit money', 指頭 zhi3-tou2 'fingertips'), and (iv) control T1-T3 disyllabic sequences (ex: 織女 zhi1-nv3 'female weavers', 知己 zhi1-ji3 'a confidant' vs. 紙牌 zhi3-pai2 'playing cards', 指頭 zhi3-tou2 'fingertips'). The results showed that the response time to the first two kinds of stimuli (i.e. disyllabic sequences with homophonous first syllables before and after application of T3 sandhi) is not significantly different from that to the third kind (i.e. disyllabic sequences without T3 sandhi application), but is longer in response time than the fourth kind (i.e. T1-T3 disyllabic sequences). The response time to the first three kinds of stimuli, made up by T2 and T3, is significantly longer than that to the last kind, made up by T1 and T3, suggesting that it takes a longer response time to process two phonetically similar tones than to process phonetically different tones. Since the response time to disyllabic sequences with and without the application of T3 sandhi is not significantly different, it suggests that T2-T3 sequences with underlying T2-T3 and T3-T3 may be processed in similar manners. In addition, T2, T3, and the derived T2 were found to be spectrographically similar in initial pitch contour. As a result, Chen et al (2012) argued that since the response time to disyllabic sequences with and without application of T3 sandhi is not significantly different, both the underlying and sandhi forms of T3 are stored and prepared for articulatory processes. In other words, the similar response time and similar initial pitch contour suggest that T3 sandhi is not fully productive phonologically and/or is lexically bound, which casts doubt on T3 sandhi's psychological reality.

5.1.1.3 The third kind: Taiwan Southern Min's tonal circle by adult L1 speakers

The third approach that examined multiple lexical and phonetic/phonological factors includes Hsieh (1970, 1976), Wang (1995), and Zhang et al (2011). The three studies consistently focused on the psychological-reality issue to examine the application rates of Taiwan Southern Min tone sandhi. Their results generally indicated that Southern Min's tone sandhi rules are not automatically applicable to novel words. In other words, they are bound to actual words, and hence are considered to be lexically bound.

As indicated in (31) below, Southern Min's tone sandhi rules form a chain shift (Peng 1997; Tsay & Myers 1996; Wang 1995; Zhang et al 2011). The chain shift looks like a tonal circle made up by seven individual rules: a. low-rising tone (Tone-24)→ mid-level tone (Tone-33) in non-final position, b. mid-level tone (Tone-33)→ low-falling tone (Tone-21), c. low-falling tone (Tone-21)→ high-falling tone (Tone-51), d. high-falling tone (Tone-51)→high-level tone (Tone-55), e. high-level tone (Tone-55)→ mid-level tone (Tone-33), f. high-checked tone (Tone-$\underline{53}$)→ low-checked tone (Tone-$\underline{21}$), and g. low-checked tone (Tone-$\underline{21}$)→ high-checked tone (Tone-$\underline{53}$).

(31) Taiwan Southern Min's tonal circle

$$\begin{tikzcd} 51 \arrow[r] & 55 \arrow[r] & 33 \arrow[dl] & 24/\_\_\_ \text{ (before any other tone) in non-final position} \arrow[l] \\ & 21 \arrow[ul] & & \underline{53} \rightleftarrows \underline{21} \end{tikzcd}$$

First of all, Hsieh (1976) compared application rates of Taiwan Southern Min tone sandhi between actual words and novel words in three Southern-Min-speaking children and five adults. These participants were instructed to produce a disyllabic modifier and a monosyllabic head as a trisyllabic compound, and the production task requires them to apply tone sandhi to the second syllable of the disyllabic modifiers. For instance, participants produce a disyllabic modifier [ka33-**to55**] 'scissors' and a monosyllabic head [tiam21] 'shop' as a trisyllabic compound [ka33-**to33**-tiam21] 'scissors shop' in which high-level tone sandhi changes the second syllable [to55] to [to33]. The results showed that the application rates of Southern Min's tone sandhi are significantly higher in actual compounds than in novel ones, and higher in adults than in children. In addition, application rates of high-level tone sandhi and low-rising tone sandhi are higher than mid-level tone sandhi, low-falling tone sandhi, and high-falling tone sandhi. The high-level and low-rising tone sandhi rules were found to be more productive, since the two target tones were arguably more familiar to Southern Min speakers than the others. The findings indicated effects of word types, linguistic exposure, and token familiarity on the application of Southern Min tone sandhi, and suggested Taiwan Southern Min tone sandhi to be lexically bound.

Second, Wang (1995) examined the effect of token familiarity on the application rates of Taiwan Southern Min tone sandhi in both actual words and novel words. He recruited 22 adult speakers to perform a production task similar to that in Hsieh (1976). These adult participants were instructed to learn 14 novel compounds in four months, and were required to perform the 14 new words and other stimuli for five evaluation sessions in the four-month span. The results showed that the application rates of Southern Min tone sandhi are generally around the 50% level. Some sandhi patterns (high-level to mid-level, mid-level to low-falling, low-falling to high-falling, and low-rising to mid-level) were found to be more productive than the other (high-falling to high-level). In addition, Wang (1995) found that the application rates in novel words are not significantly improved over five sessions. The findings indicated the effect of word types and token familiarity on the application of Taiwan Southern Min tone sandhi, which generally confirmed Hsieh's (1976) results. Although participants were found to show no progress in the application rates in novel words, Wang (1995) concluded that some sandhi patterns seem to be learnable with proper training sessions over a longer span.

Third, Zhang et al (2011) examined lexical and phonetic/phonological effects on application rates of Taiwan Southern Min tone sandhi in 12 adult speakers. They set up 120 stimuli (made up by five tone types x three word types x eight monosyllables) in a production task that requires participants to produce each monosyllabic stimulus as disyllabic adjectival reduplication. For instance, participants were instructed to produce [tam24] 'wet' as [tam**33**-tam24] 'somehow wet'. In this adjectival reduplication, low-rising tone sandhi changes the first [tam24] to [tam**33**]. The results showed that application rates of tone sandhi are higher in actual words than in novel words, and application rates of low-rising tone sandhi and high-level tone sandhi are higher than those of the others (mid-level tone sandhi, low-falling tone sandhi, and high-falling tone sandhi). The findings indicated an effect of word types and tones on application of tone sandhi. In addition, the effects of tone types were found to play a more crucial role in novel words than in actual words, and the finding indicated an interaction between lexical and phonetic/phonological factors. Zhang et al (2011) concluded that phonetically-motivated patterns are over-learned, lexical patterns are properly learned, and less phonetically-motivated patterns are under-learned. Their results seem to support a lexically-bound account for Taiwan Southern Min's tone sandhi as suggested by Hsieh (1976) and Wang (1995).

5.1.1.4 Summary of previous studies on tone sandhi productivity

These tone-sandhi studies are summarized in Table 5.1. The findings indicated that multiple factors, including lexical, phonetic/phonological, and processing ones, may exert an influence on the application of tone sandhi in Mandarin and in Taiwan Southern Min. They suggested that tone sandhi application may vary from one word to another and from one context to another. In other words, variations seem to be common in speech processing of tone sandhi: there are different patterns across words and structures (variations of kinds), or in the application rates of each word and structure (variations of degrees). In general, variations of tone sandhi result from the influence of lexical, phonetic/phonological, and processing factors, and each of these factors is discussed below.

Table 5.1 Summary of previous studies on tone sandhi productivity.

Variables / Studies	Word types	Frequency factors	Sandhi types	Phonetic factors	Processing factors
Chen et al (2010)		v			
Chen et al (2012)					v
Chuang et al (2011)	v	v	v		
Hsieh (1976)	v	v	v		
Wang C. (2011)	v				v
Wang S. (1995)		v	v		
Zhang & Lai (2010)	v	v	v	v	
Zhang et al (2011)	v	v	v	v	

As to the effect of word types, the previous studies consistently indicated that the application rates of tone sandhi are higher in actual words than in novel words. The finding indicated that participants apply tone sandhi to actual words and novel words in different manners, which supports lexical effects on speech processing of tone sandhi. The lexical effects suggest that tone sandhi is lexically bound, but it is still unclear how to interpret the lexical effects. It can be controversial to simply correlate the lexical effects to the psychological-reality issue on tone sandhi. For instance, Hsieh (1976) assumed such a correlation, but Zhang et al (2011) argued for some other factors, such as phonetic-naturalness, phonological opacity, and frequency variables.

As to the effect of frequency/familiarity, the previous studies mostly showed that the application rates of tone sandhi are higher in frequent/familiar tokens or words than in less frequent/familiar ones. The finding indicated a crucial role of frequency/familiarity factors in the application of tone sandhi. The frequency/familiarity factors refer to three kinds: (i) at the phonemic level as token frequency, (ii) at the lexical level as lexical frequency, and (iii) even at the language level as frequency of use. The last two kinds tend to be set up as control variables, such as stimuli or participants. Since the phonemic level of frequency factors is an intrinsic part of phonetic/phonological factors, it is difficult to differentiate an effect of token frequency from that of phonetic/phonological factors. For instance, Zhang & Lai (2010) argued that Mandarin half T3 sandhi is more phonetically motivated than T3 sandhi, and the former was also found to be more frequent than the latter. They found it difficult to tease apart the two influences, since the frequency/familiarity factor is an intrinsic part of sandhi types.

As to the effect of tone sandhi types, the previous studies mostly showed that the application rates of some sandhi patterns are significantly higher than those of others. The finding indicated that some tonal changes are more common and more learnable than others. However, these previous studies did not find a consistent pattern for the effect of sandhi types in Taiwan Southern Min. For instance, Wang (1995) found that the application rates of high-level, low-rising, low-falling, and mid-level tone sandhi are significantly higher than those of high-falling tone sandhi. Chen et al (2010) found that the application rates of five non-checked sandhi types are not significantly different. Hsieh (1976) and Zhang et al (2011) found that the application rates of high-level and low-rising tone sandhi are higher than others. Chuang et al (2011) found that the application rates of low-falling and mid-level tone sandhi are significantly higher than others. Some (Hsieh 1976; Wang 1995) attributed the differences to frequency/familiarity factors, whereas others (Zhang et al 2011) attributed the differences to phonetic/phonological factors. In other words, it remains unclear what factors cause sandhi types to influence the application of tone sandhi.

As to the effect of other phonetic/phonological factors, it was rarely investigated in the previous studies, with the exception of Chen et al (2010), Zhang & Lai (2010), and Zhang et al (2011). Zhang & Lai (2010) and Zhang et al (2011) indicated that phonetically motivated tone sandhi is more learnable than less phonetically motivated one, so its application rates are also predicted to be higher. Zhang et al (2011) defined phonetic factors crucially by durational properties: tonal changes from the underlying from to the sandhi form with duration decreasing were argued to be more phonetically natural than those with duration increasing; that is, a surface sandhi tone with shortened duration in non-final position is phonetically more natural. However, they found it difficult to account for different application rates of tone sandhi simply by phonetic/phonological factors. These phonetic/phonological factors were found to be correlated with frequency/familiarity factors more or less. As a result, it is still unclear whether these phonetic/phonological factors play a role in the application of tone sandhi.

As to the effect of processing factors, it was also rarely investigated in the previous studies, except Chen et al (2012) and Wang (2011). Chen et al (2012) assumed that processing different structures take various amounts of response time, and Wang (2011) showed that participants may apply different processing strategies to tone sandhi in each task. The processing factors, such as task types, were barely addressed previously, since most studies simply adopted the typical production task that requires participants to perform tone sandhi by combining two constituents into one. As a result, it is unclear how processing factors exert an influence on the application of tone sandhi.

To sum up, these previous studies on tone sandhi productivity demonstrated that multiple factors, including lexical, phonetic/phonological, and processing ones, play a crucial role in the application of tone sandhi, and seem to be responsible for different kinds of variations in tone sandhi application. They also found a more consistent pattern of lexical effects (i.e. the application rates of tone sandhi higher in actual words than novel words), a more inconsistent pattern of phonetic/phonological effects (i.e. the uncertainty about which sandhi type is more productive and less productive), and potential effects of processing factors. Although the lexical effects exhibit a consistent pattern, it remains controversial how to interpret the pattern and the psychological-reality issue on tone sandhi. As to the phonetic/phonological effects, they were argued to be less consistent for two reasons. First, they exhibit an inconsistent pattern in the application rates of each sandhi type. Second, they were found to be correlated to frequency/familiarity factors in many cases. As to the processing factors, they were much less investigated and discussed by previous studies.

5.1.2 Theoretical implications for tone sandhi

These previous studies on tone sandhi productivity consistently found variations of different degrees in the application of tone sandhi. They argued that variations of tone sandhi result from the influence of multiple lexical and phonetic/phonological factors, and these variations were argued to suggest two different implications for tone sandhi: the psychological-reality issue and the phonetic-naturalness issue. The psychological-reality issue concerns whether tone sandhi is automatically applicable to novel words. The lower application rates of tone sandhi in novel words (not to mention those in some actual words) indicate that tone sandhi is not phonological productive, and hence is not psychologically real. The phonetic-naturalness issue concerns whether phonetic factors affect the application of tone sandhi. The phonetic effect may give rise to different degrees of variations in tone sandhi, and may account for cases with lower application rates. In other words, some unproductive sandhi rules are simply less phonetically grounded (or due to other factors), but they may still be psychologically real. The first issue distinguishes tone sandhi and other tonal modifications by examining the productivity of tone sandhi in novel words, whereas the second issue classifies tone sandhi processes themselves by different modifying factors. The two issues generally point out the classification issue on how to define tone sandhi and other tonal changes, as discussed below.

5.1.2.1 The psychological- reality issue

Those studies on the psychological-reality issue (Hsieh 1976; Wang 1995; Chen et al 2010) examined the application of tone sandhi to differentiate tone sandhi from other tonal changes by conventional classification of tonal changes. As discussed earlier in section 3.1.3 on the classification issue, the conventional classifications tend to correlate tonal changes to different levels of linguistic derivations, for instance, changes induced by tonal co-articulation to the phonetic level, changed induced by tone sandhi to the phonological level, and changes induced by tone change to the morpho-phonological level. Conventionally speaking, phonetic changes refer to continuous and gradient patterns, and phonological changes refer to distinct and categorical patterns. More specifically, there are six potential diagnoses for the three kinds of tonal changes: a. causes, b. mechanisms/processing levels, c. lexical bases, d. exceptions, e. degrees of productivity, and f. types of changes, as deduced from Shen (1992), Tsay & Myers (1996:394), and Xu (2004:783) in Table 5.2 below.

Table 5.2 Conventional classifications of tone sandhi, co-articulation, and tone change.

Diagnoses	Tone sandhi	Tonal co-articulation	Tone change
Causes	Phonetic, phonological, and morphological	Phonetic	Morphological
Mechanisms	Language system: post-lexical level	Motor system: articulatory level	Language system: lexical level
Lexical-bases	Not lexically bound	Not lexically bound	Lexically bound
Patterns	No exceptions	Exceptions	Exceptions
Productivity	Fully productive	Optional	Partially productive
Changes	Categorical changes	Gradient changes	Categorical changes

Tone sandhi generally refers to a post-lexical tonal change that is susceptible to various phonetic, morphological, and syntactic factors. It is not lexically bound, and is fully productive under various kinds of conditions. In addition, tone sandhi is assumed to have few exceptions, and it involves a categorical/near-categorical tonal change. Tonal co-articulation generally refers to an implemental tonal change that is modified strictly by phonetic factors. It is not lexically bound, and it involves a gradient tonal change. Tonal co-articulation varies in different prosodic contexts, so it may have exceptions. The contextually-induce change is more likely to be optional. As to the tone change, it generally refers to a tonal change that also involves a change in morphology/meanings. It is lexically bound, and is not fully productive under various conditions. In addition, tone change has exceptions, and involves a categorical/near-categorical tonal change.

The classification illustrated in Table 5.2 above points out a crucial difference between the psychological-reality issue and the phonetic-naturalness issue. The psychological-reality issue concerns the three diagnoses on the results and patterns (i.e. bound to actual words or not, exceptions or not, and productive or not), whereas the phonetic-naturalness issue concerns the two diagnoses on the causes (i.e. factors and processing mechanisms). Those studies addressing the psychological-reality issue consider the lexical bases and the degrees of productivity as crucial indicators to define tone sandhi and other tonal changes. Those studies addressing the phonetic-naturalness issue consider the causes to define different kinds of tone sandhi.

As discussed in section 5.1.1.3 above, Hsieh (1976), Wang (1995), and Zhang et al (2011) found that Taiwanese tone sandhi rules have lower application rates in different word types consistently. The findings indicated that Taiwan Southern Min tone sandhi is not fully productive, and is bound to actual words (i.e. not automatically applicable to novel words). They suggested that Taiwan Southern Min tone sandhi may not be represented as generalizations/grammars in the same manner as other post-lexical phonological rules. Instead, Taiwan Southern Min tone sandhi was argued to be saved and processed in both underlying and sandhi dimensions during speech processing. In order to account for the dual dimensions and the variations of the application rates in Taiwan Southern Min tone sandhi, Tsay & Myers (1996) proposed the Allomorph Selection Hypothesis that considers underlying and sandhi tones as allomorphs. In other words, tone sandhi with variations of degrees is considered to be a lexical rule.

5.1.2.2 The phonetic-naturalness issue

Those studies on the phonetic-naturalness issue (Zhang & Lai 2010; Zhang et al 2011) examined the application of tone sandhi to differentiate two kinds of sandhi patterns: a phonetically-motivated change and a less phonetically-motivated change. They tried to correlate the application of tone sandhi to various phonetic and phonological influences, and the correlation predicts that (i) a phonetically-motivated tonal change is more productive, i.e. higher in application rates, whereas a less phonetically-motivated tonal change is less productive, i.e. lower in application rates, and (ii) a phonologically-opaque tonal change is less productive, whereas a less phonologically-opaque tonal change is more productive. Zhang & Lai (2010) and Zhang et al (2011) argued that phonetic influences are determined crucially by durational properties. Since syllable duration tends to be shorter in non-final position where tone sandhi tends to occur, sandhi patterns with duration shortening were argued to enhance phonetic implementation in output processes. For instance, a tonal change from rising to level is duration-shortening, and so is a tonal change from level to falling. The duration-shortening tonal changes were argued to be phonetically motivated, and hence are predicted to be higher in application rates. In other words, variations in application rates were considered to be a crucial indicator that differentiates various phonetic and phonological properties in tone sandhi.

As summarized in section 5.1.1.4 above, Chen et al (2012), Hsieh (1976), Wang (1995), Zhang & Lai (2010), and Zhang et al (2011) found that some tone sandhi patterns have higher application rates than others. The findings indicated that the application rates of tone sandhi are correlated with various lexical and phonetic/phonological factors, and tone sandhi may not be fully productive as influenced by these factors. Zhang & Lai (2010) and Zhang et al (2011) argued for a crucial role of phonetic properties in tone sandhi, and suggested variations as common occurrence in tone sandhi. However, it is not clear how to tease apart the influences from phonetic properties and other factors, as they found that more phonetically motivated tonal changes happen to be more frequent and more familiar. In other words, it is less likely to argue for a difference between phonetically-motivated and less phonetically-motivated patterns without referring to the influence from the frequency/familiarity factors.

The correlation between phonetic motivation and frequency factors results from a controversial assumption that phonetic properties are directly encoded in phonological grammars. As pointed out by Zhang & Lai (2010) and Zhang et al (2011), some approaches (Boersma 1998; Hayes 1999; Hayes et al 2004; Flemming 2004; Steriade 2000) proposed to integrate phonetic influences directly into phonological grammars, but others (Ohala 1990, 1997; Blevins 2004) challenged the direct integration by showing that commonly attested patterns tend to be less phonetically motivated (i.e. phonetically unnatural patterns). Instead, Ohala (1990, 1997) and Blevins (2004:23) proposed to examine phonetic motivations essentially in diachronic sound change, and it is less necessary to do so in phonological grammars unless it is warranted. In other words, if frequency factors are found to exert an influence, it will be less necessary to argue for phonetic motivation.

5.1.3 Summary of productivity studies and research questions

The previous findings and implications for tone sandhi (in Mandarin and Taiwan Southern Min) are summarized below. As shown in Table 5.3 below, the application rates of tone sandhi were found to be correlated with various lexical, phonetic/phonological, and processing factors, such as word types, lexical frequency/familiarity, sandhi types, and processing strategies. These multiple factors were argued to be responsible for variations of tone sandhi to different degrees. In general, these previous studies suggested two implications for tone sandhi: (i) the psychological-reality issue, and (ii) the phonetic-naturalness issue. The psychological-reality issue indicates that tone sandhi is saved and represented in both underlying and sandhi forms. The phonetic-naturalness issue indicates that tone sandhi has different degrees of phonetic bases. Those who argued for dual representations considered variations as evidence against treating tone sandhi as a post-lexical rule, and considered tone sandhi to be a lexical rule. Those studies who argued for different phonetic bases considered variations as common occurrence in speech processing, and considered tone sandhi to be a post-lexical rule. These findings and implications motivate this dissertation to investigate influences of various lexical, phonetic/phonological, and processing factors on speech processing of tone sandhi in Hai-lu Hakka.

Table 5.3 Summary of previous findings and implications for tone sandhi.

Findings / Studies	Implications	Lexical factors	Phonetic & phonological	Processing factors
Chen et al (2010)	lexical rule	v		
Chen et al (2012)	lexical rule			v
Chuang et al (2011)	post-lexical rule	v	v	
Hsieh (1976)	lexical rule	v	v	
Wang C. (2011)	post-lexical rule (?)			v
Wang S. (1995)	both rules	v	v	
Zhang & Lai (2010)	post-lexical rule	v	v	
Zhang et al (2011)	post-lexical rule	v	v	

According to those findings shown in Table 5.3 above, this dissertation poses four specific research questions to the processing of Hai-lu Hakka tone sandhi below. As shown in (32), the first three research questions on (a) the lexical effect, (b) the phonetic/phonological effect, and (c) the interaction effect, are based on the general research questions in (4) above in section 1.3, and the last one on (d) the processing effect is specific to the tone sandhi experiment, since the processing factors, such as processing strategies and task types, were less investigated previously.

(32) Four research questions on processing Hai-lu Hakka tone sandhi

a. The lexical effect: How do lexical factors affect speech processing of Hai-lu Hakka tone sandhi?

b. The phonetic/phonological effect: How do phonetic/phonological factors affect speech processing of Hai-lu Hakka tone sandhi?

(i) How do **sandhi types** affect speech processing of Hai-lu Hakka tone sandhi?

(ii) How do **vowel types** affect speech processing of Hai-lu Hakka tone sandhi?

(iii) How do **prosodic contexts** affect speech processing of Hai-lu Hakka tone sandhi?

c. The interaction effect: How do lexical and phonetic/phonological factors interact with each other to affect speech processing of Hai-lu Hakka tone sandhi?

d. The processing effect: How do different processing factors (i.e. perception and production processes and task types) affect speech processing of Hai-lu Hakka tone sandhi?

The first question (32a) concerns the lexical effect on speech processing of tone sandhi in Hai-lu Hakka. The lexical effect on tone sandhi was consistently found by previous studies, as shown in Table 5.3 above. The lexical effect refers to the influence of word types and lexical frequency/familiarity. Since those previous studies on the psychological-reality issue argued for tone sandhi to be a lexical rule crucially based on the finding of lexical influences, it is indispensable to investigate the lexical effect on speech processing of tone sandhi in Hai-lu Hakka. In addition, Hai-lu Hakka tone sandhi exhibits four specific kinds of exceptions. These exceptions are bound to word types, and they may affect speech processing of tone sandhi to some extent. As a result, word types and frequency factors are set up accordingly to examine the lexical effect on the application of tone sandhi.

The second question (32b) concerns the phonetic/phonological effect on speech processing of tone sandhi in Hai-lu Hakka. The phonetic/phonological factors refer to sandhi types and different degrees of phonetic bases, and they were argued to play a crucial role in the application of tone sandhi by Zhang & Lai (2010) and Zhang et al (2011). As discussed above, sandhi types were found to be correlated with frequency factors more or less, and it is difficult to tease apart their influences. If frequency factors are found to exert an influence, it will be less necessary to argue that the effects from sandhi types are phonetically motivated. In order to investigate the phonetic/phonological effect apart from frequency factors, two other phonetic/phonological factors (vowel types of sandhi tones and prosodic contexts provided by non-sandhi syllables) are set up. As a result, the second question includes three subsets: (i) whether **sandhi types** affect speech processing of Hai-lu Hakka tone sandhi, (ii) whether **vowel types** of sandhi syllables affect speech processing of Hai-lu Hakka tone sandhi, and (iii) whether **prosodic contexts** provided by non-sandhi syllables affect speech processing of Hai-lu Hakka tone sandhi.

The third question (32c) concerns the interaction between lexical and phonetic/phonological factors on speech processing of tone sandhi in Hai-lu Hakka. The interaction effect was barely investigated previously, but Zhang et al (2011) indicated a potential finding to support the interaction effect. They found that the application rates of phonetically-motivated tonal changes tend to be higher than those of less phonetically-motivated, and the tendency is more significant in novel words than in actual words. The findings suggested that phonetically-motivated tonal changes are over-learned in novel words, and phonetic factors may play a more significant role when lexical access is restricted. It is theoretically intriguing whether phonetic factors play a different role (quantitatively and qualitatively) according to various degrees of lexical access. If phonetic/phonological factors play a similar role in speech processing of Hai-lu Hakka tone sandhi, regardless of lexical factors, there is no interaction between lexical and phonetic/phonological factors. Otherwise, there is an interaction.

The last question (32d) concerns the effect of processing factors on speech processing of tone sandhi in Hai-lu Hakka. The processing factors currently refer to different task types. Although the processing factors were less investigated previously, they seem to be responsible for some variations of tone sandhi in speech processing. For instance, Wang

(2011) found that adult speakers and young learners may apply different cyclic and non-cyclic strategies to process tone sandhi in each type of tasks. The findings suggested that processing strategies may lead to different variations of tone sandhi in speech processing, but it is unclear how processing strategies are correlated with different task types. In order to investigate the processing effects, different task types, including an AXB discrimination task, a tonal identification task, a lexical recognition task, and a production task, are set up accordingly, which require speakers to apply different processing strategies. These tasks generally contrast two kinds of processes that may elicit different strategies: (i) perception and production processes, and (ii) different degrees of lexical access. It is an empirical issue how lexical and phonetic/phonological factors cause Hai-lu Hakka speakers to process tone sandhi in each task type.

5.2 Speech processing of Hai-lu Hakka tone sandhi

Hai-lu Hakka has two tone sandhi patterns: (i) a low-rising tone sandhi that changes low-rising tone to low-level tone in non-final position, and (ii) a high-checked tone sandhi that changes high-checked tone to low-checked tone. As to the low-rising sandhi rule, its underlying and sandhi forms remain faithful to pitch height (i.e. low), and it involves a tonal modification in pitch contour (rising to level). As to the high-checked sandhi rule, its underlying and sandhi forms remain faithful to pitch contour (i.e. checked), and it involves a tonal modification in pitch height (high to low). The two sandhi patterns happen to involve two different pitch modifications, i.e. pitch contour and pitch height. In addition, they exhibit various exceptions to four specific kinds of word classes: (i) numerals and classifiers, (ii) demonstratives, (iii) resultatives and serial verbs, and (iv) others as adverbs. Since Hai-lu Hakka tone sandhi has never been examined experimentally before, it is unclear how the different pitch modifications and the specific exceptions affect Hai-lu Hakka speakers to process tone sandhi. This section examines the potential factors in applying and processing

Hai-lu Hakka tone sandhi, and proposes four hypotheses with respect to these factors accordingly.

5.2.1 Lexical factors in the application of Hai-lu Hakka tone sandhi

Previous studies (Chen et al 2010; Hsieh 1976; Wang 1995; Zhang et al 2011; and so on) consistently demonstrated lexical effects on Mandarin and Taiwan Southern Min's tone sandhi. The lexical effects indicate that the two languages' application of tone sandhi is very likely to be lexically bound. Although Hai-lu Hakka tone sandhi is different from the two languages', it is also very likely to be lexically bound for three reasons. First of all, Hai-lu Hakka tone sandhi demonstrates exceptions to four specific kinds of word classes. These exceptions indicate that tone sandhi is not automatically applied to each word. Since it is restricted to some words, it may not be applied to less frequent/familiar and novel words. Second, Hai-lu Hakka's various focus strategies, i.e. to raise pitch height, can override the application of tone sandhi. These focus strategies typically change non-rising tones to rising, and sometimes may change checked tones to high-checked. In other words, they result in a low-rising-tone-like variant and a high-checked-tone-like variant in sandhi position, and lead to exceptions to tone sandhi. As indicated by Zhang et al (2011), 'exception-like' variations may cause application of tone sandhi to be lexically bound. Third, Hai-lu Hakka tone sandhi tends to occur in a smaller syntactic constituent, and may involve some semantic modifications. For instance, [fo13] 'fire' becomes [fo22] in [fo22-tʂ^{h}a53] 'fire-car: train' which means a fire-fueled car literally, but it remains [fo13] in [fo13-t^{h}ai22] 'fire-big: angry' which involves some semantic modifications and cannot be interpreted literally. These kinds of exceptions and semantic modifications were argued to be lexically arbitrary (Fan 1996; Hsu 2009). In the words, Hai-lu Hakka tone sandhi is likely to be subject to lexical influence. To sum up, these previous studies indicated that Hai-lu Hakka tone sandhi is sometimes correlated with different words and meanings. Therefore, lexical factors, such as word types and lexical frequency, are likely to exert an influence on speech processing of Hai-lu Hakka tone sandhi.

5.2.2 Phonetic/phonological factors in the application of Hai-lu Hakka tone sandhi

Previous studies (Zhang & Lai 2010; Zhang et al 2011) argued for phonetic effects on Mandarin and Taiwan Southern Min tone sandhi by showing that phonetically motivated sandhi patterns are more productive than less phonetically motivated patterns. The phonetic effects indicate that the two languages' application of tone sandhi is correlated with degrees of phonetic naturalness, and suggest that sandhi types may play a role in tone sandhi application. As discussed in section 5.1.2.2 above, the phonetic-naturalness issue assumes a direct integration of phonetic influences into phonological grammars, and the direct integration makes it difficult to tease apart phonetic influences and frequency variables. In order to examine more plausible phonetic/phonological effects, two additional factors, i.e. vowel types provided by sandhi syllables and prosodic contexts provided by non-sandhi syllables' tone types, are set up accordingly. These phonetic/phonological factors are argued to play a role in speech processing of Hai-lu Hakka tone sandhi, and they are discussed below.

5.2.2.1 Sandhi types

Hai-lu Hakka has two sandhi patterns: one changing from low-rising tone to low-level and the other changing from high-checked tone to low-checked. The two sandhi patterns contrast each other not only by (i) degrees of phonetic naturalness, but also by (ii) degrees of type frequency and typological universals. In general, low-rising tone sandhi is considered more phonetically natural and more frequent/familiar than high-checked tone sandhi. Both differences may account for a potential role of sandhi types in the application of tone sandhi, so it seems difficult to tease apart the two factors in the application of Hai-lu Hakka tone sandhi.

As to the degrees of phonetic naturalness, low-rising tone sandhi is argued to be more phonetically natural. According to Xu (2004), Yu (2010) and Zhang et al (2011), rising tones tend to be longer in vowel duration than level and falling tones, so the change from rising contour to level becomes shorter in duration. As to high-checked tone sandhi, it changes high-checked tone to low-checked tone in a non-final position. The tonal change is faithful to pitch contour, and its underlying and sandhi forms differ crucially in pitch height. According to the tonal universals argued by Hyman & Schuh (1974) and Maddieson (1978), low tones tend to be longer in vowel duration than high tones, so the change from high to low becomes longer in duration. The duration-shortening sandhi pattern was argued to be more favorable in non-final position than the duration-lengthening pattern by Zhang et al (2011). As a result, low-rising tone sandhi is argued to be better motivated phonetically.

As to the degrees of type frequency and typological universals, low-rising tone sandhi is also argued to be more frequent. According to Hsu (2009: chapter 3, 4), low-rising tone sandhi is more frequent in type frequency than high-checked tone sandhi, based on nearly four thousand common lexical entries. Its underlying and sandhi tones (low-rising and low-level tones) are also more frequent in token frequency than the two checked tones. In addition, according to the tonal universals argued by Hyman & Schuh (1974) and Maddieson (1978), a rule that raises tones is more common than a rule that lowers tones, and a preservative rule is more common than an anticipatory rule. Both low-rising and high-checked tone sandhi rules lower pitch to some extent (offset-pitch and overall-pitch height respectively), but low-rising tone sandhi preserves a [-H] feature from underlying to surface dimensions. In other words, rising tone sandhi also seems to be more common typologically. As a result, low-rising tone sandhi is argued to be more frequent based on various frequency factors.

5.2.2.2 Vowel types

According to the tone-vowel interaction indicated by Chan (1985), Jiang-King (1999), and

Yip (2002: 31) and the tonal universals argued by Hyman & Schuh (1974) and Maddieson (1978), vowel height may play a role in tonal changes for two reasons. First, vowel height tends to be correlated with pitch height. High tones tend to co-occur with high vowels, and low tones tend to co-occur with low vowels. Second, vowel height also tends to be correlated with pitch contour. The correlation between vowel height and pitch contour is less common and somehow controversial. For instance, Jiang-King (1999) argued that high vowels tend to co-occur with level tones, but it is unclear whether low vowels tend to co-occur with contour tones. In other words, vowel height is more likely to affect tonal changes in pitch height, and it may affect tonal changes in pitch contour to some extent. As a result, vowel types are likely to exert a phonetic/phonological influence on the application of Hai-lu Hakka tone sandhi.

As to the correlation between pitch height and vowel height, low vowels arguably facilitate the application of both low-rising tone sandhi and high-checked tone sandhi patterns. As to low-rising tone sandhi, its underlying and sandhi tones are both low tones. As low tones tend to co-occur with low vowels, low vowels may facilitate the change from low-rising tone to low-level. High-checked tone sandhi changes high-checked tone to low-checked. Since low tones tend to co-occur with low vowels, low vowels may also facilitate the change from high-checked tone to low-checked.

As to the less common co-occurrence between high vowels and level tones, high vowels arguably facilitate the application of low-rising tone sandhi and are irrelevant to the application of high-checked tone sandhi. Low-rising tone sandhi changes low-rising tone to low-level. If level tones tend to co-occur with high vowels, high vowels may facilitate the change from rising to level tones. Since checked tones are not predicted to co-occur with high vowels, high vowels are irrelevant to the change from high-checked tone to low-checked.

5.2.2.3 Prosodic types

The phonetic/phonological factor of prosodic contexts refers to non-sandhi syllables' tone types. The tone types contrast two kinds of prosodic contexts: (i) pitch height (high versus low) and (ii) vowel duration (long versus low). They are argued to affect the application of tone sandhi based on a potential influence from tonal co-articulation. According to Jiang (2003), Peng (1997), Xu (2004), and many others, a target tone's offset pitch tends to vary with following tones' onset pitches. The higher the following tone's onset pitch, the higher the target tone's offset pitch will be. As non-sandhi tones follow sandhi tones in a given sandhi domain, their tone types can affect sandhi tones' phonetic implementation. In addition, according to Zhang et al (2011), vowel duration tends to be shorter in non-final position, and to be longer in final position. Prosodic positions are also correlated with vowel duration. It is an empirical issue as to whether sandhi and non-sandhi positions exhibit a complementary pattern in vowel duration, vowel duration in these two positions is also likely to be correlated. As a result, non-sandhi tones' durational properties are also likely to affect sandhi tones' phonetic implementation.

As to the prosodic contexts of pitch height, low tones arguably facilitate the application of both low-rising tone sandhi and high-checked tone sandhi patterns. Low-rising tone sandhi, essentially turns non-low offset pitch to low. If low offset pitch is likely to be co-articulated with low-onset tones, a following tone with lower onset pitch (i.e. low tones) may facilitate the change from low-rising tone to low-level. High-checked tone sandhi turns high overall-pitch to low, and it also results in lower offset pitch. As low offset pitch is likely to be co-articulated with low-onset tones, a following tone with lower onset pitch (i.e. low tones) may facilitate the change from high-checked tone to low-checked.

The prosodic contexts of vowel duration are likely to affect the application of tone sandhi. As discussed above, low-rising tone sandhi changes low-rising tone to low-level, shortening sandhi syllables' vowel duration. High-checked tone sandhi changes high-checked tone to low-checked, lengthening sandhi syllables' vowel duration. Since it is unclear how sandhi and non-sandhi positions' vowel durations are correlated, it is necessary to examine whether longer tones (i.e. rising tones) or shorter tones (i.e. falling tones) are more likely to facilitate the application of either sandhi pattern. In other words, it is theoretically plausible for prosodic contexts of vowel duration to exert an influence on application of tone sandhi, but it is unclear what the influence will be.

5.2.3 Potential processing factors in the application of Hai-lu Hakka tone sandhi

Previous studies seldom addressed the influence of processing factors on the application of tone sandhi, except for Wang (2011). Wang (2011) found that adult and young Mandarin speakers may apply different strategies to process T3 sandhi in each task, and their different strategies seem to give rise to variations of T3 sandhi application. The findings indicated that language experiences and task types may play a role in the application of tone sandhi, and suggested that each task may elicit different application strategies due to potential processing factors. As a result, task types seem to play a role in the application of tone sandhi.

Two kinds of processing factors are considered in the application of Hai-lu Hakka tone sandhi: (i) a potential difference between perception and production processes, and (ii) different degrees of lexical access. As to the difference between perception and production processes, it was controversial as to whether various lexical and phonetic/phonological factors play a compatible or a conflicting role in the two processes. Theoretically speaking, some argued for a similar effect, while others argued for a different one. Since previous studies on tone sandhi simply adopted a production approach, it is unclear how perception and production processes are correlated in the application of tone sandhi. As to the different degrees of lexical access, they were barely discussed in previous studies, and are currently defined by each kind of task type. Conventionally speaking, some tasks, such as lexical decision and recognition formats, require participants to access their lexical memory, whereas others, such as discrimination formats, may dispense with their lexical knowledge to some extent. It is likely for the degrees of lexical access to affect how lexical and phonetic/phonological factors influence speech processing, but it is unclear how they may be correlated with the lexical and phonetic/phonological effects in the application of tone sandhi.

5.2.3.1 Perception and production processes

The first kind of processing factors refers to a potential difference between perception and production processes. Perception and production are two crucial cognitive processes in speech communication. The former governs input processes from acoustic signals to lexical memory, and the latter governs output processes from internal lexicon to its physical dimensions. However, it has been a long-standing debate whether perception and production processes share certain knowledge/mechanisms to decode and encode speech signals (Kess 1992:63-65). Most speech models argued for similar knowledge/mechanisms in the two processes. For instance, as discussed in section 3.2, the direct-realist model and the motor theory proposed articulatory gestures as common knowledge/mechanisms to perceive and to produce speech signals. The linguistic proposals from a functional perspective (Boersma 1998) and a phonetically-based perspective (Flemming 2004) proposed that the two processes form conflicting forces that shape phonological grammars in an opposite manner: (i) to maximize perceptual distinctiveness and (ii) to minimize articulatory efforts. Although these models and proposals examine how perception and production processes are related, they seem to contradict each other. Presumably, the proposal of common knowledge suggests consistent patterns resulting from the two processes, while that of conflicting forces suggests inconsistent ones. Therefore, it is still unclear whether perception and production processes decode and encode speech signals in a similar or a different manner.

5.2.3.2 Different degrees of lexical access

The second kind of processing factors refers to different degrees of lexical access. Lexical access theoretically differentiates itself from sensor-motor mechanisms by triggering a potential influence of lexical memory. It tends to be set up as lexical factors, such as word types and lexical frequency, in various stimuli, as demonstrated in Yeh & Lin (2011), Zhang & Lai (2010), Zhang et al (2011), and many others. Lexical access was also set up as processing factors in various types of task design, as demonstrated in Polka (1991) and Werker & Tees (1984), but it is controversial how to interpret results of different tasks. For instance, Polka (1991) considered discrimination formats a task to target participants' phonetic knowledge, but Huang 2004 found that participants might also apply their phonological knowledge in discrimination formats. Participants were arguably able to apply phonological or lexical knowledge in the discrimination task, since they might resort to a top-down strategy. In other words, task types are likely to elicit participants' different problem-resolving skills/strategies, including a bottom-up strategy, a top-down strategy, and an analysis-by-synthesis approach (i.e. both bottom-up and top-down). As discussed in section 3.2 above, these processing strategies may affect how participants process speech signals by triggering different degrees of lexical access, i.e. minimal or full. As a result, task types are set up as processing factors that may activate lexical access to different extents in speech processing.

5.2.4 Summary of various factors in the application of Hai-lu Hakka tone sandhi

As discussed above, there are three kinds of factors that have potential effects on Hai-lu Hakka's two sandhi rules, and these potential factors are summarized below. As shown in Table 5.4, the three kinds of factors are lexical factors, phonetic/phonological factors, and processing factors.

Table 5.4 Three kinds of factors in the application of Hai-lu Hakka tone sandhi.

	Examples and effects
Lexical factors	a. Word types: The application of tone sandhi in actual words is higher than in novel words.
	b. Lexical frequency: The application of tone sandhi in frequent words is higher than in less frequent words.
Phonetic/ phonological factors	a. Sandhi types: The application of phonetically-based tone sandhi is higher than that of less phonetically-based one.
	b. Vowel types: Vowel height tends to co-occur with pitch height and pitch contour, and may affect the application of tone sandhi.
	c. Prosodic contexts: Tonal co-articulation (between the target and neighboring tones) may affect the application of tone sandhi.
Processing factors	a. The perception-production asymmetry: Lexical and phonetic/ phonological factors may play a different role in the perception and production of tone sandhi.
	b. The degrees of lexical access: Lexical and phonetic/ phonological factors may play a different role in tone sandhi, when participants have different degrees of lexical access.

The lexical factors shown in the top rows of Table 5.4 above refer to word types and lexical frequency. As found by Chen et al (2010), Hsieh (1976), Wang (1995), Zhang et al (2011), and many others, tone sandhi application is higher when participants apply tone sandhi to actual words than to novel words, and to frequent words than to less frequent words. The differences indicate the lexical influence on the application of tone sandhi, and suggest tone sandhi as a lexically bound rule.

The phonetic/phonological factors shown in the middle rows of Table 5.4 above refer to sandhi types, vowel types, and prosodic contexts. First, the sandhi types distinguish tone sandhi rules by different degrees of phonetic bases: more phonetically natural versus less phonetically natural. As found by Zhang & Lai (2010) and Zhang et al (2011), the application of phonetically natural rules is higher than that of less phonetically natural ones. Second, the vowel types distinguish sandhi tones' vowels by vowel height: high versus low. As indicated by Chan (1985), Jiang-King (1999), and Yip (2002: 31), a tone's pitch height tends to co-occur with vowel height. The tone-vowel co-occurrence may affect sandhi tones' pitch modifications derived from tone sandhi. Third, the prosodic contexts distinguish sandhi tones' following tones by pitch height and vowel duration. As indicated by Peng (1997) and Xu (2004), a tone's offset pitch height varies with following tones' onset pitch. The tonal co-articulation may affect sandhi tones' pitch modifications derived from tone sandhi.

The processing factors shown in the bottom rows of Table 5.4 above refer to a potential difference between perception and production processes, and different degrees of lexical access. First, as argued by (Boersma 1998) and (Flemming 2004), perception and production are conflicting forces that shapes grammars in different manners. Such an argument suggests the two processes as potential factors that affect participants' processes of tone sandhi. Second, as suggested from Polka (1991) and Werker & Tees (1984), participants seem to apply different processing strategies to different task types. Each processing strategy may restrict participants to different degrees of lexical access, and the degrees of lexical access may affect how lexical and phonetic/phonological factors influence tone sandhi application.

5.2.5 Hypotheses on speech processing of Hai-lu Hakka tone sandhi

Based on the discussion in section 5.1 and 5.2 above, the four hypotheses are proposed accordingly below. As shown in (33) below, the four hypotheses are (a) the lexical hypothesis, (b) the phonetic/phonological hypothesis, (c) the interaction hypothesis, and (d) the processing hypothesis. The phonetic/phonological hypothesis includes three subset hypotheses that consider (i) sandhi types, (ii) vowel types, and (iii) prosodic contexts.

(33) Four hypotheses on speech processing of Hai-lu Hakka tone sandhi

a. The lexical hypothesis: Lexical factors affect how participants perceive and produce Hai-lu Hakka tone sandhi.

b. The phonetic/phonological hypothesis: Phonetic/phonological factors affect how participants perceive and produce Hai-lu Hakka tone sandhi.

(i) Tone sandhi's **sandhi types** affect how participants perceive and produce Hai-lu Hakka tone sandhi.

(ii) Sandhi tones' **vowel types** affect how participants perceive and produce Hai-lu Hakka tone sandhi.

(iii) Sandhi tones' **prosodic contexts** affect how participants perceive and produce Hai-lu Hakka tone sandhi.

c. The interaction hypothesis: Lexical and phonetic/phonological factors interact with each other to affect how participants perceive and produce Hai-lu Hakka tone sandhi.

d. The processing hypothesis: Processing factors (i.e. task types) affect how participants process Hai-lu Hakka tone sandhi.

As shown in (33a) above, the lexical hypothesis concerns how lexical factors affect speech processing of Hai-lu Hakka tone sandhi. The lexical effect refers to the influence of word types and lexical frequency. The lexical influence was extensively supported by previous studies (Chen et al 2010; Hsieh 1976; Wang 1995; Zhang & Lai 2010; Zhang et al 2011), and thus is hypothesized to exert a significant influence on speech processing of Hai-lu Hakka tone sandhi. For instance, Zhang et al (2011) found that the application of Taiwan Southern Min tone sandhi is higher in actual words than in accidental-gap words. The finding indicated that word types play a crucial role in the application of tone sandhi, and suggested a significant lexical effect. The lexical effect was also found in Children's acquisition of Mandarin tones. Yang (2012) indicated that 1 to 2 year-olds' production accuracy is correlated to lexical factors, such as lexical frequency. In addition, lexically-based models of speech processing, i.e. Johnson (2007) and Pierrehumbert (2001, 2003), argued that lexical knowledge, such as word types and lexical frequency, is stored in exemplars to process speech signals. Since participants access/retrieve word types and lexical frequency as lexical knowledge, these lexical factors are hypothesized to exert an influence on speech processing of Hai-lu Hakka tone sandhi.

As shown in (33b) above, the phonetic/phonological hypothesis concerns how phonetic/phonological factors affect speech processing of Hai-lu Hakka tone sandhi. The phonetic/phonological effect currently refers to the influence of (i) tone sandhi' phonetic bases as sandhi types, (ii) sandhi tones' vowel types, and (iii) sandhi tones' following tones as prosodic contexts. Although these phonetic/phonological influences, except for sandhi types, were barely investigated by previous studies on Mandarin and Taiwan Southern Min tone sandhi (Chen et al 2010; Hsieh 1976; Wang 1995; Zhang & Lai 2010; Zhang et al 2011), they are likely to affect speech perception and production of Hai-lu Hakka tone sandhi. Hai-lu Hakka's sandhi types are hypothesized to exert an influence, as Zhang & Lai (2010) and Zhang et al (2011) found that phonetically-based sandhi types are more applicable than less phonetically-based ones in Mandarin and Taiwan Southern Min. Sandhi tones' vowel types are hypothesized to exert an influence, for a potential tone-vowel interaction between sandhi tones' vowel types and tonal modifications (Chan 1985; Jiang-King 1999; Yip 2002: 31). Sandhi tones' following tones are also hypothesized to exert an influence, for a potential tonal co-articulation between a sandhi tone's offset pitch and the following tone's onset pitch (Peng 1997; Xu 2004).

As shown in (33c), the interaction hypothesis concerns the interaction between lexical and phonetic/phonological factors in speech processing of Hai-lu Hakka tone sandhi. The interaction effect suggests an additional or enhanced influence of phonetic/phonological factors on novel words, but no additional influence on actual words. The phonetic/phonological factors are hypothesized to exert an additional influence on novel words, based on two empirical findings demonstrated by Good (2008) and Zhang et al (2011). Good (2008) examined how adults and children use prosody to disambiguate phrases that can be interpreted either as a list of two items (e.g., fruit, salad) or as a single compound item (e.g., fruit-salad). The results indicated that adults tend to parse stimuli based on lexical meanings, and children tend to respond based on prosodic information. When the same stimuli are tested with abstract shapes as novel words rather than representational images as actual words, adults were found to make greater use of prosody. Similarly, Zhang et al (2011) examined how Taiwan Southern Min speakers apply tone sandhi of different phonetic bases, i.e. phonetically-based and less phonetically-based tone sandhi. The results indicated that participants are more likely to apply phonetically-based tone sandhi, e.g., low-rising tone sandhi, than less phonetically-based one, e.g., low-falling tone sandhi, to novel words. These findings suggest that participants may apply more phonetic/phonological knowledge to novel words than actual words. As a result, the interaction effect is hypothesized to exert an additional influence on novel words in speech processing of Hai-lu Hakka tone sandhi.

In (33d), the processing hypothesis concerns how processing types and strategies affect speech processing of Hai-lu Hakka's tone sandhi. The processing effect refers to the influence of two potential factors that may affect participants' strategies to apply different lexical and phonetic/phonological knowledge. The two processing factors are defined as (i) the perception-production asymmetry and (ii) different degrees of lexical access, and are currently set up as task types. The processing factors are hypothesized to exert an influence on speech processing of Hai-lu Hakka tone sandhi, based on theoretical claims argued by Boersma (1998) and Flemming (2004) and empirical findings demonstrated by Polka (1991) and Werker & Tees (1984). The difference between perception and production processes is hypothesized to exert an influence, as Boersma (1998) and Flemming (2004) proposed that the two processes constitute conflicting forces that shape phonological grammars in different manners. The degrees of lexical access is hypothesized to exert an influence, as Polka (1991) and Werker & Tees (1984) found that participants may apply different kinds of lexical and phonetic/phonological knowledge to the same stimuli in different tasks, e.g. discrimination versus identification formats. Since these processing factors are likely to affect participants' access to different processing strategies and knowledge, they are hypothesized to exert an influence on speech processing of Hai-lu Hakka tone sandhi.

In order to compare the current results with previous findings of Mandarin and Taiwan

Southern Min tone sandhi, two additional hypotheses on psychological-reality and phonetic-naturalness issues are proposed accordingly as in (34) below. The psychological-reality hypothesis, as shown in (34a), concerns whether Hai-lu Hakka tone sandhi is lexically bound. Although Hai-lu Hakka tone sandhi is not phonologically as opaque as Taiwan Southern Min tone sandhi, it was found to exhibit a variety of exceptions (Chang 2002; Fan 1996; Hsu 2009). These exceptions mostly occur in four kinds of word classes: numerals and classifiers, demonstratives, resultatives and serial verbs, and suggest that Hai-lu Hakka tone sandhi may be lexically bound. As a result, Hai-lu Hakka tone sandhi is hypothesized to be not phonologically productive and hence not psychologically real. As shown in (34b), the phonetic-naturalness hypothesis concerns whether phonetic grounding enhances application of tone sandhi. Phonetically-motivated tone sandhi is hypothesized to be more productive than less phonetically-motivated one, based on empirical findings demonstrated by Zhang & Lai (2010) and Zhang et al (2011). For instance, Zhang & Lai (2010) argued that half T3 sandhi is phonetically more natural than T3 sandhi in Mandarin, and their results indicated that half T3 sandhi is more productive than T3 sandhi. Similarly, Zhang et al (2011) found that phonetically motivated low-rising tone sandhi is more productive than less phonetically motivated tone sandhi in Taiwan Southern Min. As a result, phonetic grounding is also hypothesized to exert an influence on Hai-lu Hakka tone sandhi.

(34) Additional hypotheses on Hai-lu Hakka tone sandhi

a. Psychological-reality hypothesis:

Hai-lu Hakka tone sandhi is not psychologically real, which indicates that the two tonal rules are lexically bound, and not phonological productive in novel words.

b. Phonetic-naturalness hypothesis:

Phonetically-motivated tone sandhi is more productive than less phonetically-motivated one in Hai-lu Hakka.

5.3 Method on Hai-lu Hakka tone sandhi

In order to verify the hypotheses shown in (33) and (34) above, three kinds of factors, including lexical, phonetic/phonological, and processing factors, are set up as independent variables in the experiment. First, the lexical factors include word types and lexical frequency, and they are set up as three levels of lexical types (frequent actual words, less frequent actual words, and novel words) in stimuli. Second, the phonetic/phonological factors include Hai-lu Hakka's tone sandhi types, sandhi tones' vowel types, and sandhi tones' following tones as prosodic contexts. The sandhi types include low-rising tone sandhi and high-checked tone sandhi, and each tone sandhi consists of underlying and surface forms. Two sandhi rules and two sandhi forms make up four levels of sandhi types (phonetically motivated and less phonetically motivated tone sandhi, underlying and surface forms). The sandhi tones' vowel types include low and high vowels, and they are set up as two levels of vowel types (low and high). The sandhi tones' prosodic contexts include pitch height and vowel duration, and they are set up as three levels of prosodic types (high-falling tone, low-falling tone, and low-rising tone). All these phonetic/phonological factors are set up as variables in stimuli. Third, the processing factors include the perception-production asymmetry and different degrees of lexical access, and they are set up as four levels of processing variables as four conventional tasks (AXB discrimination, tonal identification, lexical recognition, and production) in design of task types. The experimental setup is discussed in detail as follows.

5.3.1 Participants

The participants are 31 Hai-lu Hakka speakers recruited from the Hsinchu area of Taiwan. Since there are no Hakka monolinguals available in Taiwan, the 31 participants are all Hakka-Mandarin bilinguals. These bilinguals were born in Hai-lu Hakka speaking family, and they still speak Hai-lu Hakka on a daily basis. In addition, most of them are still Hakka-dominant, and one third of them teach Hai-lu Hakka at an elementary or an middle school. These participants' demographic background is shown in Table 5.5 below. Generally speaking, they are older (mean age: 45.2 years old), and there are more female (F) participants than male (M) ones. The age variables were considered for the potential issue of language attrition in Hakka. As indicated by Hsiao (2007) and Yeh & Lu (2013), young speakers, especially those younger than the age of thirties, are no longer daily users of their mother tongue, not to mention their speaking fluency. The decrease in frequency of use (argued as a main cause of language attrition) has a damaging effect on non-daily users' linguistic knowledge. In order to avoid the attrition effect, fluent daily speakers were chosen, and they happen to be in their 40s and 50s. As to the gender variables, it is simply by chance.

Table 5.5 Demographic background of Hai-lu Hakka participants.

Languages	N	Age range	Mean age	Gender
Hakka	31	25- 63 yrs	45.2 yrs	M: 8; F: 23

5.3.2 Stimuli

The current stimuli are 72 disyllabic words (3 lexical types x 2 sandhi rules x 2 sandhi forms x 2 vowel types x 3 prosodic types), as shown in Table 5.6 below. These disyllabic stimuli were made up by three control variables and four independent variables as follows.

Table 5.6 The list of disyllabic stimuli.

Lexical types / Prosodic types		Low-rising tone sandhi				High-checked tone sandhi			
		Und.	Surf.	Und.	Surf.	Und.	Surf.	Und.	Surf.
		High vowel		Low vowel		High vowel		Low vowel	
Frequent words	Words	fu13 苦	fu22 傅	ʐa13 抓	ʐa22 夜	şuk5 叔	şuk2 熟	ts^hap5 插	ts^hap2 雜
	High-falling	fu13 +fu53	fu22 +fu53	ʐa13 +fu53	ʐa22 +fu53	şuk5 +fu53	şuk2 +fu53	ts^hap5 +fu53	ts^hap2 +fu53
	Low-falling	fu13 +fu31	fu22 +fu31	ʐa13 +fu31	ʐa22 +fu31	şuk5 +fu31	şuk2 +fu31	ts^hap5 +fu31	ts^hap2 +fu31
	Low-rising	fu13 +fu13	fu22 +fu13	ʐa13 +fu13	ʐa22 +fu13	şuk5 +fu13	şuk2 +fu13	ts^hap5 +fu13	ts^hap2 +fu13
Less frequent words	Words	vu13 武	fuk5 福	şa13 捨	şa22 社	fuk5 福	fuk2 服	sap5 圾	sap2 煠
	High-falling	vu13 +fu53	vu22 +fu53	şa13 +fu53	şa22 +fu53	fuk5 +fu53	fuk2 +fu53	sap5 +fu53	sap2 +fu53
	Low-falling	vu13 +fu31	vu22 +fu31	şa13 +fu31	şa22 +fu31	fuk5 +fu31	fuk2 +fu31	sap5 +fu31	sap2 +fu31
	Low-rising	vu13 +fu13	vu22 +fu13	şa13 +fu13	şa22 +fu13	fuk5 +fu13	fuk2 +fu13	sap5 +fu13	sap2 +fu13
Novel words	Words	hu13 [illegible]	hu22 [illegible]	tşa13 [illegible]	tşa22 [illegible]	huk5 [illegible]	huk2 [illegible]	vap5 [illegible]	vap2 [illegible]
	High-falling	hu13 +fu53	hu22 +fu53	tşa13 +fu53	tşa22 +fu53	huk5 +fu53	huk2 +fu53	vap5 +fu53	vap2 +fu53
	Low-falling	hu13 +fu31	hu22 +fu31	tşa13 +fu31	tşa22 +fu31	huk5 +fu31	huk2 +fu31	vap5 +fu31	vap2 +fu31
	Low-rising	hu13 +fu13	hu22 +fu13	tşa13 +fu13	tşa22 +fu13	huk5 +fu13	huk2 +fu13	vap5 +fu13	vap2 +fu13

5.3.2.1 Control variables

In order to avoid potential confounds, these stimuli's segmental parts, including (i) the first syllable's onset, (ii) the first syllable's rime, and (iii) the second syllable's syllable type, were controlled carefully. First, all these stimuli's first syllables consist of fricative onsets, except for two affricates. As shown in Table 5.6 above, those stimuli of frequent words consist of [f], [ʐ], [ş] and [ts^h]; those of less frequent words consist of [v], [ş], [f] and [s]; and those of novel words consist of [h], [tş] and [v]. Fricative (affricate) onsets were chosen for a practical purpose: it is more plausible to set up three lexical types with fricative onsets. Second, all these stimuli's first syllables consist of simple vowels as rimes. As shown in Table 5.6 above, these stimuli's first syllables have only two rime types: [-u] and [-a]. Simple vowels were selected as rime types to avoid a potential influence of vowel contour and codas on tonal processing. As indicated by Lai & Su (2011), complex vowels and nasal codas may exert an influence on the contrast between T2 and T3 in Mandarin. Third, all these stimuli's second syllables consist of [fu] as syllable types. The [fu] syllable was controlled for a similar reason: to avoid potential confounds from the second syllables.

5.3.2.2 Independent variables

As shown in Table 5.6 above, the 72 stimuli consist of four independent variables: one lexical factor and three phonetic/phonological factors, including sandhi types, vowel types, and prosodic types. First, the lexical factor contrasts three lexical types: frequent words, less frequent words, and novel words. As shown in the top row of Table 5.6, those frequent words are 苦 [fu13] 'bitter', 傅 [fu22] 'master', 抓 [ʐa13] 'to catch', 夜 [ʐa22] 'tonight', 叔 [ʂuk5] 'uncle', 熟 [ʂuk2] 'well-cooked', 插 [ts^{h}ap5] 'to plug', and 雜 [ts^{h}ap2] 'complex'. As shown in the middle row of Table 4.6, those less frequent words are 武 [vu13] 'martial', 芋 [vu22] 'taro', 捨 [ʂa13] 'to throw', 社 [ʂa22] 'society', 福 [fuk5] 'lucky', 服 [fuk2] 'to obey', 圾 [sap5] 'garbage', and 煠 [sap2] 'to steam'. As shown in the bottom row of Table 4.6, those novel words are蛲 [hu13] 'insect A', 蝏 [hu22] 'insect B', 鮍 [tʂa13] 'fish A', 鮷 [tʂa22] 'fish B', 鶩 [huk5] 'bird A', 鶖 [huk2] 'bird B', 猫 [vap5] 'animal A', and 猔 [vap2] 'animal B'. Second, the sandhi types contrast two sandhi rules (low-rising tone sandhi, high-checked tone sandhi) and two sandhi forms (underlying, surface). As to the low-rising tone sandhi which changes low-rising tone to low-level tone in non-final position, the underlying form is Tone-13, and the surface form is Tone-22. As to the high-checked tone sandhi which changes high-checked tone to low-checked tone, the underlying form is Tone-5, and the surface form is Tone-2. Third, the vowel types contrast low and high vowels. The low vowel is [a], and the high vowel is [u]. Fourth, the prosodic contexts contrast three tone types as prosodic types following the sandhi tones: high-falling tone, low-falling tone, and low-rising tone.

5.3.3 Design of task types

The experiment includes four tasks, including three perception tasks (AXB discrimination, tonal identification, and lexical recognition) and one production task. The four task types contrast two processing factors: the difference between perception and production processes, and different degrees of lexical access. Conventionally, a discrimination format requires participants to focus on the phonetic contrast, and it was designed to simulate phonetic processing. An identification format requires participants to apply phonemic knowledge, and it was designed to simulate representation-mapping between acoustic signals and categories. A lexical recognition format requires participants to access lexical memory, and it was designed to simulate lexical access. A production format requires participants to retrieve lexical knowledge and to implement words by articulatory gestures, and it was designed to simulate production processing.

5.3.3.1 AXB discrimination task

In the AXB discrimination task, there are 144 trials made up by three lexical types (frequent words, less frequent words, and novel words), two sandhi rules (low-rising tone sandhi, high-checked tone sandhi), two sandhi tones' forms (underlying, surface), two vowel types, (high vowels, low vowels), three prosodic types (high-falling tone, low-falling tone, low-rising tone), and two repetitions, i.e., 144= 3 x 2 x 2 x 2 x3 x 2, as shown in Appendix B. The discrimination task was designed to examine whether participants are able to distinguish sandhi tones' underlying and surface forms. In each trial, participants were given three disyllabic stimuli that contrast an underlying form and a surface form, and then were asked to tell whether the second disyllabic stimulus is the same as the first one or the third. They have only two options: the first or the third. For example, when participants hear a trial '*vu22-fu31*, *vu22-fu31*, and *vu13-fu31*,' contrasting a surface form *vu22-fu31* and an underlying form *vu13-fu31*, they are supposed to answer *the first* because the second stimulus is the same as the first one.

The temporal interval between each stimulus (inter-stimulus interval: ISI) is 300 ms, and the temporal interval between each trial (inter-trial interval: ITI) is 500 ms. The ISI and ITI were set up to be short for simulating phonetic processing, since shorter ISI and ITI are conventionally assumed to target phonetic knowledge (Polka 1991; Werker & Tees 1984). Participants were explicitly instructed to finish each trial as soon as possible due to the relatively short ITI. If they finish a trial in more than 500 ms, they automatically fail the trial, and receive a wrong response. Participants were given an optional three-minute break after finishing half of 144 trials, and most of them just skipped the break. In general, it takes approximately 7 to 10 minutes to complete the discrimination task.

5.3.3.2 Tonal identification task

In the tonal identification task, there are 144 trials made up by three lexical types (frequent words, less frequent words, and novel words), two sandhi rules (low-rising tone sandhi, high-checked tone sandhi), two sandhi tones' forms (underlying, surface), two vowel types, (high vowels, low vowels), three prosodic types (high-falling tone, low-falling tone, low-rising tone), and two repetitions, i.e., 144= 3 x 2 x 2 x 2 x3 x 2, as shown in Appendix C. The tonal identification task was designed to examine whether participants are able to categorize sandhi tones' underlying and surface forms. In each trial, participants were given only one disyllabic stimulus, and then were asked to identify the first syllables' tone types. They have two responses: either rising tone (Tone-13) or level tone (Tone-22) in a low-rising tone sandhi condition, and either high tone (Tone-5) or low tone (Tone-2) in a high-checked tone sandhi condition. Before the identification task, there was a brief training session on these tonal responses: rising versus level, and high versus low. The tonal training is indispensible, since most Hai-lu Hakka participants had never learned these tonal labels before. The two tonal contrasts, rising vs. level and high vs. low, were instructed with two minimal pairs for each tonal contrast. For instance, the rising-level contrast was instructed with the two minimal pairs: 體 [t^hi13] ‘body’ vs. 地 [t^hi22] ‘land’ and 土 [t^hu13] ‘soil’ vs. 度 [t^hu22] ‘degree’. The two words, 體 [t^hi13] ‘body’ and 土 [t^hu13] ‘soil’, have a low-mid rising pitch, and the two words, 地 [t^hi22] ‘land’ and 度 [t^hu22] ‘degree’, have a low-low flat pitch. As participants consider the first word to be a rising sound, such as [t^hi13] ‘body’ and [t^hu13] ‘soil’, then they are supposed to choose *rising* out of the two responses: rising and level. Otherwise, as they consider the first word to be flat in pitch contour, they should respond to *level*. Similarly, the high-low contrast was instructed with the two minimal pairs: 笪 [tat5] ‘fence’ vs. 値 [tat2] ‘value’ and 脫 [t^hot5] ‘take off’ vs. 奪 [t^hot2] ‘to rob’. The two words, 笪 [tat5] ‘fence’ and 脫 [t^hot5] ‘take off’, have a higher pitch, and the two words, 値 [tat2] ‘value’ and 奪 [t^hot2] ‘to rob’, have a lower pitch. As participants consider the first word to be a high sound, such as [tat5] ‘fence’ and [t^hot5] ‘take off’, then they are supposed to choose *high* out of the two responses: high and low. Otherwise, they should respond to *low*.

The identification task has no ISI, since there is only one stimulus in each trial. It has no ITI, either, since the identification format was designed to target phonemic knowledge. In other words, the identification task is self-paced. The next trial was presented in 500 ms, right after the response of previous trials was made. Each participant was given an optional 3-minute break after finishing half of 144 trials, and most of them just skipped the break. In general, it takes approximately 10 to 15 minutes to complete the identification task.

5.3.3.3 Lexical recognition task

In the lexical recognition task, there are also 144 trials made up by three lexical types (frequent words, less frequent words, and novel words), two sandhi rules (low-rising tone sandhi, high-checked tone sandhi), two sandhi tones’ forms (underlying, surface), two vowel types, (high vowels, low vowels), three prosodic types (high-falling tone, low-falling tone, low-rising tone), and two repetitions, i.e., 144= 3 x 2 x 2 x 2 x3 x 2, as shown in Appendix C. These trials are exactly the same as those in the tonal identification task. The difference between the identification and lexical recognition tasks is the type of responses: tonal or lexical. The lexical recognition task was designed to examine whether participants are able to recognize lexical meanings of sandhi tones' underlying and surface forms. In each trial, participants were given one disyllabic stimulus, and then were asked to recognize the first syllables' lexical meanings. They also have two responses: 苦 [fu13] 'bitter' or 傅 [fu22] 'master'; 武 [vu13] 'martial' or 芋 [vu22] 'taro'; 抓 [ʐa13] 'to catch' or 夜 [ʐa22] 'tonight'; 捨 [ʂa13] 'to throw' or 社 [ʂa22] 'society'; 叔 [ʂuk5] 'uncle' or 熟 [ʂuk2] 'well-cooked'; 福 [fuk5] 'lucky' or 服 [fuk2] 'to obey'; 插 [ts^{h}ap5] 'to plug' or 雜 [ts^{h}ap2] 'complex'; 圾 [sap5] 'garbage' or 煠 [sap2] 'to steam'. Before the lexical task, participants were explicitly instructed to recognize these lexical responses to ensure that all participants may have an equal lexical access, especially those eight novel words: [hu13] or [hu22], [tʂa13] or [tʂa22], [huk5] or [huk2], and [vap5] or [vap2]. These novel words were provided with artificial meanings of exotic fish, birds, insects, and animals, and were instructed with Chinese characters and cartoon pictures. For example, [hu13] refers to ⿰虫戔 'an insect A'; [hu22] refers to ⿰虫寧 'an insect B'; [tʂa13] refers to ⿰魚戔 'a fish A'; [tʂa22] refers to ⿰魚彖 'a fish B'; [huk5] refers to 鶩 'a bird A'; [huk2] refers to 鷔 'a bird B'; [vap5] refers to ⿰犭蚩 'an animal A'; and [vap2] refers to ⿰犭悉 'an animal B'.

The lexical task has no ISI, either, since there is only one stimulus in each trial. Similarly, it has no ITI, since the recognition format was designed to target participants' lexical knowledge. In other words, the task is also self-paced. The next trial was presented in 500 ms, right after the response of previous trials was made. Each participant was given an optional 3-minute break after finishing half of 144 trials, and most of them just skipped the break. In general, it takes approximately 10 to 15 minutes to complete the lexical task.

5.3.3.4 Production task

In the production task, there are a total of 384 trials, including 288 test trials and 96 filler trials, as illustrated in Appendix D. The 288 test trials were made up by three lexical types (frequent words, less frequent words, and novel words), two sandhi rules (low-rising tone sandhi, high-checked tone sandhi), two sandhi tones' forms (underlying, surface), two vowel types, (high vowels, low vowels), three prosodic types (high-falling tone, low-falling tone, low-rising tone), and four repetitions, i.e., 288= 3 x 2 x 2 x 2 x 3 x 4. The 96 filler trials were made up by three lexical types (frequent words, less frequent words, novel words), two sandhi rules (low-rising tone sandhi, high-checked tone sandhi), two sandhi tones' forms (underlying, surface), two vowel types (high, low), and four repetitions, i.e., 96= 3 x 2 x 2 x 2 x 4. The production task was designed to examine whether the participants are able to apply Hai-lu Hakka tone sandhi automatically. In each trial, participants were given two monosyllabic words separately and a picture of corresponding meanings (representational or artificial meanings), and then were asked to produce the two monosyllabic words together as a compound phrase with a corresponding meaning to the picture presented. The picture is arguably essential, since it provides participants with additional visual information to enhance lexical access. For example, participants saw a picture of organic chicken and heard two monosyllabic words [t^{h}u13] 'soil' and [kai53] 'chicken' separately in a trial. They were required to apply tone sandhi, and to pronounce them as a compound [t^{h}u**22**-kai53] 'organic chicken' without changing the word order and segmental features. Before the task, participants were provided with five training trials to practice, and they were explicitly instructed not to change the word order and segments of the words they heard.

The temporal interval between each monosyllabic word (similar to ISI) is 800 ms. The longer ISI was designed to target lexical knowledge. The production task is also self-paced (without ITI), and the next trial will be presented in 500 ms, right after the response of previous trials is made. Each participant was given a 3-minute break after finishing each 96 trials, and there are a total of three break sessions. The second break is compulsory, while the two others are optional. In general, it takes approximately 30 to 35 minutes to complete the production task.

5.3.4 Procedure

The four-task experiment took place in a computer lab or in a noise-free conference room. Participants were brought to the place, and were instructed how to do the experiment. They run the experiment with a headphone (Sennheiser CX300ii) through the sound processing software Praat (Boersma & Weenink 2009) on a laptop (HP 6530b). Their perceptual responses were recorded digitally by the Praat scripts on the laptop (HP 6530b), and their production results were recorded through an Audio-Technica miniature clip-on microphone (AT831B Cardioid Condenser Lavalier microphone) by the other sound software Audacity 1.3 (2011). The four tasks were conducted randomly to neutralize any potential training effect. The four tasks take approximately 60 to 90 minutes to complete.

After the four tasks, participants were instructed to judge lexical familiarity of all disyllabic stimuli on a five-point scale: 5 indicating that they frequently hear and speak these Hai-lu Hakka words; 4 indicating that they hear these words frequently, but not speak very often; 3 indicating that they hear and speak these words occasionally; 2 indicating that they hear these words occasionally, but rarely speak them; and 1 indicating that they hardly hear and speak these words. The degrees of lexical familiarity, known as subjective lexical frequency, were considered for the same reasons as in the previous experiment on falling tones. As discussed in section 4.3.4 above, Hai-lu Hakka participants' familiarity ratings were analyzed for two reasons. First, there have been no known corpus studies on Hai-lu Hakka. The only corpus study on Hakka languages (Chui & Lai 2009) has very limited tokens (six recordings, and about 30 minutes for each), and its analysis fails to distinguish Hai-lu Hakka from other Hakka varieties. The two methodological issues make it difficult to adopt Chui &

Lai's (2009) results of objective lexical frequency in Hakka. Second, some studies (Gernsbacher 1984; Gelfand 2009: 254) showed that participants' subjective familiarity ratings are a more reliable predictor of lexical access than actual word counts of a given corpus. Therefore, participants' familiarity ratings were collected.

5.3.5 Coding

The raw responses were first encoded into percent accuracy in each task. Since the production results are not simply correct/wrong responses, some criteria were proposed to evaluate production accuracy. Then the independent variables were encoded into dummy variables to analyze the results of percent accuracy. These coding processes are discussed in detail below.

5.3.5.1 Percent accuracy

All participants' responses were encoded into percent accuracy by 72 stimulus types (3 lexical types x 2 sandhi types x 2 sandhi tones' forms x 2 vowel types x 3 prosodic types). The results of percent accuracy were derived from the equation below. As demonstrated in (35) below, percent accuracy is equal to a percentage of correct responses divided by all repetitions. All participants have one accuracy rate for 72 stimulus types in each task, which makes a total of 2232 accuracy results (31 participants x 72 stimulus types).

(35) Equation for percent accuracy

$$\frac{\text{counts of correct responses}}{\text{counts of all repetitions}} \times 100\ (\%)$$

5.3.5.2 Production accuracy

Participants' production results were evaluated by two Hai-lu Hakka L1 speakers as independent raters. Both the two raters have formal linguistic background, and teach elementary-level Hai-lu Hakka for at least a year. Since the production results are not simply correct/wrong responses, some criteria were proposed for consistency, as shown in (36) below.

Generally speaking, both independent raters' judgments are quite similar, up to 90% consistency. As to the less-than-10% inconsistent results, a spectrographic analysis was adopted to settle the inconsistency.

(36) Criteria of production accuracy

a. The first syllable' (sandhi tone) onset and coda errors are not considered, as long as tones and nuclei are accurate.

b. The second syllable' (sandhi tone's following tone) segmental errors are not considered, as long as tones are accurate.

c. In the case of low-rising tone sandhi, it is not an application error to pronounce a low-level surface form as low-falling tone.

As illustrated in (36) above, the three criteria indicate three conditions in which mispronunciations are not considered to be production errors. First, as illustrated in (36a), since the current hypotheses focus on sandhi tones and a potential influence of vowel types on sandhi tones, tonal and vocal pronunciations are more crucial than consonantal parts. It is not saying that onset and coda exert no effect on tone sandhi, but the consonantal influence is less relevant to the current research interests. As long as the tonal and vocal pronunciations are correct, the first syllable's onset and coda errors are not considered. Second, as illustrated in (36b), the second syllable's segmental errors are not considered for the similar reason, since the current hypotheses focus on tones (rather than vowels and consonants) as a factor of prosodic types.

Third, as illustrated in (36c), it is not counted as an application error for some participants to produce low-rising tone sandhi's surface form, i.e. low-level tone (Tone-22), as low-falling tone (Tone-31), since low-level tone was found to gradually become low-falling as one of the ongoing tonal mergers (Yeh 2011; Yeh & Lin 2013, 2015; Yeh & Lu 2013). Those who gradually change low-level tone into low-falling tone were also found to change low-rising tone sandhi's low-level surface form to a low-falling surface form. As discussed in section 2.2 above, the ongoing tonal merger gives rise to a new pattern for low-rising tone sandhi. In other words, they simply apply low-rising tone sandhi in a new way (changing low-rising tone to low-falling, i.e. Tone-13→ ø → Tone-31), which still indicates a case of tone sandhi application. Therefore, to pronounce low-level tone as low-falling is not counted as production errors.

5.3.5.3 Dummy variables for analyses

In the following analyses, a multiple regression model was adopted. In order to run the multiple-regression analyses, it is indispensible to set up dummy variables for each independent variable. As shown in Table 5.7 below, there are seven dummy variables in total, including L_1/L_2, R, T, V, and P_1/P_2. The dummy variables L_1/L_2[8] encode stimuli of frequent words into 1/0, those of less frequent words into 0/1, and those of novel words into 0/0. That is, L_1 contrasts frequent words and two others, and L_2 contrasts less frequent words and two others. The dummy variable R encodes stimuli of low-rising tone sandhi into 1 and those of high-checked tone sandhi into 0, contrasting two tone sandhi rules. The dummy variable T encodes stimuli of underlying forms (Tone-13 and Tone-5) into 1 and those of surface forms (Tone-22 and Tone-2) into 0, contrasting sandhi tones' two forms. The dummy variable V encodes stimuli of high vowels into 1 and those of low vowels into 0, contrasting sandhi tones' two vowel types. The dummy variables P_1/P_2 encode stimuli of high-falling-tone prosody into 1/0, those of low-falling-tone prosody into 0/1, and those of low-rising-tone prosody into 0/0. That is, P_1 contrasts high tones and low tones, and P_2 contrasts low-falling-tone prosody words and two other prosodic types.

[8] The dummy variables 1 or 0 of each factor are set up randomly for statistical analyses without linguistic implications, and the assignment of 1 and 0 doesn't affect the results.

Table 5.7 Dummy variables for multiple regression analyses.

Factors	Codes	L_1	L_2	R	T	V	P_1	P_2
Lexical types	Frequent w.	1	0					
	Less freq. w.	0	1					
	Novel w.	0	0					
Sandhi types	Low-rising TS			1				
	H-checked TS			0				
Two forms	Underlying t.				1			
	Surface t.				0			
Vowel types	High v.					1		
	Low v.					0		
Prosodic types	H-falling t.						1	0
	L-falling t.						0	1
	L-rising t.						0	0

5.3.6 Detailed predictions

The detailed predictions for the experimental results are summarized below in terms of the four research hypotheses, (i.e. the lexical hypothesis, the phonetic/phonological hypothesis, the interaction hypothesis, and the processing hypothesis) and two additional hypotheses on psychological-reality and phonetic-naturalness issues demonstrated in Mandarin and Taiwan Southern Min tone sandhi.

Table 5.8 Detailed predictions for results of Hai-lu Hakka tone sandhi.

Hypothesis	Predictions
The Lexical Hypothesis	Both perception and production accuracy of Hai-lu Hakka tone sandhi are higher in frequent words than in less frequent and novel words, and they are the lowest in novel words (i.e. frequent > less frequent > novel).
The Phonetic/ Phonological Hypothesis	a. Sandhi effect: Production accuracy of low-rising tone sandhi is higher than that of high-checked tone sandhi, so is perception accuracy (i.e. low-rising tone sandhi > high-checked tone sandhi).
	b. Vowel effect: Production accuracy is higher when sandhi tones co-occur with low vowels than when co-occurring with high vowels, so is perception accuracy (i.e. low vowels > high vowels).
	c. Prosodic effect: Production accuracy is higher when sandhi tones precede low tones than when preceding high tones, so is perception accuracy (i.e. low-tone prosody > high-tone prosody).
The Interaction Hypothesis	There is an additional or enhanced influence of phonetic/phonological factors on novel words. That is, phonetic/phonological factors exert a more significant influence on novel words than frequent and less frequent words.
The Processing Hypothesis	a. The perception-production asymmetry: Based on the potential difference between perception and production processes, phonetic/phonological factors play a different role in perception and production tasks.
	b. The degrees of lexical access: Lexical and phonetic/phonological factors play a different role in each perception task that requires different degrees of lexical access.
The Psychological-Reality Hypothesis	Hai-lu Hakka tone sandhi is bound to actual words (not to novel words), so it is not phonologically productive and not psychologically real.
The Phonetic-Naturalness Hypothesis	Phonetically-driven tone sandhi is more applicable to speech processes than less phonetically-driven tone sandhi.

The lexical hypothesis, as shown in the first row of Table 5.8 above, predicts a significant influence of lexical factors on both perception and production processes of Hai-lu Hakka tone sandhi. Word types and lexical frequency/familiarity are predicted to enhance both perception and production accuracy. In other words, perception and production accuracy are predicted to be higher in frequent words than less frequent words, and higher in actual words (both frequent and less frequent words) than novel words. The perception and production accuracy are predicted to be the lowest in novel words.

The phonetic/phonological hypothesis, as shown in the second row of Table 5.8, predicts a significant influence of phonetic/phonological factors on both perception and production processes of Hai-lu Hakka tone sandhi. Phonetic grounding, tone-vowel interaction, and tonal co-articulation are predicted to enhance both perception and production accuracy. First, Hai-lu Hakka's low-rising tone sandhi arguably has a stronger phonetic basis than high-checked tone sandhi. The low-rising tonal change (from rising to level contour) is duration-shortening, while the high-checked tonal change (from high to low) is duration-lengthening, according to the tonal universals proposed by Hyman & Schuh (1974), Maddieson (1978), and Yu (2010). Zhang et al (2011) argued that vowel duration tends to be shorter in sandhi position, so the duration-shortening tone sandhi is predicted to have stronger phonetic grounding than the duration-lengthening one. In other words, low-rising tone sandhi is predicted to be more applicable (higher in production accuracy) than high-checked tone sandhi. Second, both Hai-lu Hakka's sandhi rules involve a pitch-lowering process. The tonal change from low-rising to low-level becomes lower in offset pitch, and that from high-checked to low-checked becomes lower in overall pitch. According to the tone-vowel interaction proposed by Chan (1985), Jiang-King (1999), and Yip (2002: 31), low tones tend to occur with low vowels, and low vowels may enhance a pitch-lowering process. As a result, production accuracy is predicted to be higher, when sandhi tones consist of low vowels than when consisting of high vowels. Third, both Hai-lu Hakka's tone sandhi rules involve tonal modifications that lower offset pitch height. Since preceding tones' offset pitch height tends to be assimilated to following tones' onset pitch (Peng 1997; Xu 2004), following tones' onset pitch may exert an influence on preceding tones' offset pitch. In other words, a following tone with a low onset pitch may enhance the preceding tone's change to lower offset pitch. As to the current variables, both low-falling tone and low-rising tone have low onset pitch, and they are predicted to enhance Hai-lu Hakka tone sandhi. Therefore, production accuracy is predicted to be higher, when sandhi tones precede low-falling tone and low-rising tone than when preceding high-falling tone. The perception accuracy is tentatively predicted to follow the same patterns; however, given the possibility of asymmetrical production and perception processes, the production and perception accuracy patterns may differ under some conditions.

The interaction hypothesis, as shown in the third row of Table 5.8, predicts a significant interaction between lexical and phonetic/phonological factors in both perception and production processes of Hai-lu Hakka tone sandhi. The interaction refers to an additional or enhanced influence of phonetic/phonological factors on novel words. The additional influence may result from sandhi types, vowel types, or prosodic types. That is, all these phonetic/phonological factors are predicted to exert an influence on all lexical types (the phonetic/phonological hypothesis), and the influence is predicted to be more significant to novel words than actual words (the interaction hypothesis). As a result, the difference induced by phonetic/phonological factors in perception and production accuracy is more significant to novel words than to actual words.

The processing hypothesis, as shown in the antepenultimate row of Table 5.8, predicts the influence of processing strategies on participants' access to lexical and phonetic/phonological knowledge in processing Hai-lu Hakka tone sandhi. The processing strategies vary with two factors: the asymmetry between perception and production processes and different degrees of lexical access. As proposed by Boersma (1998) and Flemming (2004), perception and production are two conflicting forces that shape phonological grammars. Since the two processes are argued to prefer opposite linguistic patterns: maximizing perceptual distinctiveness and minimizing articulatory efforts, they may affect participants' access to phonetic/phonological knowledge. If this line of thinking is on the right track, then the phonetic/phonological effects may exhibit opposite patterns on the perception and production results at least in some cases. For instance, low-rising tone sandhi may be higher in production accuracy, while it may be lower in perception results. Similarly, as indicated by Polka (1991) and Werkers & Tees (1984), phonetic/phonological factors may play a different role in each type of perception tasks. Some tasks, i.e. identification and recognition formats, are more likely to activate lexical access, but others, i.e. discrimination formats, are less likely to do so. The different degrees of lexical access may affect participants' access to lexical and phonetic/phonological knowledge. In other words, those lexical and phonetic/phonological effects, especially the lexical one, may be restricted to a minimal degree of lexical access provided by discrimination formats or other experimental manipulations.

The two additional hypotheses, as shown in the last two rows of Table 5.8, concern the psychological-reality and the phonetic-naturalness issues which motivated interests in Mandarin and Taiwan Southern Min tone sandhi previously. The two issues were argued to be supported by lexical and phonetic effects on the application of tone sandhi respectively, but they are not equivalent to the current hypotheses on lexical and the phonetic/phonological effects for a methodological difference. That is, the current hypotheses define sandhi types by tone sandhi rules as well as sandhi tones' two forms (underlying and surface), but the two forms were not considered previously to examine the psychological-reality and the phonetic-naturalness issues. In order to compare the current results with the two issues argued by previous studies (Zhang & Lai 2010; Zhang et al 2011), the variable of sandhi forms was excluded to examine psychological reality and phonetic naturalness of Hai-lu Hakka tone sandhi. Since Hai-lu Hakka's tone sandhi rules were found to exhibit various exceptions (Fan 1996; Chang 2002; Hsu 2009), they are predicted to be not automatically applicable to novel words (i.e. bound to actual words). In addition, since Hai-lu Hakka's low-rising tone sandhi arguably has stronger phonetic grounding than high-checked tone sandhi, it is predicted to be more applicable to speech processes. As a result, Hai-lu Hakka tone sandhi is predicted to be a lexical rule motivated by different degrees of phonetic grounding.

5.4 Results and analyses

Participants' responses were first encoded into percent accuracy by 72 stimulus types in each task. The accuracy results were summarized by each variable as preliminary results in section 5.4.1, and then were analyzed statistically by a multiple-regression model in section 5.4.2 to verify the four research hypotheses and the two additional hypotheses.

5.4.1 Preliminary results of percent accuracy

The overall results for each task are illustrated in Table 5.9 and Figure 5.1 below. The discrimination accuracy (AXB) is generally up to 93.7% (from 98.6% to 88.1%). The identification accuracy (IDN) and the production accuracy (PRO) are about 83% (IDN from 99.3% to 55.5%; PRO from 89.9% to 75.3%). The recognition accuracy (LEX) is down to 68.4% (from 93.7% to 41.6%). The results show that the percent accuracy is higher in the discrimination task than the others, and the percent accuracy is the lowest in the lexical recognition task. However, the standard deviation indicates an opposite pattern. It is higher in the lexical recognition task (up to 15.4%) than the others, and it is the lowest in the discrimination task (about 2.6%). The results suggest that Hai-lu Hakka participants encounter fewer difficulties in discriminating sandhi tones' surface forms (low-level tone and low-checked tone) from their underlying forms (low-rising tone and high-checked tone) than in identifying the two sandhi forms' tonal types, recognizing the sandhi forms' lexical meanings, and producing the two sandhi forms, and it is the most difficult for them to recognize the two sandhi forms' lexical meanings. The less difficult task exhibits fewer individual deviations than the more difficult one.

Table 5.9 Overall results of percent accuracy in each task.

Task Types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	93.73%	98.61%	88.19%	2.61%
IDN	83.49%	99.31%	55.56%	12.33%
LEX	68.46%	93.75%	41.67%	15.48%
PRO	83.35%	89.93%	75.35%	4.53%

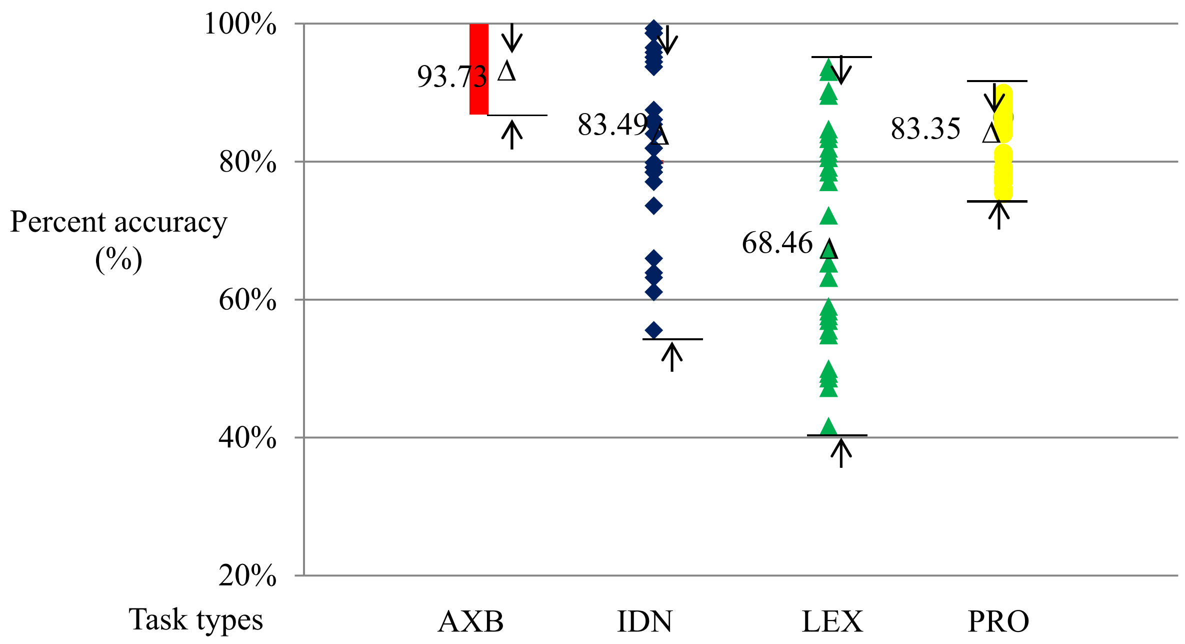

Figure 5.1 Overall results of percent accuracy in each task (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

5.4.1.1 Results of lexical types

The accuracy results are summarized by three lexical types in each task, and the results of lexical types are illustrated in Table 5.10 and Figure 5.2 below. The results show that the percent accuracy is higher in actual words (F: frequent words, LF: less frequent words) than in novel words (N) across the four tasks, as indicated by the arrows in Table 5.10 and Figure 5.2. The accuracy is the highest in frequent words, except for the identification results. In the identification results, the accuracy is slightly higher in less frequent words than in frequent words (i.e. LF: 86.02% > F: 84.95%). In addition, the results indicate that the difference (among three lexical types) is smaller in the discrimination results (AXB: from 95.9% to 90.8%) and the identification results (IDN: from 84.9% to 79.5%) than in the recognition results (LEX: from 83.6% to 45.6%) and the production results (PRO: from 96.5% to 65.2%). In other words, Hai-lu Hakka participants perceive and produce tone sandhi more accurately in actual words than in novel words. The findings suggest that lexical types exert an influence on speech processing of Hai-lu Hakka tone sandhi, and such an influence is smaller in the discrimination and the identification processes than in the recognition and the production processes. However, the identification results exhibit an exception to the effect of lexical frequency. The exception might result from a potential influence of additional training before the identification task, and the training effect might have neutralized the effect of lexical frequency. To sum up, the results generally confirm the predictions in Table 5.8 above, and hence support the lexical effect on speech processing of Hai-lu Hakka tone sandhi.

Table 5.10 Results of three lexical types (AXB: discrimination task; IDN: identification task; LEX: lexical recognition task; PRO: production task).

Tasks	Lexical factors	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	Frequent words (F)	95.90%	100.00%	87.50%	3.33%
	Less frequent w. (LF)	94.42%	97.92%	87.50%	2.50%
	Novel words (N)	90.86%	97.92%	79.17%	4.00%
IDN	Frequent words (F)	84.95%	100.00%	58.33%	12.98%
	Less frequent w. (LF)	86.02%	100.00%	58.33%	12.86%
	Novel words (N)	79.50%	97.92%	41.67%	13.20%
LEX	Frequent words (F)	83.60%	100.00%	56.25%	13.84%
	Less frequent w. (LF)	76.14%	97.92%	39.58%	15.57%
	Novel words (N)	45.63%	87.50%	8.33%	21.65%
PRO	Frequent words (F)	96.54%	100.00%	88.54%	3.22%
	Less frequent w. (LF)	88.21%	96.88%	76.04%	6.23%
	Novel words (N)	65.29%	78.13%	52.08%	7.38%

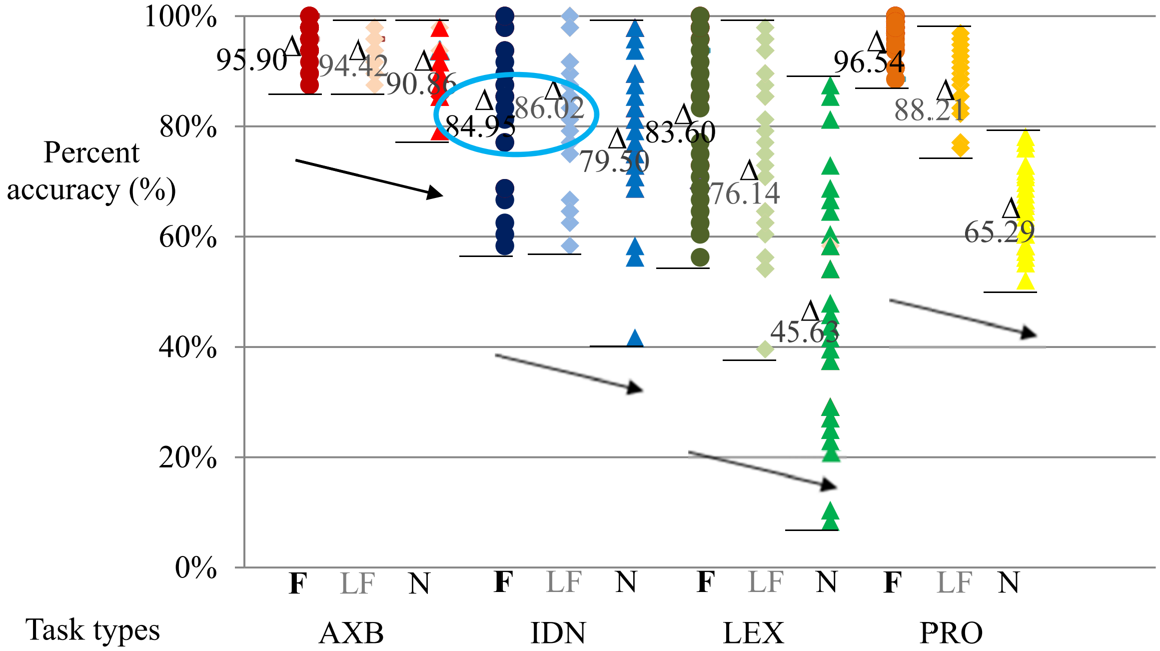

Figure 5.2 Results of three lexical types (AXB: discrimination task; IDN: identification task; LEX: lexical recognition task; PRO: production task).

5.4.1.2 Results of sandhi types

The accuracy results are summarized by sandhi types in each task, and the sandhi types include two rule types (low-rising tone sandhi and high-checked tone sandhi) and sandhi tones' two forms (underlying and surface forms). The results of rule types are illustrated in Table 5.11 and Figure 5.3 below. The results show that the percent accuracy of high-checked tone sandhi (HC) is higher than that low-rising tone sandhi (LR) in the discrimination, identification, and recognition results, but the percent accuracy of low-rising tone sandhi (LR) is slightly higher than that of high-checked tone sandhi (HC) in the production results, as indicated by the arrows in Table 5.11 and Figure 5.3. In other words, Hai-lu Hakka participants perceive high-checked tone sandhi more accurately than low-rising tone sandhi, but they produce low-rising tone sandhi more accurately than high-checked tone sandhi. The findings suggested that sandhi types exert an influence on speech processing of Hai-lu Hakka tone sandhi, and such an influence exhibit a different pattern between perception and production processes. In general, the production results confirm the predictions that phonetically-based low-rising tone sandhi is more applicable than less phonetically-based high-checked tone sandhi, and hence support the phonetic/phonological effect on speech processes of Hai-lu Hakka tone sandhi. The different patterns between perception and production processes, i.e. the perception-production asymmetry, also confirm the predictions based on the processing hypothesis, and support the processing effect.

Table 5.11 Results of sandhi types (AXB: discrimination task; IDN: identification task; LEX: lexical recognition task; PRO: production task).

Tasks	Rule types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	Low-rising tone sandhi (LR)	90.55%	97.22%	81.94%	3.68%
	High-checked t. sandhi (HC)	96.91%	100.00%	91.67%	2.31%
IDN	Low-rising tone sandhi (LR)	82.08%	98.61%	54.17%	13.15%
	High-checked t. sandhi (HC)	84.90%	100.00%	48.61%	13.93%
LEX	Low-rising tone sandhi (LR)	64.20%	90.28%	37.50%	17.00%
	High-checked t. sandhi (HC)	72.72%	100.00%	36.11%	16.67%
PRO	Low-rising tone sandhi (LR)	83.38%	93.75%	67.36%	5.68%
	High-checked t. sandhi (HC)	83.31%	95.14%	71.53%	5.89%

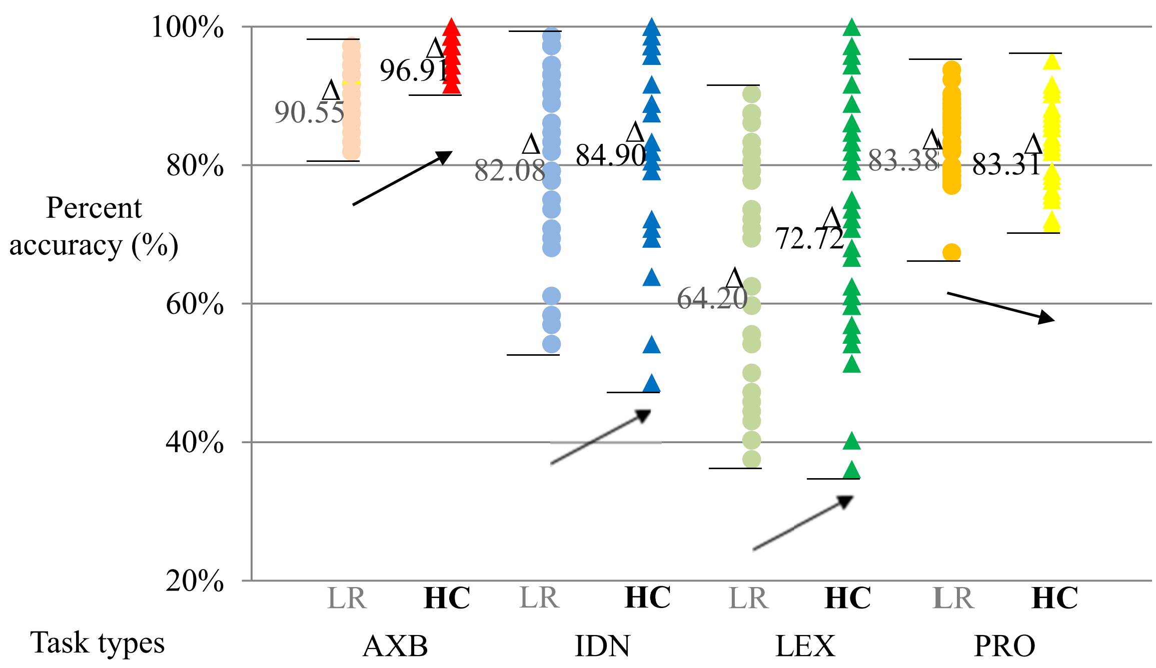

Figure 5.3 Results of sandhi types (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

The results of sandhi forms are illustrated in Table 5.12 and Figure 5.4 below. The results show that the percent accuracy of the underlying forms (UT) is higher than that of the surface forms (ST) in the identification and recognition results, but the percent accuracy of the surface forms (ST) is higher than that of the underlying forms (UT) in the discrimination and the production results, as indicated by the arrows in Table 5.12 and Figure 5.4. In other words, (i) Hai-lu Hakka participants discriminate surface-underlying sequences more accurately than underlying-surface sequences; (ii) they identify sandhi tones' underlying forms (Tone-13 and Tone-5) more accurately than surface forms (Tone-22 and Tone-2); (iii) they recognize underlying forms' corresponding meanings more accurately than surface forms'; and (iv) they produce surface forms (Tone-22 and Tone-2) more accurately than underlying forms (Tone-13 and Tone-5). It is not surprising that these participants produce sandhi tones' surface forms more accurately, since they are not required to apply tone sandhi to any surface form. It is intriguing why the discrimination results exhibit the opposite pattern from the identification and the recognition results. The difference seems to result from an influence of processing factors, since it happens to contrast different degrees of lexical access provided by the three perception tasks.

Table 5.12 Results of sandhi tones' two forms (AXB: discrimination task; IDN: identification task; LEX: lexical recognition task; PRO: production task).

Tasks	Sandhi tones' forms	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	Underlying tone (UT)	92.03%	97.22%	84.72%	3.28%
	Surface tone (ST)	95.43%	100.00%	88.89%	2.98%
IDN	Underlying tone (UT)	85.62%	100.00%	55.56%	11.72%
	Surface tone (ST)	81.36%	100.00%	51.39%	13.93%
LEX	Underlying tone (UT)	72.45%	100.00%	47.22%	14.43%
	Surface tone (ST)	64.47%	93.06%	36.11%	17.72%
PRO	Underlying tone (UT)	68.93%	81.25%	52.78%	8.76%
	Surface tone (ST)	97.76%	100.00%	81.94%	3.48%

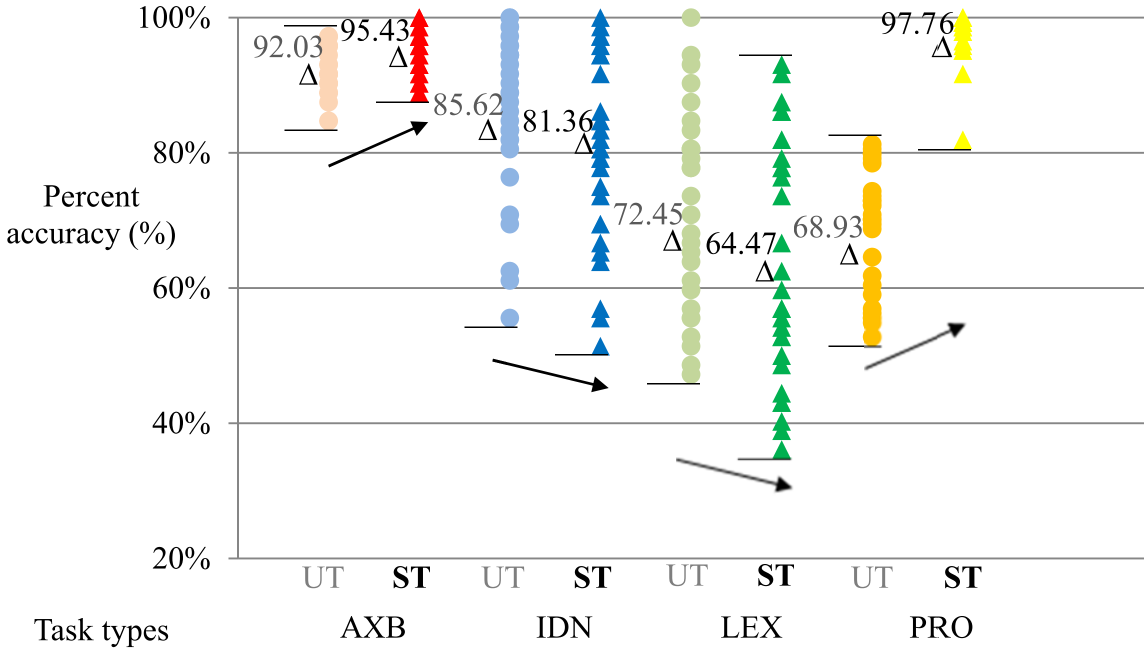

Figure 5.4 Results of sandhi tones' two forms (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

5.4.1.3 Results of vowel types

The accuracy results are summarized by two vowel types in each task, and the results of vowel types are illustrated in Table 5.13 and Figure 5.5 below. The results show that the percent accuracy of high vowels (H) is higher than that of low vowels (L) in the discrimination and the identification results, but the percent accuracy of low vowels is higher than that of high vowels in the recognition and the production results, as indicated by the arrows in Table 5.13 and Figure 5.5. In other words, (i) Hai-lu Hakka participants discriminate tone sandhi and identify sandhi tones more accurately, when sandhi tones co-occur with high vowels than with low vowels; (ii) they recognize sandhi tones' corresponding meanings more accurately, when sandhi tones co-occur with low vowels than when with high vowels; and (iii) they produce tone sandhi more accurately, when sandhi tones co-occur with low vowels than with high vowels. It is intriguing that the discrimination and the identification results exhibit the opposite pattern from the recognition and the production results. In general, the production results confirm the predictions that production accuracy is higher when sandhi tones co-occur with low vowels than with high vowels, and hence support the phonetic/phonological effect on speech processes of Hai-lu Hakka's tone sandhi. The different patterns between the discrimination/identification results and the recognition/production results seem to be influenced by processing factors.

Table 5.13 Results of vowel types (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

Tasks	Vowel types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	High vowel (H)	↓ 94.76%	98.61%	88.89%	2.70%
	Low vowel (L)	92.70%	98.61%	87.50%	2.70%
IDN	High vowel (H)	↓ 85.71%	100.00%	58.33%	11.71%
	Low vowel (L)	81.27%	100.00%	52.78%	13.39%
LEX	High vowel (H)	↑ 67.11%	91.67%	27.78%	16.44%
	Low vowel (L)	69.80%	98.61%	43.06%	16.05%
PRO	High vowel (H)	↑ 78.27%	87.50%	69.44%	4.81%
	Low vowel (L)	88.42%	98.61%	76.39%	5.41%

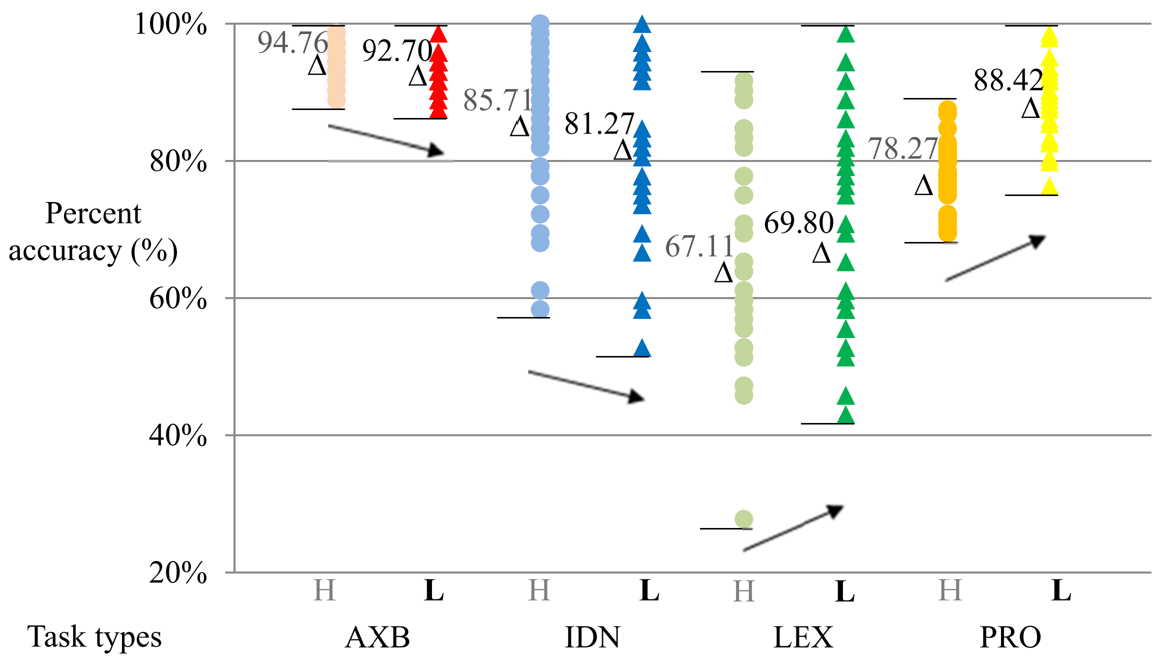

Figure 5.5 Results of vowel types (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

5.4.1.4 Results of prosodic types

The accuracy results are summarized by three prosodic types in each task, and the results of prosodic types are illustrated in Table 5.14 and Figure 5.6 below. The results show that the percent accuracy is higher under the low-falling prosody (LF) condition than under the low-rising prosody (LR) and high-falling prosody (HF) conditions in the perception results, but is higher under the high-falling prosody (HF) and low-rising prosody (LR) conditions than under the low-falling prosody (LF) condition in the production results. As indicated by the arrows in Table 5.14 and Figure 5.6 below, the black indicate higher percent accuracy, while the red indicate the lowest. As to the low-falling prosody condition, the perception accuracy is the highest, but the production accuracy is the lowest. In other words, Hai-lu Hakka participants perceive and produce sandhi tones more accurately, when the sandhi tones precede low-rising tone than when preceding high-falling tone, but they process low-falling prosody in the opposite manner. They perceive sandhi tones more accurately, but produce tone sandhi less accurately before low-falling tone. The low-falling prosody's opposite patterns indicate an asymmetry between perception and production processes. In general, the production results partially confirm the predictions that production accuracy is higher, when sandhi tones precede low tones (LR) than when preceding high tones (HF), with an exception before low-falling tone, and hence may support the phonetic/phonological effect on speech processes of Hai-lu Hakka tone sandhi. The low-falling prosody's different patterns between perception and production results also confirm the predictions based on the processing hypothesis, and support the processing effect.

Table 5.14 Results of prosodic types (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

Tasks	Prosodic types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
AXB	High-falling tone (HF)	↓ 91.94%	100.00%	83.33%	4.99%
	Low-falling tone (LF)	↑ 96.64%	100.00%	91.67%	8.26%
	Low-rising tone (LR)	↑ 92.61%	97.92%	81.25%	4.13%
IDN	High-falling tone (HF)	↓ 77.76%	100.00%	45.83%	15.71%
	Low-falling tone (LF)	↑ 88.24%	100.00%	56.25%	12.32%
	Low-rising tone (LR)	↑ 84.48%	100.00%	64.58%	12.39%
LEX	High-falling tone (HF)	↓ 64.85%	93.75%	35.42%	17.31%
	Low-falling tone (LF)	↑ 73.72%	100.00%	41.67%	16.97%
	Low-rising tone (LR)	↑ 66.80%	93.75%	37.50%	15.40%
PRO	High-falling tone (HF)	↑ 85.18%	93.75%	71.88%	5.87%
	Low-falling tone (LF)	↓ 78.90%	85.42%	68.75%	4.30%
	Low-rising tone (LR)	↑ 85.95%	94.79%	76.04%	5.49%

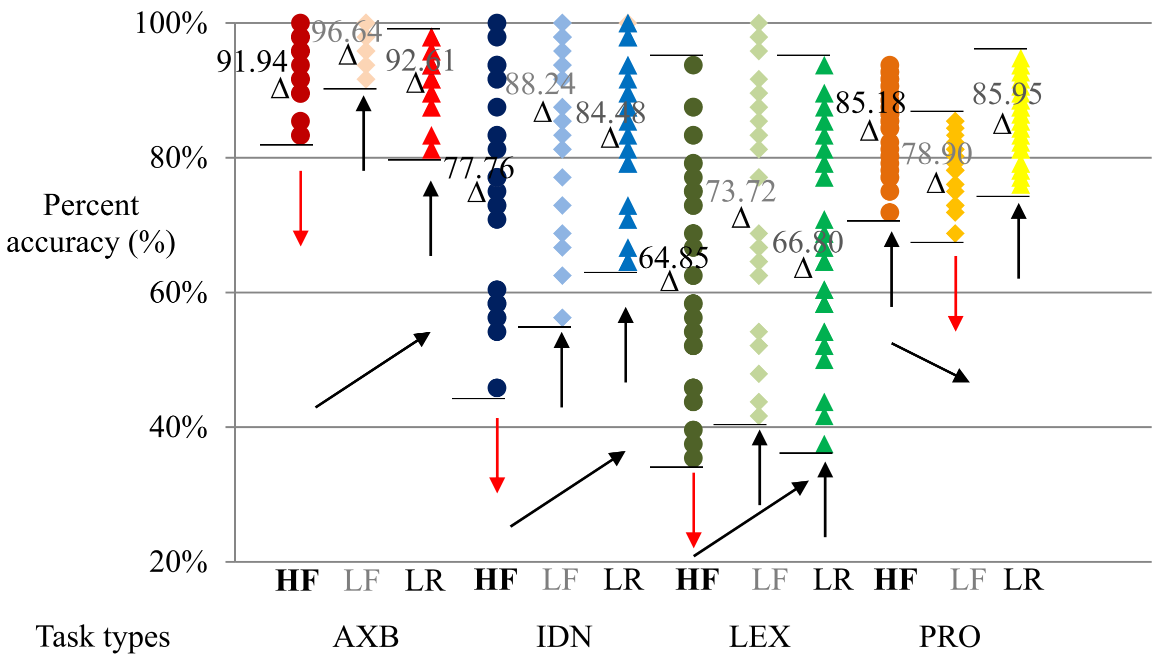

Figure 5.6 Results of prosodic types (AXB: discrimination task; IDN: identification task; LEX: lexical task; PRO: production task).

5.4.1.5 Summary of preliminary results

The preliminary results above are summarized by lexical and phonetic/phonological factors in each task below. As shown in Table 5.15 below, the **BLACK** parts indicate those results confirming the predictions, and the RED parts indicate the exceptions to the predictions. The preliminary results generally support the effects of lexical types, sandhi types, and vowel types on speech processes of Hai-lu Hakka tone sandhi, and partially support the effect of prosodic types. These results also exhibit some different patterns among four tasks. First, as to the results of vowel types, there is a different pattern between discrimination/identification (AXB/IDN) and lexical/production (LEX/PRO) results. The difference may result from an influence of different degrees of lexical access. As to the results of sandhi types and prosodic types, there is a different pattern between perception and production results. The difference seems to indicate a perception-production asymmetry. In other words, these different patterns may support the effect of processing factors. These preliminary findings are further discussed below.

Table 5.15 Summary of preliminary results in four tasks (F: frequent words, LF: less frequent words, N: novel words; HC: high-checked tone sandhi, LR: low-rising tone sandhi; H: high vowels, L: low vowels; HF: high-falling prosody, LF: low-falling prosody, LR: low-rising prosody).

	AXB	IDN	LEX	PRO
Lexical types	**F > LF> N**	LF, F > N	**F > LF > N**	**F > LF > N**
Sandhi types	HC > LR	HC > LR	HC > LR	**LR > HC**
Vowel types	H > L	H > L	**L > H**	**L > H**
Prosodic types	**LF > LR > HF**	**LF > LR > HF**	**LF > LR > HF**	LR > HF > LF

As to the lexical types, the percent accuracy is higher in actual words (F, LF) than in novel words (N) across the four tasks, and the accuracy is the highest in frequent words (F), except for the identification results (LF > F). The results indicate a consistent pattern across each task, and the sole exception may result from additional training (or a minimal degree of lexical access) provided by the identification format. These findings generally confirm the prediction based on the lexical hypothesis, and hence support the lexical effect on speech processes of Hai-lu Hakka tone sandhi. The exception occurring in the identification results may support the effect of processing factors.

As to the sandhi types, the percent accuracy of high-checked tone sandhi (HC) is higher than that of low-rising tone sandhi (LR) in the perception results, but vice versa in the production results. The results indicate different patterns between perception and production results, and the difference seems to be correlated to the asymmetry between perception and production processes. In general, the production results confirm the prediction based on the phonetic/phonological hypothesis, and hence support the effect of sandhi types on speech processes of Hai-lu Hakka tone sandhi. The different patterns between perception and production results may support the processing effect (i.e. the perception-production asymmetry). There is a further issue regarding why low-rising tone sandhi tends to be implemented with ease, but to be perceived with difficulty.

As to the vowel types, the percent accuracy of low vowels (L) is higher than that of high vowels (H) in the recognition and the production results, but vice versa in the discrimination and the identification results. The results indicate different patterns between recognition/production results and discrimination/identification results, and the difference seems to be correlated to the degrees of lexical access. In general, the recognition and the production results confirm the prediction based on the phonetic/phonological hypothesis, and hence support the effect of vowel types on speech processes of Hai-lu Hakka tone sandhi. The different patterns between recognition/production results and discrimination/identification results may support the effect of processing factors (i.e. different degrees of lexical access). What is of interest is that the effect of vowel types is correlated to different degrees of lexical access.

As to the prosodic types, the percent accuracy is higher under the low-falling prosody (LF) condition than under the low-rising prosody (LR) and high-falling (HF) conditions in the perception results (i.e. LF> <u>LR> HF</u>), but vice versa in the production results (i.e. <u>LR> HF</u>> LF). The results indicate different patterns between perception and production results, in particular to the low-falling prosody, and the difference can be correlated to the asymmetry between perception and production processes. In general, the perception results confirm the prediction based on the phonetic/phonological hypothesis, and hence support the effect of vowel types on speech processes of Hai-lu Hakka tone sandhi. The production results do so partially, since they exhibit an exception in which the production accuracy is the lowest under the low-falling prosody condition. The low-falling prosody's different patterns between perception and production results may support the processing effect (i.e. the perception-production asymmetry). There is a further issue regarding why the low-falling prosody enhances perception accuracy, but reduces production accuracy.

In sum, the preliminary results indicate that various kinds of factors, including lexical types, sandhi types, vowel types, and prosodic types, exert an influence on speech processes of Hai-lu Hakka tone sandhi. These influences seem to be conditioned by processing factors which may result in exceptions to these influences. According to the current findings, the processing factors refer to (i) the asymmetry between perception and production processes, (ii) different degrees of lexical access, and (iii) other experimental manipulations and setup, such as training and instructions. These processing factors have already been proposed and discussed by Boersma (1998), Flemming (2004), Polka (1991), Werker & Tees (1984), and many others, but it is still unclear how these processing factors affect lexical access and phonetic and phonological effects. For instance, why does low-rising tone sandhi tend to be implemented with ease, but to be perceived with difficulty? Why is the effect of vowel types correlated to different degrees of lexical access? Why does the low-falling prosody enhance perception accuracy, but reduce production accuracy? These questions may turn out to be crucial to understanding speech processes of Hai-lu Hakka tone sandhi as well as to evaluating a model of speech processing.

5.4.2 Statistical analyses

The preliminary results generally support the effects of various factors, but also indicate some different patterns for these effects in each process. In order to examine whether these effects and patterns are statistically valid, the results are further analyzed by a multiple-regression model below. As shown in (37) below, the logarithmic model includes (i) an analysis for each factor and (ii) an analysis for two-way interaction. The analysis for each factor considers the results of three lexical types (dummy variables: L_1, L_2), sandhi types (R, T), two vowel types (V), and three prosodic types (P_1, P_2). The analysis for two-way interaction examines whether there is an additional influence of phonetic/phonological factors in different lexical types, and considers the interaction between lexical factors and sandhi types (four combinations: L_1*R, L_2*R, L_1*T, L_2*T), between lexical factors and vowel types (L_1*V, L_2*V), and between lexical factors and prosodic types (L_1*P_1, L_2*P_1, L_1*P_2, L_2*P_2). That is, the model includes a total of 17 variables (7 dummy variables+ 10 combinations= 17). In addition, the model includes three other tokens: Y, a, and b. Token **Y** refers to percent accuracy of each stimulus type; token **a** refers to an intercept; and token **b** (from $\mathbf{b_1}$ to $\mathbf{b_{17}}$) refers to a regression coefficient of each variable.

(37) Equation of multiple-regression model

$$Y = a + \sum_{i=1}^{k} b_k x_k \qquad (\boldsymbol{x}\text{= each dummy variable})$$

$$= a + b_1{*}L_1 + b_2{*}L_2 + b_3{*}R + b_4{*}T + b_5{*}V + b_6{*}P_1 + b_7{*}P_2 \qquad \text{(each factor)}$$

$$+ b_8{*}L_1{*}R + b_9{*}L_2{*}R + b_{10}{*}L_1{*}T + b_{11}{*}L_2{*}T \qquad \text{(lexical \& sandhi types)}$$

$$+ b_{12}{*}L_1{*}V + b_{13}{*}L_2{*}V \qquad \text{(lexical \& vowel types)}$$

$$+ b_{14}{*}L_1{*}P_1 + b_{15}{*}L_1{*}P_2 + b_{16}{*}L_2{*}P_1 + b_{17}{*}L_2{*}P_2 \qquad \text{(lexical \& prosodic types)}$$

5.4.2.1 Analysis for lexical and phonetic/phonological effects

The overall results show that the analyses are significant in each task: (i) $R^2 = 0.0865$[9], $F(17,2214) = 63.6850$, $p < 0.001$*** in the AXB discrimination results (AXB), (ii) $R^2 = 0.0561$, $F(17,2214) = 32.1630$, $p < 0.001$*** in the tonal identification results (IDN), (iii) $R^2 = 0.2373$, $F(17,2214) = 16.7090$, $p < 0.001$*** in the lexical recognition results (LEX), and (iv) $R^2 = 0.5727$, $F(17,2214) = 57.8830$, $p < 0.001$*** in the production results (PRO). In general, the analyses include a total of 17 variables (7 dummy variables x 10 combinations= 17) and 2232 analysis tokens (31 participants x 72 stimulus types= 2232). The amount of analysis tokens is much larger than the amount of variables, and it allows a legitimate degree of freedom (2214) for these analyses. The results of analyses for each lexical and phonetic/phonological factor are summarized in Table 5.16 below.

Table 5.16 Results of multiple-regression analyses for lexical and phonetic/phonological factors (RED: $p > 0.10$; GOLD: $0.05 < p < 0.10$; BLACK: $p < 0.05$).

Factors / Tasks	Lexical types	Phonetic/phonological factors			
		Rules	Forms	Vowels	Prosody
AXB	L_1: $p < 0.10$ L_2: $p < 0.10$	$p < 0.001$	$p < 0.001$	$p < 0.001$	P_1: $p < 0.05$ P_2: $p < 0.001$
IDN	L_1: $p > 0.10$ L_2: $p > 0.10$	$p < 0.10$	$p < 0.10$	$p < 0.05$	P_1: $p < 0.001$ P_2: $p < 0.10$
LEX	L_1: $p < 0.001$ L_2: $p < 0.001$	$p<0.001$	$p < 0.001$	$p < 0.001$	P_1: $p < 0.10$ P_2: $p < 0.05$
PRO	L_1: $p < 0.01$ L_2: $p > 0.10$	$p > 0.10$	$p < 0.001$	$p < 0.001$	P_1: $p > 0.10$ P_2: $p < 0.001$

As shown in Table 5.16 above, the analyses show that not all the lexical and phonetic/phonological effects referred above are significant in each process. The effect of lexical types, as shown in the second column of Table 5.16, is significant in the recognition (LEX) and the production (PRO) results, except for L_2 in the production results, and less

[9] The R square seems to be too low for the multiple-regression analyses, which indicates that those variables involved may not be logarithmic to the accuracy results. In other words, those variables may need reconfiguring more or less to fit the logarithmic model. Since the overall analyses are found to be very significant (p< ***) at least, there is no further configuration in these analyses.

significant in the discrimination (AXB) and the identification (IDN) results. The effect of sandhi types (rules only), as shown in the third column of Table 5.16, is significant in the perception results (AXB, IDN, and LEX), but less significant in the production results. The effect of vowel types, as shown in the penultimate column of Table 5.16, is significant in all the results. The effect of prosodic types, as shown in the last column of the table, is significant in most of the results, except for P_1 in the production results. In order to interpret these statistic results, the analyses are summarized along with the patterns demonstrated in Table 5.15 above, and the summary is shown in Table 5.17 below.

Table 5.17 Summary of multiple-regression analyses for lexical and phonetic/phonological factors and patterns (L_1: difference between frequent words and others, L_2: difference between less frequent words and others; P_1: difference between high-falling prosody and others, P_2: difference between low-falling prosody and others).

	AXB	IDN	LEX	PRO
Lexical types	F≧ LF≧ N L_1: $p < 0.10$+ L_2: $p < 0.10$+	LF= F= N L_1: $p > 0.05$ L_2: $p > 0.05$	F> LF> N L_1: $p < 0.001$*** L_2: $p < 0.001$***	F> LF= N L_1: $p < 0.01$** L_2: $p > 0.05$
Sandhi types (rules)	HC> LR $p < 0.001$***	HC≧ LR $p < 0.10$+	HC> LR $p < 0.001$***	LR= HC $p > 0.05$
Sandhi types (forms)	ST> UT $p < 0.001$***	UT≧ ST $p < 0.10$+	UT> ST $p < 0.001$***	ST> UT $p < 0.001$***
Vowel types	H> L $p < 0.001$***	H> L $p < 0.05$*	L> H $p < 0.001$***	L> H $p < 0.001$***
Prosodic types	LF> LR> HF P_1: $p < 0.05$* P_2: $p < 0.001$***	LF≧ LR> HF P_1: $p < 0.001$*** P_2: $p < 0.10$+	LF> LR≧ HF P_1: $p < 0.10$+ P_2: $p < 0.05$*	LR= HF> LF P_1: $p > 0.10$ P_2: $p < 0.001$***

As shown in the first row of Table 5.17 above, the analyses show that the effect of lexical types is less significant in the discrimination (AXB) and the identification (IDN) results, especially the identification ones, and more significant in the recognition (LEX) and the production (PRO) results, except for the difference between less frequent words (LF) and novel words (N) in the production ones. In other words, Hai-lu Hakka participants process tone sandhi more accurately in frequent words than less frequent and novel words, when they recognize and produce the tonal changes. Although the difference is also found in two other tasks, it is less significant in the discrimination results, and not significant in the identification results. The findings indicate that these lexical types exhibit a consist pattern (frequent words > less frequent words > novel words) in each process, but their influence is correlated to different degrees of lexical access granted by each task: i.e. more significant in recognition and production formats with a higher degree of lexical access, and less (or not) significant in discrimination and identification formats with a minimal degree of lexical access. To sum up, the significant results support the lexical effect on speech processes of Hai-lu Hakka tone sandhi, and the less significant results suggest a potential influence of processing factors (i.e. different degrees of lexical access). Therefore, the analyses confirm both the lexical hypothesis and the processing hypothesis.

As shown in the second row of Table 5.17, the analyses show that the effect of sandhi types is significant in the perception (AXB, IDN, and LEX) results, except for the less significant identification ones, but not significant in the production (PRO) results. In other words, Hai-lu Hakka participants perceive high-checked tone sandhi (HC) more accurately than low-rising tone sandhi (LR), but the difference is not significant in the production process. The findings indicate that the sandhi types exhibit different patterns between perception and production processes (AXB, IDN, LEX: HC > LR; PRO: LR > HC), and their influence also seems to be conditioned by the similar processing factor (i.e. the asymmetry between perception and production processes). To sum up, the significant results support the sandhi effect on speech perception of Hai-lu Hakka's tone sandhi (HC > LR), and the less significant results suggest a potential influence of processing factors. Therefore, the analyses confirm both the phonetic/phonological hypothesis and the processing hypothesis.

As shown in the penultimate row of Table 5.17, the analyses show that the effect of vowel types is significant across the four tasks. In other words, Hai-lu Hakka participants recognize and produce tone sandhi more accurately, when sandhi tones co-occur with low vowels (L) than when co-occurring with high vowels (H). On the contrary, they discriminate and identify sandhi tones more accurately, when sandhi tones co-occur with high vowels (H) than with low vowels (L). The findings indicate that the vowel types exhibit different patterns between discrimination/identification results (H > L) and recognition/production results (L > H), and the difference can be correlated to different degrees of lexical access granted by each task: i.e. L > H in recognition and production formats with a higher degree of lexical access, and H > L in discrimination and identification formats with a minimal degree of lexical access, which is similar to the lexical effect. To sum up, the significant results support the vowel effect on speech processes of Hai-lu Hakka tone sandhi, and the different patterns across different tasks suggest a potential influence of processing factors (different degrees of lexical access). Therefore, the analyses confirm both the lexical hypothesis and the processing hypothesis.

As shown in the last row of Table 5.17, the analyses show that the effect of prosodic types is significant across the four tasks, except for the less significant difference between low-falling prosody (LF) and low-rising prosody (LR) in the identification results, the less significant difference between low-rising prosody (LR) and high-falling prosody (HF) in the recognition results, and no significant difference between low-rising prosody (LR) and high-falling prosody (HF) in the production results. In other words, Hai-lu Hakka participants perceive tone sandhi more accurately, when sandhi tones precede low-falling tone than when preceding high-falling tone, but they produce tone sandhi more accurately, when sandhi tones precede high-falling tone than preceding low-falling tone. As to the low-rising prosody, it shows a relatively arbitrary pattern (similar to low-falling tone in the identification results, but similar to high-falling tone in the recognition and the production results). The findings indicate that these prosodic types exhibit different patterns between perception and production processes (AXB, IDN, and LEX: LF > HF; PRO: HF > LF), which exhibits a perception-production asymmetry. Although the prosodic types are found to exert an influence on speech production of Hai-lu Hakka tone sandhi, the production pattern (HF > LF) is different from the prediction based on tonal co-articulation (low tones > high tones). The difference indicates that tonal co-articulation may not able to account for the prosodic effect on speech production of Hai-lu Hakka tone sandhi. To sum up, the significant results support the prosodic effect on speech processes of Hai-lu Hakka's tone sandhi, and the different patterns suggest a potential influence of processing factors (the perception-production asymmetry). Therefore, the analyses confirm both the phonetic/phonological hypothesis and the processing hypothesis.

In general, the analyses confirm the lexical hypothesis, the phonetic/phonological hypothesis, and the processing hypothesis. The analyses also demonstrate three issues on speech processing of Hai-lu Hakka tone sandhi. First, the three kinds of phonetic/phonological factors are found to exert an influence more or less, but these phonetic/phonological effects may exhibit a different pattern from the predictions. For instance, the sandhi-type effect was predicted to enhance low-rising tone sandhi's production accuracy, but it is not statistically significant. It turns out to increase high-checked tone sandhi's perception accuracy. Likewise, the prosodic effect was predicted to enhance tone sandhi's production accuracy when sandhi tones precede low tones, but it is not. It turns out to increase tone sandhi's production accuracy when sandhi tones precede high-falling tone. These differences indicate that these phonetic/phonological effects may result from causes other than the predictions based on tonal co-articulation. Second, these phonetic/phonological effects seem to exhibit a less consistent pattern than the lexical effect. As mentioned above, the phonetic/phonological effects may exhibit different patterns between perception and production tasks (or between discrimination/identification and recognition/production tasks), but the lexical effects have a more consistent pattern across the four tasks. Third, these effects and their patterns are found to be correlated to the processing factors: the perception-production asymmetry and different degrees of lexical access. The questions are: how and why does the perception-production asymmetry happen to affect the sandhi effect and the prosodic effect, and how and why do the degrees of lexical access happen to affect the lexical effect and the vowel effect. These three issues will be further discussed later in this chapter.

5.4.2.2 Analysis for effects of two-way interaction

In addition to the analysis for each lexical and phonetic/phonological factor, the multiple-regression model, as shown in (37) above, also includes the analysis for two-way interaction between lexical and phonetic/phonological factors to examine whether there is an additional influence of phonetic/phonological factors on novel words (not on actual words). The results of analysis for two-way interaction are summarized in Table 5.18 below.

Table 5.18 Results of multiple-regression analyses for two-way interaction (L_1: difference between frequent words and others, L_2: difference between less frequent words and others; P_1: difference between high-falling prosody and others, P_2: difference between low-falling prosody and others; RED: $p > 0.10$, GOLD: $0.05 < p < 0.10$, BLACK: $p < 0.05$).

Tasks	Factors	pp= Phonetic/phonological factors			
		Rules	Forms	Vowels	Prosody
AXB	L_1 & pp	$p > 0.10$	$p > 0.10$	$p < 0.10$	P_1: $p > 0.10$ P_2: $p > 0.10$
	L_2 & pp	$p > 0.10$	$p > 0.10$	$p < 0.10$	P_1: $p < 0.10$ P_2: $p > 0.10$
IDN	L_1 & pp	$p > 0.10$	$p > 0.10$	$p > 0.10$	P_1: $p > 0.10$ P_2: $p > 0.10$
	L_2 & pp	$p > 0.10$	$p > 0.10$	$p > 0.10$	P_1: $p < 0.01$ P_2: $p > 0.10$
LEX	L_1 & pp	$p > 0.10$	$p > 0.10$	$p < 0.001$	P_1: $p > 0.10$ P_2: $p > 0.10$
	L_2 & pp	$p > 0.10$	$p < 0.05$	$p < 0.05$	P_1: $p > 0.10$ P_2: $p > 0.10$
PRO	L_1 & pp	$p > 0.10$	$p < 0.001$	$p < 0.001$	P_1: $p > 0.10$ P_2: $p < 0.01$
	L_2 & pp	$p < 0.001$	$p < 0.001$	$p < 0.001$	P_1: $p > 0.10$ P_2: $p > 0.10$

The results show that the interaction between lexical and phonetic/phonological factors is generally not significant in the four tasks. As to the degree of significance, the two-way interaction is more significant in the recognition and the production results (i.e. $p < 0.01$ and 0.001) than in the discrimination and the identification results (i.e. $p < 0.10$). As to the kind of interaction, the interaction is more likely to occur in the production results (between lexical types and sandhi types, between lexical types and vowel types, between lexical types and prosodic types) than in the perception results (between lexical types and vowel types, between lexical types and prosodic types). The two-way interaction seems to be correlated to different task types. In other words, the two kinds of factors (lexical, phonetic/phonological) and their interaction may be conditioned by processing factors. These results are further discussed as follows.

As to the interaction between lexical types and sandhi types, the results show that there is a significant interaction (only between L_2 & sandhi type) in the production results, but not in the perception results. The significant interaction indicates that the difference of production accuracy between low-rising tone sandhi and high-checked tone sandhi (low-rising tone sandhi> high-checked tone sandhi) is more significant to L_2 (difference between less frequent words and others), but not to L_1 (difference between frequent words and others). In other words, the difference is not more significant between frequent and less frequent words (i.e. actual words). The findings suggest that the sandhi types play a more different role in novel words than in actual words, and confirm the prediction that the sandhi effect has an additional influence on novel words. As a result, the findings support the interaction hypothesis.

As to the interaction between lexical types and vowel types, the results show that there is a slightly significant interaction (i.e. $p < 0.10$) in the discrimination results, a significant interaction in the recognition and the production results (i.e. $p < 0.05$ and 0.001), but no significant interaction in the identification results. The significant interaction indicates that the difference of recognition accuracy between low vowels and high vowels (low > high) is more significant to novel words than to actual words (less frequent words > frequent words), and so is the difference of production accuracy. The difference is significant across each lexical type. The findings suggest that the vowel types play a more significant role in novel words than in actual words, and confirm the prediction that the vowel effect has an additional influence on novel words. As a result, the findings support the interaction hypothesis.

As to the interaction between lexical types and prosodic types, the results show that there is a slightly significant interaction (between L_2 & P_1) in the discrimination results, a significant interaction (between L_2 & P_1) in the identification results, a significant interaction (between L_1 & P_2) in the production results, but not in the recognition results. The significant interaction indicates that the difference of discrimination/identification accuracy between high-falling prosody and low-rising/low-falling prosody (low tones > high tones) is more significant to L_2, but not to L_1. In addition, the difference of production accuracy between low-falling prosody and low-rising/high-falling prosody (low-rising tone, high-falling tone > low-falling) is more significant to L_1, but not to L_2. The findings suggest that the prosodic types play a more significant role in novel words than in actual words, and confirm the prediction that the prosodic effect has an additional influence on novel words. As a result, the findings support the interaction hypothesis.

To sum up, the analyses indicate that phonetic/phonological factors may interact with lexical factors to bring forth an additional influence of these phonetic/phonological factors on novel words in speech processes of Hai-lu Hakka tone sandhi. The additional influence as an interaction effect suggests that Hai-lu Hakka speakers are more likely to access phonetic/phonological factors to process tone sandhi in novel words than in actual words (in less frequent words than in frequent words). In other words, their access to phonetic/phonological factors seems to be correlated to lexical knowledge (lexical frequency and word types). When lexical knowledge is not available during speech processing of Hai-lu Hakka tone sandhi, the processing may resort to non-lexical knowledge, which therefore enhances the effects of phonetic/phonological factors more significantly.

5.4.3 Results and analysis of lexical familiarity

The results of participants' lexical familiarity ratings are summarized by each lexical and phonetic/phonological factor, and the results of lexical factors are shown below. As illustrated in Table 5.19 and Figure 5.7, these familiarity ratings are positively correlated to the three lexical types. Those frequent words are found to have a higher rating score (i.e. 4.44 out of 5 in average) than less frequent words (mean: 2.81) and novel words (mean: 1.00), and the novel words have the lowest ratings. The results indicate that the lexical familiarity ratings are consistent with the three lexical types (frequent words > less frequent words > novel words).

Table 5.19 Results of lexical familiarity (5: the most familiar; 1: the least familiar).

	Lexical types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
Familiarity ratings	Frequent words (F)	4.44	4.83	3.46	0.28
	Less frequent w. (LF)	2.81	3.71	1.75	0.43
	Novel words (N)	1.00	1.00	1.00	0.00

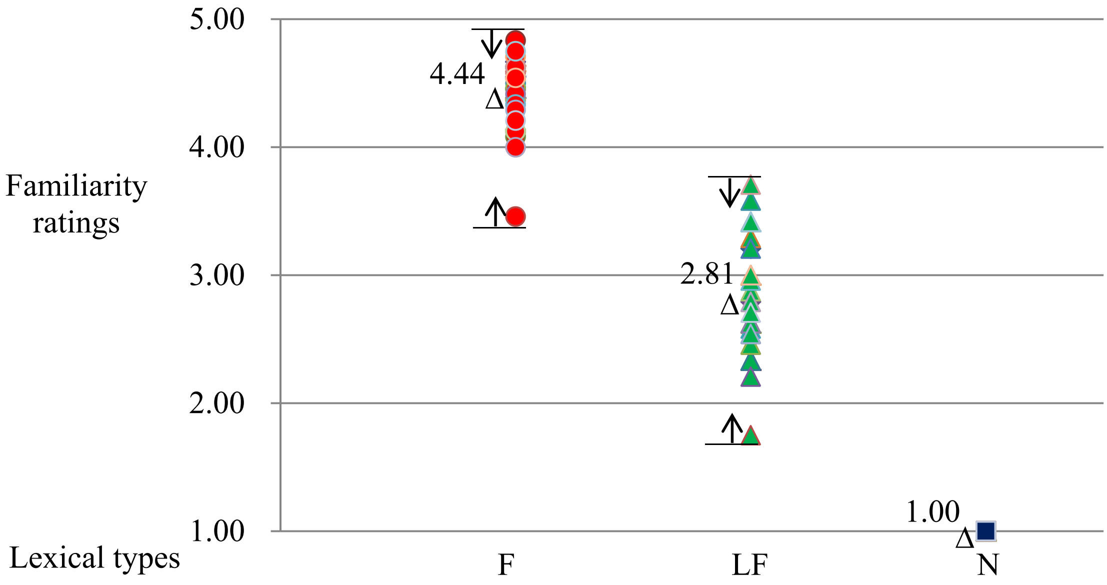

Figure 5.7 Results of lexical familiarity ratings in terms of lexical types on a five-point scale (5: the most familiar, 1: the least familiar; F: frequent words, LF: less frequent words, N: novel words).

In addition to the results of lexical types, the lexical familiarity ratings also show that (i) those stimuli with low-rising tone sandhi have a higher rating score than those with high-checked tone sandhi (low-rising tone sandhi > high-checked tone sandhi). (ii) Those stimuli with low-vowels have a higher rating score than those with high vowels (low vowels > high vowels). (iii) Those stimuli with high-falling prosody and low-rising prosody have a higher rating score than those with low-falling prosody, and those with high-falling prosody have the highest ratings (high-falling-tone prosody > low-rising-tone prosody> low-falling-tone prosody).

In order to examine whether the familiarity ratings are correlated to these factors and their two-way interaction, the results of lexical familiarity ratings are analyzed by the multiple-regression model shown in (37) above. The multiple-regression analyses for each factor and two-way interaction are summarized in Table 5.20 below. These analyses are generally statistically legitimate, as the model indicates a significant difference (R^2= 0.7717, $F(17, 2214)$= 14.3510, $p< 0.001$***). In general, the analyses show that the familiarity ratings are significantly different according to each lexical types, but not to any of phonetic/phonological factors. In addition, the familiarity ratings are correlated to the interaction between lexical and phonetic/phonological ratings to some extent, such as between L_2 and sandhi types, between L_1 and vowel types, and between L_2 and P_2. These findings are further discussed as follows.

Table 5.20 Results of multiple-regression analyses for lexical familiarity ratings (L_1: difference between frequent words and others, L_2: difference between less frequent words and others; P_1: difference between high-falling prosody and others, P_2: difference between low-falling prosody and others; RED: $p> 0.10$, GOLD: $0.05< p< 0.10$, BLACK: $p< 0.05$).

Tasks \ Factors	Lexical types	pp = Phonetic/phonological factors			
		Rules	Forms	Vowels	Prosody
Each factor	L_1: $p< 0.001$ L_2: $p< 0.001$	$p> 0.10$	$p> 0.10$	$p> 0.10$	P_1: $p> 0.10$ P_2: $p> 0.10$
Interaction	L_1 & pp	$p< 0.10$	$p> 0.10$	$p< 0.05$	P_1: $p> 0.10$ P_2: $p> 0.10$
	L_2 & pp	$p< 0.001$	$p< 0.05$	$p> 0.10$	P_1: $p> 0.10$ P_2: $p< 0.001$

First, the analyses show that the familiarity ratings are significantly different across different lexical types. The rating scores of frequent words are significantly higher than those of less frequent and novel words, and the ratings of novel words are the lowest. The results suggest that the familiarity ratings (subjective lexical frequency) and the lexical factors are strongly correlated. The correlation indicates that the lexical effect demonstrated in Table 5.16 above is very likely to result from participants' inherent lexical knowledge.

Second, the analyses show that the familiarity ratings are not significantly different according to any of phonetic/phonological factor. Although the preliminary results indicate a potential pattern for each phonetic/phonological factor, (i) sandhi types: low-rising tone sandhi > high-checked tone sandhi, (ii) vowel types: low vowels > high vowels, and (iii) prosodic types: high-falling-tone prosody > low-rising-tone prosody > low-falling-tone prosody, the three patterns are found to be not significant. In other words, the rating scores of stimuli with low-rising tone sandhi are not significantly higher than those of stimuli with high-checked tone sandhi. The rating scores of stimuli with low vowels are not significantly higher than those of stimuli with high vowels. The rating scores of stimuli with high-falling/low-rising prosody are not significantly higher than those of stimuli with low-falling prosody. The results suggest that the familiarity ratings and the phonetic/phonological factors are not correlated, which indicates that the phonetic/phonological effects demonstrated in Table 5.16 above are less likely to result from participants' inherent lexical knowledge. The phonetic/phonological effects seem to result from non-lexical knowledge (i.e. phonetic grounding and token/type frequency).

Third, the analyses show that the familiarity ratings are slightly different in the interaction between L_1 and sandhi types, and are significantly different in the interaction between L_2 and sandhi types. The rating scores of two sandhi rules are significantly more different in actual words than in novel words, and are slightly more different in less frequent words than to frequent words. The results suggest that the familiarity ratings and the sandhi types are more likely to be correlated in less frequent words than in frequent words and novel words. The ratings and the sandhi types are the least likely to be correlated in novel words, since participants consistently regarded novel words as the least familiar (1 out of 5). In other words, the sandhi types are more likely to exert an influence on the familiarity rating of less frequent words and frequent words than novel words. This pattern (actual words > novel words) is contrary to the pattern of interaction effects, i.e. additional phonetic/phonological influences on novel words (novel words > actual words). The difference indicates that the interaction effect (between L_2 and sandhi types) demonstrated in Table 5.18 above is less likely to result from participants' inherent lexical knowledge. The interaction effect therefore may result from non-lexical knowledge or processing factors.

Fourth, the analyses show that the familiarity ratings are slightly different in the interaction between L_1 and vowel types. The rating scores of two vowel types are significantly more different in frequent words than to less frequent and novel words. The results suggest that the familiarity ratings and the vowel types are more likely to be correlated in frequent words than in less frequent and novel words. The ratings and the vowel types are the least likely to be correlated in novel words, since participants consistently regarded novel words as the least familiar (1 out of 5). In other words, the vowel types are more likely to exert an influence on the familiarity rating of frequent and less frequent words than novel words. This pattern is contrary to the pattern of interaction effects. The difference indicates that the interaction effect (between L_1/L_2 and vowel types) demonstrated in Table 5.18 above is less likely to result from participants' inherent lexical knowledge. The interaction effect hence may result from non-lexical knowledge or processing factors.

Fifth, the analyses show that the familiarity ratings are slightly different in the interaction between L_2 and P_2. The rating scores of three prosodic types (only P_2: difference between low-falling prosody and high-falling/low-rising prosody) are significantly more different in less frequent words than in frequent words and novel words. The results suggest that the familiarity ratings and the prosodic types (low-falling prosody vs. high-falling/low-rising prosody) are more likely to be correlated in less frequent words than in frequent words and novel words. The ratings and the prosodic types are the least likely to be correlated in novel words, since participants consistently regarded novel words as the least familiar (1 out of 5). In other words, the prosodic types are more likely to exert an influence on the familiarity ratings of frequent and less frequent words than novel words. This pattern is contrary to the pattern of interaction effects. The difference indicates that the interaction effect (between L_1/L_2 and P_1/P_2) demonstrated in Table 5.18 above is less likely to result from participants' inherent lexical knowledge. The interaction effect may then result from non-lexical knowledge or processing factors.

To sum up, these analyses for familiarity ratings indicate three general findings. First, the lexical effect is very likely to result from participants' inherent lexical knowledge. Second, the phonetic/phonological effects (including sandhi types, vowel types, and prosodic types) seem to result from non-lexical knowledge (i.e. phonetic grounding and token/type frequency). Third, the interaction effect may result from non-lexical knowledge or processing factors. The three findings generally support the lexical effect, the phonetic/phonological effects, and the interaction effect.

5.4.4 Summary of multiple-regression analyses

The results of multiple-regression analyses for each factor and two-way interaction generally confirm the predictions, except for the pattern of prosodic effects in the production results, and they are summarized below.

Table 5.21 Summary of all multiple-regression analyses (L_1: difference between frequent words and others, L_2: difference between less frequent words and others; P_1: difference between high-falling prosody and others, P_2: difference between low-falling prosody and others; RED: p> 0.10, GOLD: 0.05< p< 0.10, BLACK: p< 0.05).

Tasks \ Factors		Lexical types	pp= Phonetic/phonological factors			
			Rules	Forms	Vowels	Prosody
AXB Discrimination Task	Patterns	F≧LF≧N	HC> LR	ST> UT	H> L	LF>LR>HF
	Each factor	L_1: <0.10 L_2: <0.10	<0.00	<0.001	<0.001	P_1 <0.05 P_2 <0.001
	Interaction	L_1 & pp	>0.10	>0.10	<0.10	P_1 >0.10 P_2 >0.10
		L_2 & pp	>0.10	>0.10	<0.10	P_1 <0.10 P_2 >0.10
Tonal Identification Task	Patterns	LF= F= N	HC≧LR	UT≧ST	H> L	LF≧LR>HF
	Each factor	L_1: >0.10 L_2: >0.10	<0.10	<0.10	<0.05	P_1< 0.001 P_2 <0.10
	Interaction	L_1 & pp	>0.10	>0.10	>0.10	P_1 >0.10 P_2 >0.10
		L_2 & pp	>0.10	>0.10	>0.10	P_1< 0.01 P_2 >0.10
Lexical Recognition Task	Patterns	F> LF> N	HC>LR	UT>ST	L>H	LF>LR≧HF
	Each factor	L_1: <0.001 L_2: <0.001	<0.001	<0.001	<0.001	P_1 <0.10 P_2 <0.05
	Interaction	L_1 & pp	>0.10	>0.10	<0.001	P_1 >0.10 P_2 >0.10
		L_2 & pp	>0.10	<0.05	<0.05	P_1 >0.10 P_2 >0.10
Production Task	Patterns	F> LF= N	LR=HC	ST>UT	L>H	LR= HF> LF
	Each factor	L_1: <0.01 L_2: >0.10	>0.10	<0.001	<0.001	P_1 >0.10 P_2 <0.001
	Interaction	L_1 & pp	>0.10	<0.001	<0.001	P_1 >0.10 P_2 <0.01
		L_2 & pp	<0.001	<0.001	<0.001	P_1 >0.10 P_2 >0.10
Lexical Familiarity Ratings	Patterns	F> LF> N	HC=LR	UT=ST	L=H	HF=LR=LF
	Each factor	L_1: <0.001 L_2: <0.001	>0.10	>0.10	>0.10	P_1 >0.10 P_2 >0.10
	Interaction	L_1 & pp	<0.10	>0.10	<0.05	P_1 >0.10 P_2 >0.10
		L_2 & pp	<0.001	<0.05	>0.10	P_1 >0.10 P_2 <0.001

As shown in the third column of Table 5.21 above, the effect of lexical types generally exhibit a consistent pattern (F> LF> N) across the four tasks, except for the identification results (LF, F> N). The lexical effect is more significant in the recognition and the production tasks which require participants to access lexical knowledge, and is less significant in the discrimination and the identification tasks which tend to target non-lexical knowledge. The difference seems to result from the influence of processing factors (i.e. lexical access to different degrees). In addition, the lexical effect is found to be correlated to the familiarity ratings of three lexical types, supporting that the lexical effect results from participants' inherent lexical knowledge. In general, these findings suggest that (i) the lexical effect results from inherent lexical knowledge, and exhibits a consistent pattern across the task types. (ii) Despite the consistent pattern, the lexical effect may be modulated by different degrees of lexical access. The more likely the participants have access to lexical knowledge, the more significant the lexical effect is. These findings, therefore, support the lexical hypothesis and the processing hypothesis.

As shown in the fourth and the fifth columns of Table 5.21 above, the effect of sandhi types exhibits different patterns between perception and production results, and its influences are also correlated to the two processes. In the perception results, the sandhi effect exhibits a pattern in which stimuli with high-checked tone sandhi are more accurate than those with low-rising tone sandhi (HC > LR), whereas in the production results, it exhibits the opposite pattern (LR> HC). The perception pattern is statistically significant, whereas the production pattern is not. The differences are suggested to result from the influence of processing factors (i.e. the perception-production asymmetry). In addition, the sandhi effect is found to interact with the lexical effect (L_2: difference between less frequent words and novel words) in the production results, but not in the perception ones. The interaction effect (more significant sandhi effect on novel words) also exhibits the perception-production asymmetry. In general, the sandhi effect and the interaction effect are found to be not correlated to the lexical familiarity ratings. The finding indicates that the sandhi effect and the interaction effect are less likely to result from participants' inherent lexical knowledge, but more likely to result from non-lexical knowledge (i.e. phonetic grounding and token/type frequency). These findings show that (i) the sandhi effect exhibits different patterns between perception and production results, and (ii) the degrees of the effect are also modulated by the asymmetry. (iii) Although the sandhi effect is not significant in the production results, it is more significant to novel words than actual words. These findings, therefore, support the phonetic/phonological hypothesis, the interaction hypothesis, and the processing hypothesis.

As shown in the penultimate column of Table 5.21 above, the effect of vowel types exhibits different patterns between discrimination/identification and recognition/production results, and the degrees of the effect are also modulated by the difference. In the discrimination and the identification results, the vowel effect exhibits a pattern in which stimuli consisting of high vowels are more accurate than those consisting of low vowels (H > L), whereas in the recognition and the production results, it exhibits the opposite pattern (L > H). The latter (L> H) is statistically significant, whereas the former (H> L) is not. The differences seem to result from an influence of processing factors (i.e. different degrees of lexical access). In addition, the vowel effect is found to interact with the lexical effect in the recognition/production results, but not in the discrimination/identification ones. The interaction effect (more significant vowel effect on novel words) also varies with different degrees of lexical access. In general, the vowel effect and the interaction effect are found to be not correlated to the lexical familiarity ratings. The finding indicates that the vowel effect and the interaction effect are less likely to result from participants' inherent lexical knowledge, but more likely to result from non-lexical knowledge. These findings show that (i) the vowel effect exhibits different patterns between discrimination/identification and recognition/production results, and (ii) the degrees of the effect are modulated by the degrees of lexical access. (iii) The vowel types not only play a significant role in the recognition/production results, but also exert an additional influence on novel words. These findings, therefore, support the phonetic/phonological hypothesis, the interaction hypothesis, and the processing hypothesis.

As shown in the last column of Table 5.21 above, the effect of prosodic types is significant across the four tasks, but it exhibits different patterns between perception and production results. In the perception results, the prosodic effect exhibits a pattern in which stimuli with low-falling prosody are more accurate than those with high-falling/low-rising prosody (LF > LR, HF), whereas in the production results, it exhibits the opposite pattern (LR, HF > LF). The differences are suggested to result from an influence of the perception-production asymmetry. In addition, the prosodic effect is found to interact with the lexical effect in the identification and the production results, but not in the two others. In the identification results, the prosodic types (P_1: difference between high-falling prosody and low-rising/low-falling prosody) exert an additional influence on novel words (L_2). In the production results, the prosodic types (P_2: difference between low-falling prosody and high-falling/low-rising prosody) exert an additional influence on less frequent and novel words (L_1). In general, the prosodic effect and the interaction effect are found to be not correlated to the lexical familiarity ratings. The finding indicates that the prosodic effect and the interaction effect are less likely to result from participants' inherent lexical knowledge, but more likely to result from non-lexical knowledge. These findings show that (i) the prosodic effect is significant across the four tasks, but (ii) it exhibits different patterns between perception and production results. (iii) The prosodic types not only play a significant role across the four tasks, but also exert an additional influence on novel words in the identification and the production results. These findings, therefore, support the phonetic/phonological hypothesis, the interaction hypothesis, and the processing hypothesis.

To sum up, these analyses generally confirm the four research hypotheses. The lexical and the phonetic/phonological factors exert a significant influence on speech processes of Hai-lu

Hakka tone sandhi. The two kinds of factors may also interact with each other to bring forth an additional influence. The degrees and the patterns of the various effects seem to be correlated to different types of tasks (currently defined as processing factors). In other words, these various factors are inherent to speech processing, and their degrees and patterns may simply be conditioned by each process (as a processing factor). In general, the analyses demonstrate four issues on speech processing of Hai-lu Hakka tone sandhi, and these issues are shown in (38) below.

(38) Four issues on Hai-lu Hakka tone sandhi

a. Phonetic/phonological factors exert an influence across tasks, but the influence exhibits different patterns in each task.
b. Lexical factors exert an influence on each task to different degrees, but the influence exhibits a consistent pattern across different tasks in general.
c. Phonetic/phonological factors exert an additional influence on novel words as a result of the interaction between lexical and phonetic/phonological factors, and the interaction may vary in each task.
d. The degrees and the patterns of lexical and phonetic/phonological effects seem to be conditioned by processing factors, so does their interaction effect.

As shown in (38a) above, the first issue concerns the inconsistent pattern of phonetic/phonological effects across different tasks. As mentioned briefly in section 5.4.2.1 above, these phonetic/phonological factors exert an influence on each task more or less, but they exhibit different patterns across the tasks. The different patterns are correlated to two processing factors. That is, the patterns of sandhi and prosodic effects are correlated to the asymmetry between perception and production processes, and the patterns of vowel effects are correlated to different degrees of lexical access. It is intriguing why these patterns are correlated to two different processing factors.

The second issue, shown in (38b), concerns the different degrees of lexical effects across different tasks. As mentioned briefly in section 5.4.2.1 above, the lexical factors exert an influence on each task to different degrees, but they exhibit a consistent pattern across the tasks. The different degrees of lexical influences seem to be correlated to lexical access. The more access to lexical knowledge there is, the more significant the lexical influence is. The correlation seems reasonable. In general, it is worth noting that the lexical influence has a more consistent pattern than each of the phonetic/phonological ones.

The third issue, shown in (38c), concerns the inconsistent interaction between lexical and phonetic/phonological factors. The analyses show that the three phonetic/phonological factors exert an additional influence on novel words in different tasks. That is, (i) the sandhi types have a significant interaction with the lexical types in the production results; (ii) the vowel types have a significant interaction with the lexical types in the recognition and the production results; and (iii) the prosodic types have a significant interaction with the lexical types in the identification and the production results. The interaction varies with the three phonetic/phonological factors in each task, and is also correlated to processing factors. In general, the interaction effect is less inconsistent than the phonetic/phonological effect.

The fourth issue, shown in (38d), concerns the crucial role processing factors/strategies play in speech processing. As mentioned briefly in section 5.4.2.1 above, the two processing factors, the perception-production asymmetry and the different degrees of lexical access, seem to exert a masking effect on the lexical influence (to modulate the degrees of the effect), and a modifying effect on the phonetic/phonological influences (to change the patterns of the effects). They also affect the interaction between lexical and phonetic/phonological effects. These processing factors seem to govern the access to lexical and phonetic/phonological knowledge. In other words, these various kinds of knowledge are inherent to speech processing, but the degrees of access and the patterns of the effects are susceptible to different processing factors/strategies.

5.5 Analysis for psychological-reality and phonetic-naturalness hypotheses

In addition to the four hypotheses, the results are further analyzed to examine the psychological-reality and phonetic-naturalness hypotheses on Hai-lu Hakka's tone sandhi. As discussed in section 5.2.5 above, the psychological-reality and the phonetic-naturalness issues were previously proposed to examine lexical and phonetic effects on tone sandhi in Mandarin and Taiwan Southern Min (Zhang & Lai 2010; Zhang et al 2011). The two additional issues are different from the current lexical and phonetic/phonological hypotheses for several reasons. First, Zhang & Lai (2010) and Zhang et al (2011) argued for the phonological productivity and phonetic naturalness only based on production results. Second, their analyses simply only focused on the surface forms of sandhi tones, and did not set up control stimuli in general. In order to compare Hai-lu Hakka's tone sandhi with that in Mandarin and Taiwan Southern Min, our experimental results are reconfigured to conform to the previous methods. In other words, the results and the analyses for the two additional issues only include 36 stimulus types (3 lexical types x 2 rules x 2 vowel types x 3 prosodic types).

5.5.1 Productivity results of lexical types

The production results are summarized by each lexical and phonetic/phonological factor, and the results of lexical types are shown below. As illustrated in Table 5.22 and Figure 5.8 below, the production results show that production accuracy is higher in frequent words (F) than in less frequent words (LF) and novel words (N), and the novel words have the lowest percent accuracy. The percent accuracy of frequent words (mean: 93.41%) is consistently higher than the 90% and the 75% standards of children's phonological acquisition. The percent accuracy of less frequent words (mean: 78.76%) is mostly higher than the 75% standard of children's phonological acquisition. However, the percent accuracy of novel words (mean: 34.61%) is consistently lower than the 75% standard of children's phonological acquisition. The findings indicate that the three lexical types exert an influence on the productivity of Hai-lu Hakka tone sandhi, and confirm the prediction for the lexical effect (F > LF > N). According to the 90% and the 75% standards of children's phonological acquisition, the results suggest that (i) Hai-lu Hakka tone sandhi is not fully productive across different words, and (ii) Hai-lu Hakka tone sandhi is bound to actual words (frequent and less frequent words). In other words, Hai-lu Hakka tone sandhi does not seem to be phonologically productive, and hence may not be psychologically real. The findings support the psychological-reality hypothesis.

Table 5.22 Productivity results of Hai-lu Hakka tone sandhi for psychological reality.

Task	Lexical Types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
PRO	Frequent words (F)	93.41%	100.00%	77.08%	6.53%
	Less frequent w. (LF)	78.76%	93.75%	54.17%	11.16%
	Novel words (N)	34.61%	62.50%	10.42%	15.37%
	Mean	68.93%	81.25%	52.78%	8.76%

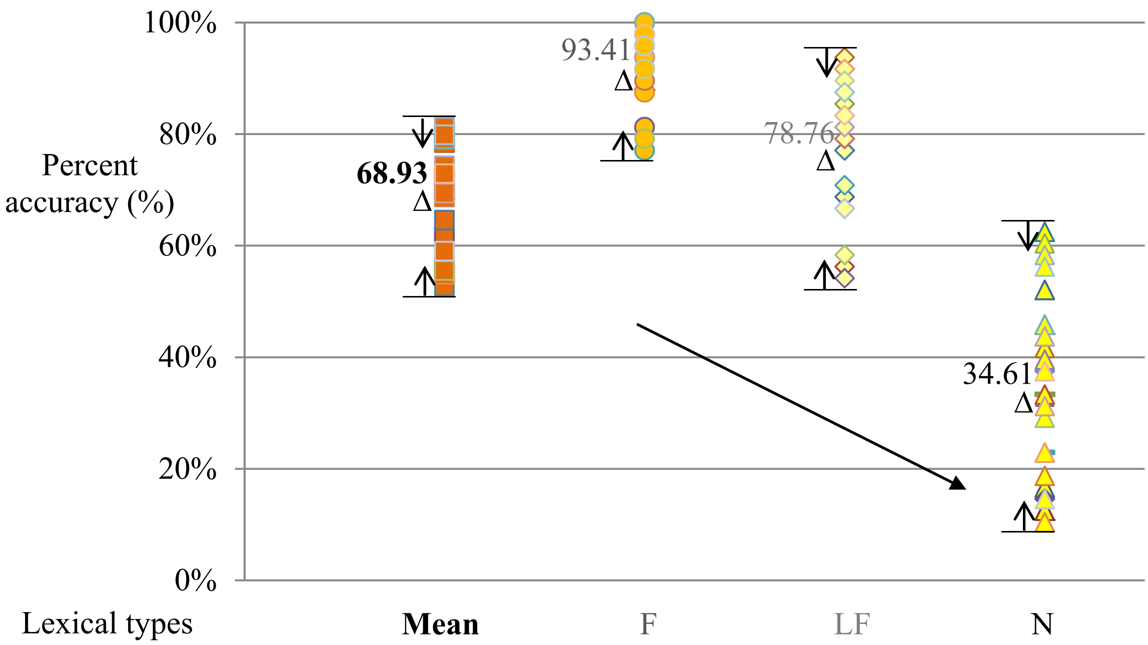

Figure 5.8 Productivity results of Hai-lu Hakka tone sandhi for psychological reality (F: frequent words, LF: less frequent words, N: novel words).

5.5.2 Productivity results of sandhi types

The production results of phonetic/phonological factors include three subsets: rule types, vowel types, and prosodic types. Since the previous studies (Zhang & Lai 2010; Zhang et al 2011) focused on sandhi types, this section simply demonstrates the results of sandhi types. First of all, as illustrated in Table 5.23 and Figure 5.9 below, the results show that the production accuracy of low-rising tone sanshi (LR) is higher than that of high-checked tone sandhi (HC), i.e. LR: 69.76%> HC: 68.10%. The findings indicate that the sandhi types exert an influence on the productivity of Hai-lu Hakka tone sandhi. The phonetically-driven tonal rule (LR) is more productive than the less phonetically-driven one (HC). The results generally confirm the prediction for the phonetic-naturalness hypothesis (LR > HC).

Table 5.23 Productivity results of Hai-lu Hakka tone sandhi for phonetic naturalness.

Task	Rule Types	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
PRO	Low-rising TS (LR)	69.76%	87.50%	55.56%	9.44%
	High-checked TS (HC)	68.10%	93.06%	44.44%	12.36%
	Mean	68.93%	90.28%	50.00%	10.90%

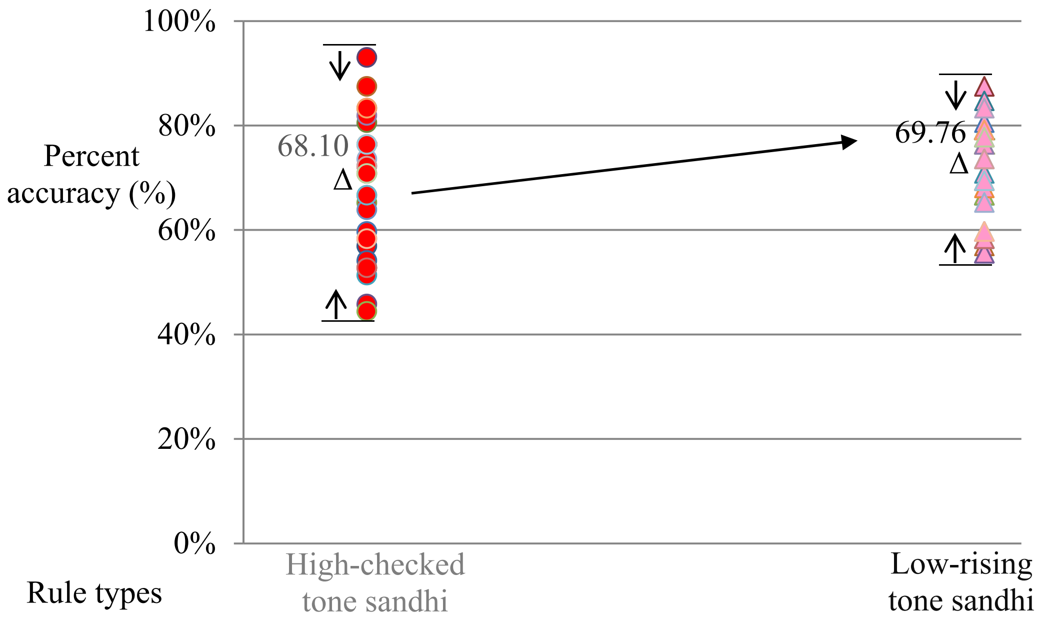

Figure 5.9 Productivity results of Hai-lu Hakka tone sandhi for phonetic naturalness (low-rising tone sandhi: more phonetically natural, high-checked tone sandhi: less phonetically natural).

In addition, the results of vowel types show that the production accuracy of low vowels (L) is higher than that of high vowels (H), that the production accuracy is higher under the high-falling prosody (HF) condition than under the low-rising prosody (LR) and low-falling prosody (LF) conditions, and that the percent accuracy is the lowest under the low-falling prosody condition. These findings indicate that the vowel types and the prosodic types both exert an influence on the productivity of Hai-lu Hakka tone sandhi. In general, these findings support the phonetic/phonological effects on the productivity of Hai-lu Hakka tone sandhi.

5.5.3 Analysis for effects of each factor and two-way interaction

The production results generally support the psychological-reality and the phonetic-naturalness hypotheses on Hai-lu Hakka tone sandhi. In order to examine whether the results are statistically significant, the production results are further analyzed by a multiple-regression model. As shown in (39) below, this model is adapted from the logarithmic model illustrated in (37) above, which includes both (i) an analysis for each factor and (ii) an analysis for two-way interaction. The adaption is generally similar to the original model, but it does not include sandhi tones' forms (T). As a result, the adapted model has only a total of 14 variables (6 dummy variables: L_1, L_2, R, V, P_1, P_2 + 8 combinations: L_1*R, L_2*R, L_1*V, L_2*V, L_1*P_1, L_2*P_1, L_1*P_2, L_2*P_2).

(39) Equation of multiple-regression model for phonological productivity

$$
\begin{aligned}
Y &= a + \sum_{i=1}^{k} b_k x_k \quad (\boldsymbol{x}\text{= each dummy variable}) \\
&= a + b_1{*}L_1 + b_2{*}L_2 + b_3{*}R + b_4{*}V + b_5{*}P_1 + b_6{*}P_2 && \text{(each factor)} \\
&\quad + b_7{*}L_1{*}R + b_8{*}L_2{*}R && \text{(lexical \& rule types)} \\
&\quad + b_9{*}L_1{*}V + b_{10}{*}L_2{*}V && \text{(lexical \& vowel types)} \\
&\quad + b_{11}{*}L_1{*}P_1 + b_{12}{*}L_1{*}P_2 + b_{13}{*}L_2{*}P_1 + b_{14}{*}L_2{*}P_2 && \text{(lexical \& prosodic types)}
\end{aligned}
$$

The overall results show that the analysis is significant: (R^2= 0.5674, F(14,1101)= 103.2, p< ***). The analysis includes a total of 14 variables (6 dummy variables x 8 combinations= 14) and 1116 analysis tokens (31 participants x 36 stimulus types= 1116). The amount of analysis tokens is much larger than the amount of variables, and it allows a legitimate degree of freedom (1101) for the analysis. The analysis for each factor and two-way interaction is then summarized in Table 5.24 below. The results show that lexical and the phonetic/phonological factors all exert a significant influence on the production results, except for the difference between high-falling prosody and low-rising prosody (P_1). In addition, the phonetic/phonological factors also exert an additional influence on novel words as a result of the interaction effects. These analyses generally support the psychological-reality hypothesis and the phonetic-naturalness hypothesis.

Table 5.24 Multiple-regression analysis for phonological-productivity and phonetic-naturalness hypotheses of Hai-lu Hakka's tone sandhi (L_1: difference between frequent words and others, L_2: difference between less frequent words and others; P_1: difference between high-falling prosody and others, P_2: difference between low-falling prosody and others; RED: $p > 0.10$, GOLD: $0.05 < p < 0.10$, BLACK: $p < 0.05$).

Factors / Types	Lexical types	pp. = Phonetic/phonological factors		
		Sandhi types	Vowel types	Prosodic types
Patterns	F > LF > N	LR > HC	L > H	HF = LR > LF
Each factor	L_1: $p < 0.001$*** L_2: $p < 0.001$***	$p < 0.01$**	$p < 0.001$***	P_1: $p > 0.10$ P_2: $p < 0.001$***
Interaction	L_1 & pp.	$p > 0.10$	$p < 0.001$***	P_1: $p < 0.10$+ P_2: $p < 0.001$***
	L_2 & pp.	$p < 0.001$***	$p < 0.001$***	P_1: $p < 0.10$+ P_2: $p > 0.10$

As shown in the third row of Table 5.24 above, the analyses show that the patterns of each lexical and phonetic/phonological factor are significant. First of all, the significant lexical pattern indicates that participants produce Hai-lu Hakka's tone sandhi significantly more accurately in actual words (F, LF) than novel words (N), and the production accuracy is the highest to frequent words (F), i.e. F> LF> N. The findings support the psychological-reality hypothesis predicting that Hai-lu Hakka's tone sandhi is bound to actual words (based on the 75% standard of children's phonological acquisition) and is not phonologically productive. Second, the significant pattern of rule types indicates that participants produce low-rising tone sandhi (LR) more accurately than high-checked tone sandhi (HC), i.e. LR > HC. The findings support the phonetic-naturalness hypothesis predicting that a more phonetically-driven tonal rule is more productive than less phonetically-driven one. Third, the significant pattern of vowel types indicates that participants produce Hai-lu Hakka tone sandhi significantly more accurately when sandhi tones consist of low vowels (L) than high vowels (H), i.e. L > H. Fourth, the significant pattern of prosodic types indicates that participants produce Hai-lu Hakka's tone sandhi significantly more accurately when sandhi tones precede high-falling prosody (HF) and low-rising prosody (LR) than when preceding low-falling prosody (LF), but the difference between high-falling prosody and low-rising prosody is not significant, i.e. HF= LR> LF. In general, the analyses suggest that these various kinds of factors exert a significant influence on the phonological productivity of Hai-lu Hakka tone sandhi.

As shown in the last row of Table 5.24, the analyses also show that the lexical and the phonetic/phonological factors may interact with each other, and the interaction is significant across the three phonetic/phonological factors. First of all, the sandhi rule types are found to have a significant interaction with the lexical variable L_2, but not with the other (L_1). The significant interaction indicates that participants demonstrate the pattern of rule types (LR > HC) more significantly in novel words than in actual words, and the difference between frequent and less frequent words is not significant. The findings suggest that the sandhi rule types exert an additional influence on novel words, but not on actual words. Second, the vowel types are found to have a significant interaction with the three lexical types. The significant interaction indicates that participants demonstrate the pattern of vowel types (L > H) more significantly in novel words than in actual words, and in less frequent words than in frequent words. The findings suggest that the vowel types exert an additional influence on novel words as well as less frequent words. Third, the prosodic variable P_2 is found to have a significant interaction with the lexical variable L_1, and the other (P_1) is found to have a slightly significant interaction with the three lexical types. The significant interaction indicates that participants demonstrate the pattern of prosodic types (HF = LR > LF) more significantly in novel words and less frequent words than in frequent words, and the difference between novel and less frequent words is not significant. The findings suggest that the prosodic types (difference between high-falling/low-rising prosody and low-falling prosody) exert an additional influence on novel words as well as less frequent words. These findings suggest that phonetic/phonological factors exert an additional influence on novel words (or less frequent words) in the productivity of Hai-lu Hakka tone sandhi. In other words, phonetic/phonological factors play a more significant role when lexical access is restricted.

To sum up, the production results indicate that Hai-lu Hakka tone sandhi is not fully productive based on the 90% and the 75% standards of children's phonological acquisition. As indicated in section 5.5.1 above, the percent accuracy of actual words (mean: 93.41% and 78.76% respectively) is mostly higher than the 75% standard, and the percent accuracy of novel words (mean: 34.61%) is consistently lower. The findings indicate that Hai-lu Hakka tone sandhi is bound to actual words, and not automatically applicable to novel words. The results suggest that Hai-lu Hakka tone sandhi is not phonologically productive and hence not psychologically real, supporting the psychological-reality hypothesis. In addition, the results indicate that low-rising tone sandhi is significantly more productive than high-checked tone sandhi. The difference indicates that phonetic grounding plays a role in the productivity of Hai-lu Hakka tone sandhi. The phonetic/phonological factors are also found to play a different role in each lexical type. That is, the rule types, as well as the vowel and the prosodic types, exert an additional influence on novel words (or less frequent words), but not on frequent words. In general, the results support both the psychological-reality hypothesis and the phonetic-naturalness hypothesis on Hai-lu Hakka tone sandhi.

5.6 Discussion

The results and analyses illustrated above generally support the four research hypotheses (the lexical, the phonetic/phonological, the interaction, and the processing hypotheses), and also verify the two additional hypotheses on phonological productivity/psychological reality and phonetic naturalness. The experimental results are compared to the detailed predictions shown in Table 5.8 above, and the comparisons are summarized in Table 5.25 below.

Table 5.25 Comparisons between the detailed predictions and the current results.

Hypotheses	Predictions vs. Results
(33a) The Lexical Hypothesis	Both perception and production accuracy of Hai-lu Hakka's tone sandhi are higher in frequent words than in less frequent and novel words, and the results are the lowest in novel words.
Results	**Confirmed:** (i) The lexical effect exhibits a consistent pattern across the tasks, i.e. **frequent > less frequent > novel**, except for the identification results (no difference between frequent and less frequent words). In addition, (ii) the lexical effect is significant in the recognition and the production results, but less significant in the discrimination and the identification results due to different degrees of lexical access.
(33b) The Phonetic/ phonological Hypothesis	a. Sandhi effect: Production accuracy of low-rising tone sandhi is higher than that of high-checked tone sandhi, so is perception accuracy (i.e. LR > HC).
	b. Vowel effect: Production accuracy is higher when sandhi tones co-occur with low vowels than with high vowels, so is perception accuracy (i.e. L > H).
	c. Prosodic effect: Production accuracy is higher when sandhi tones precede low tones than when high tones, so is perception accuracy (i.e. LR, LF > HF).
Results	a. **Partially confirmed**: (i) The production results show LR > HC, but the perception results show HC > LR (due to the perception-production asymmetry). In addition, (ii) the sandhi effect is significant in the perception results, but not in the production results.
	b. **Partially confirmed**: (i) The recognition and the production results show L > H, but the discrimination and the identification results show H > L (due to different degrees of lexical access). In addition, (ii) the vowel effect is significant across the tasks.
	c. **Partially confirmed**: (i) The perception results show LF > (LR) > HF, but the production results show HF (LR) > LF (due to the perception-production asymmetry). In addition, (ii) the prosodic effect is significant across the tasks.
(33c) The Interaction Hypothesis	There is an additional influence of phonetic/phonological factors on novel words. That is, phonetic/phonological factors exert a more significant influence on novel words than frequent and less frequent words.
Results	**Confirmed:** (i) The sandhi effect exerts an additional influence on novel words in the production results, but not in the perception results (due to the perception-production asymmetry). (ii) The vowel effect exerts an additional influence on novel words in the recognition and the production results (due to the different degrees of lexical access). (iii) The prosodic effect exerts an additional influence on novel words in the identification and the production results (processing factors).
(33d) The Processing Hypothesis	a. The perception-production asymmetry: Based on the potential difference between perception and production, phonetic/phonological factors play a different role in perception and production tasks.
	b. The degrees of lexical access: Lexical and phonetic/phonological factors play a different role in each perception task that requires different degrees of lexical access.

Table 5.25 (cont'd).

Results	a. **Confirmed**: (i) The degrees and patterns of the sandhi effect exhibit the perception-production asymmetry. (ii) The patterns of the prosodic effect exhibit the perception-production asymmetry. (iii) The interaction between sandhi types and lexical types also exhibits the perception-production asymmetry.
	b. **Confirmed**: (i) The degrees of the lexical effect vary with different degrees of lexical access. (ii) The patterns of the vowel effect vary with different degrees of lexical access. (iii) The interaction between vowel types and lexical types also varies with different degrees of lexical access.
(34a) The Psycho.-Reality Hypothesis	Hai-lu Hakka's tone sandhi is bound to actual words (not automatically applicable to novel words), so it is not phonologically productive and hence not psychologically real.
Results	**Confirmed**: (i) the production accuracy of actual words is mostly higher than the 75% standard of children's phonological acquisition, but that of novel words is consistently lower than the same standard. (ii) The degrees and the patterns of the lexical effect (i.e. F > LF > N) is significant.
(34b) The Phonetic-Naturalness Hypothesis	Phonetically-driven tone sandhi (i.e. low-rising tone sandhi) is more applicable to speech processes than less phonetically-driven tone sandhi (i.e. high-checked tone sandhi).
Results	**Confirmed**: (i) More phonetically-natural low-rising tone sandhi is more productive than less phonetically-natural high-checked tone sandhi. (ii) The degrees and the patterns of the sandhi effect (i.e. LR > HC) is significant.

5.6.1 The lexical hypothesis

As shown in the first two rows of Table 5.25 above, the current results generally support the lexical hypothesis (33a) that predicts the lexical effect (i.e. word types and lexical frequency) on speech processing of Hai-lu Hakka tone sandhi. The result show that the lexical effect exhibits a consistent pattern across the four tasks, except for the identification results (LF = F > N), but the degrees of the effect seem to vary with the task types. That is, the lexical influence is more significant in the recognition and the production tasks (designed to target lexical knowledge), but is less significant in the discrimination and the identification tasks (designed to target non-lexical knowledge). The more likely the lexical access is to be activated, the more significant the lexical effect is. The varying degrees of the lexical effect are correlated to the degrees of lexical access. These findings (the more consistent pattern, the varying degrees of lexical influences, and the degrees of lexical access) are further discussed as follows.

5.6.1.1 The consistent pattern

The current results show that the lexical effect exhibits a consistent pattern across the tasks. The consistent pattern indicates that the percent accuracy is higher in frequent and less frequent words (F, LF) than in novel words (N), and the percent accuracy of frequent words is the highest among the three lexical types, i.e. F > LF > N. The more frequent the stimuli are, the more accurate the results are. This pattern is also consistent with all participants' lexical familiarity ratings. The more frequent the stimuli are, the higher the rating scores are. The lexical familiarity ratings indicate that the lexical effect is likely to result from Hakka participants' inherent lexical knowledge. These findings indicate that participants tend to process Hai-lu Hakka tone sandhi in frequent words more accurately than in less frequent and novel words, and they process tone sandhi the least accurately in novel words. These findings generally confirm the prediction.

However, the results indicate one exception to the consistent pattern in the identification format. The identification results show that the perception accuracy is slightly higher to less frequent words than to frequent words (i.e. LF ≥ F). Although the pattern is less consistent with the prediction, the difference between frequent and less frequent words is not significant. The identification results' less consistent pattern may result from two potential factors: (i) different degrees of lexical access and/or (ii) the additional training on tonal responses in the identification format. First, the discrimination and identification formats tend to be designed to target participants' non-lexical knowledge (i.e. phonetic and phonological), in particular with shorter ISI and ITI, such as 300 and 500 ms respectively in the current setup. The experimental design is less likely to activate an access to lexical knowledge. Since participants won't have to access lexical knowledge, lexical knowledge (such as word types and lexical frequency) is less likely to exert an influence on discrimination and identification processes. Second, as discussed in section 5.3.3.2 above, the additional training is indispensible, since Hai-lu Hakka participants never learned these tonal labels before. The tonal training was designed to provide equivalent tonal knowledge for each participant, and the additional knowledge may interfere with lexical access to some extent. Since participants may not need to access lexical knowledge, lexical knowledge is less likely to exert an influence on discrimination and identification processes. In other words, the identification format's conventional setup and additional training may affect participants' use of processing strategies, and the strategies may elicit a different degree of access to lexical knowledge. As discussed earlier, the more likely the lexical access is to be activated, the more significant the lexical effect is. As a result, the less consistent pattern of identification results may result from the minimal degree of lexical access, and hence does not undermine the lexical hypothesis.

5.6.1.2 The degree of lexical influences and the lexical access

The patterns of the lexical effect are more consistent across the tasks, but the analyses show that such a consistent pattern is not consistently significant in each task. The lexical effect is significant in the recognition and the production results, but is less significant in the discrimination and the identification results. The degrees of lexical influences are correlated to the degrees of lexical access provided by different task types. As discussed above in section 5.6.1.1, participants are more likely to apply non-lexical knowledge (phonetic and phonological) in discrimination and identification processes, and the two task formats are less likely to activate the access to lexical knowledge. Since participants may not need to access lexical knowledge in the two task formats, lexical knowledge (i.e. word types and lexical frequency as lexical factors) is less likely to exert a significant influence. The less likely the lexical access is to be activated, the less significant the lexical influences are. In other words, the less significant lexical effect may result from the minimal degree of lexical access, and hence does not undermine the lexical hypothesis. In addition, the analyses also show that the difference between less frequent and novel words is less significant in the production results. The less significant difference between less frequent and novel words is less relevant to the degree of lexical access provided by the production format, since the current production task requires participants to access lexical knowledge. It may instead result from some methodological issues. Nevertheless, it does not seem to undermine the significant lexical effect granted by the difference between frequent words and the others. As a result, the current analyses generally indicate that the lexical influence is significant, except for the two less significant cases in the discrimination and identification results. Since the two exceptions to the significant lexical influences seem to be correlated to the degrees of lexical access, they arguably do not undermine the lexical hypothesis.

5.6.1.3 Summary of the lexical effect

In general, the current findings indicate that the lexical effect exhibits a consistent pattern across the tasks, except for the identification results, and the consistent lexical effect is less significant in some tasks that may not require Hakka participants to access lexical knowledge. There is a correlation between the degrees of lexical influences and the degrees of lexical access. The less likely the lexical access is to be activated, the less significant the lexical influences are. In other words, the exceptions to the consistent pattern and the significant influences may be attributed to interference from the different degrees of lexical access as currently suggested. The interference from the varying degrees of lexical access is arguably the cause of the less significant influences, and the processing factors arguably do not contradict the lexical hypothesis. As a result, the current results indicate that the lexical effect exhibits a more consistent pattern to varying degrees in each task, although it may vary with the degrees of lexical access. The findings generally support the lexical hypothesis.

5.6.2 The phonetic/phonological hypothesis

As shown in the third and the fourth rows of Table 5.25, the current results generally support the phonetic/phonological hypothesis (33b) that predicts an effect of phonetic and phonological factors (including sandhi types, vowel types and prosodic types) on speech processing of Hai-lu Hakka tone sandhi. The result show that these phonetic/phonological factors exert an influence to significant degrees almost across the tasks, except for the sandhi effect on the production results, but these significant influences seem to exhibit a varying pattern in each task. For instance, the sandhi effect demonstrates that low-rising tone sandhi (LR) is more accurate than high-checked tone sandhi (HC) in the production results, i.e. LR > HC, but the pattern is just opposite in the perception results, i.e. HC > LR. The vowel effect demonstrates that sandhi tones consisting of low vowels (L) are more accurate than those consisting of high vowels (H) in the recognition and the production results, i.e. L > H, but the pattern is opposite in the discrimination and the identification results, i.e. H > L. The prosodic effect demonstrates that sandhi tones preceding low-falling prosody (LF) are more accurate than those preceding high-falling prosody (HF) in the perception results, i.e. LF > HF, but the pattern is also opposite in the production results, i.e. HF > LF. In other words, the sandhi effect and the prosodic effect are correlated to the asymmetry between perception and production processes, and the vowel effect is correlated to the degrees of lexical access. These findings are further discussed in each phonetic/phonological factor as follows.

5.6.2.1 The sandhi effect and the perception/production asymmetry

The results show that low-rising tone sandhi is more accurate than high-checked tone sandhi in the production results, confirming the prediction, but it is not the case in the perception results. The analyses show that the perception pattern (HC > LR) is significant across the three perception tasks, but the production pattern (LR > HC) is not statistically significant. The findings indicate that participants perceive high-checked tone sandhi significantly more accurately than low-rising tone sandhi, but they produce low-rising tone sandhi just slightly better than high-checked tone sandhi. In other words, the tonal modification from high-checked tone to low-checked tone (i.e. faithful to pitch contour) is more perceptually distinct, but is less productive. The tonal modification from low-rising tone to low-level tone (i.e. faithful to pitch height) is less perceptually distinct, but is more productive. The sandhi effect's patterns and the degrees of influences both are correlated to the differences between perception and production processes.

The sandhi effect is less likely to result from an internal influence of lexical knowledge since the analyses of lexical familiarity (in section 5.4.3 above) show that the sandhi factors do not exert a significant influence on participants' rating scores. Low-rising tone sandhi is not significantly more familiar than high-checked tone sandhi, and not the other way around. The findings indicate that the sandhi effect result from non-lexical knowledge of the two tonal rules, and exhibits the perception-production asymmetry. The non-lexical knowledge may refer to sandhi tones' durational properties (Zhang & Lai 2010; Zhang et al 2011), token frequency and type frequency (Zhang & Lai 2010; Zhang et al 2011), and sandhi tones' pitch height and pitch contour (Yeh & Lin 2015). The three potential non-lexical factors are discussed as follows.

First of all, Zhang & Lai (2010) and Zhang et al (2011) argued for durational modifications as a crucial phonetic basis of tone sandhi in non-final position, as hypothesized as the sandhi effect in (33b) above. Hai-lu Hakka's low-rising tone sandhi is duration-shortening, and was found to be slightly more productive than high-checked tone sandhi. The duration-shortening account can predict the difference in the production results, but it is unclear how the durational modifications lead to the significant difference in the perception results. Both the underlying and surface tones of low-rising tone sandhi are longer in vowel duration than those of high-checked tone sandhi. Based on the duration-based account, the longer duration is predicted to enhance perceptual distinctiveness, but the perceptual accuracy of low-rising tone sandhi is lower than that of high-checked tone sandhi. The durational variables that Zhang & Lai (2010) and Zhang et al (2011) proposed to account for the production pattern seem unable to explain the perception pattern.

Second, the type frequency of two sandhi types and the token frequency of underlying/surface tones may also be responsible for the sandhi effect. According to Hsu (2009:48), Hai-lu Hakka's low-rising tone sandhi and its underlying/surface tones have a wider occurrence distribution than high-checked tone sandhi and its underlying/surface tones. However, the frequency factors seem able to account for the difference in the production results, but it is unclear how the less frequent rule and underlying/surface tones are more perceptually accurate than the more frequent counterparts. In other words, the frequency factors also cannot account for the asymmetry.

Third, based on the perception-production asymmetry exhibited in Hai-lu Hakka's low-level tone change (Yeh & Lu 2012; Yeh & Lin 2015), tonal modifications of pitch height and pitch contour may play a different role in perception and production processes. As argued by Yeh & Lin (2015), it is crucial to keep faithful the pitch height in production, and to keep faithful the pitch contour in perception. The two tendencies happen to be consistent with the sandhi effect's perception and production patterns. That is, low-rising tone sandhi's two forms (i.e. low-rising tone and low-level tone) are similar in pitch height, and the similar low pitch seems to enhance production accuracy. High-checked tone sandhi's two forms (i.e. high-checked tone and low-checked tone) are similar in pitch contour, and the similar pitch contour seems to enhance perception accuracy. As a result, the current findings seem to suggest that sandhi tones' internal pitch height and pitch contour play a crucial role in the sandhi effect.

5.6.2.2 The vowel effect and the degrees of lexical access

The results show that sandhi tones co-occurring with low vowels are more accurate than those with high vowels in the recognition and the production results, confirming the prediction, but not so in the discrimination and the identification results. The analyses show that both the patterns L > H in the recognition and the production results, and H > L in the discrimination and the identification results are significant across the tasks. The findings indicate that participants identify/produce low-vowel sandhi tones significantly more accurately than high-vowel ones, but they discriminate/identify high-vowel sandhi tones significantly more accurately than low-vowel ones. In other words, the high vowel [u] enhances discrimination and identification processes of sandhi tones, but hinders recognition and production processes. The low vowel [a] enhances recognition and production processes, but hinders discrimination and identification processes. The vowel effect's patterns are correlated to the degrees of lexical access.

Based on the analyses of lexical familiarity (in section 5.4.3 above) indicating that the vowel types do not exert a significant influence on participants' rating scores, the vowel effect is less likely to result from an internal influence of lexical knowledge. Stimuli co-occurring with low vowels are not more familiar than those co-occurring with high vowels, and not the other way around, either. The findings indicate that the vowel effect results from non-lexical knowledge of the two vowels, and the patterns of the vowel effect vary with the different degrees of lexical access. The non-lexical knowledge refers to tone-vowel interaction (Chan 1985; Jiang-King 1999; Yip 2002:31), token frequency, and vowels' supra-laryngeal movements (Torng 2000; Erickson et al 2004; Hu 2004). The three potential non-lexical factors are discussed as follows.

First of all, according to the tone-vowel interaction that low tones tend to co-occur with low vowels (Chan 1985; Jiang-King 1999; Yip 2002:31; and many others), low vowels may help both Hai-lu Hakka's tone sandhi rules derive low tones (i.e. low-level tone and low-checked tone) from their underlying forms (i.e. low-rising tone and high-checked tone respectively). The co-occurrence may enhance both tonal derivations, and constitute a potential cause for the vowel effect hypothesized in (44b) above. The tone-vowel interaction seems able to account for higher production accuracy, as well as recognition accuracy, in those stimuli with sandhi tones consisting of low vowels, but it is unclear why discrimination and identification accuracy is significantly higher in those stimuli with sandhi tones co-occurring with high vowels. It is also unclear how the tone-vowel interaction leads to different patterns between discrimination/identification results and recognition/production results.

Second, the two vowels' token frequency may also be responsible for the vowel effect. According to Hsu (2009:47), Hai-lu Hakka's low vowel [a] has a wider occurrence distribution than the high vowel [u]. The higher token frequency may enhance speech processes of tone sandhi in those stimuli with sandhi tones co-occurring with low vowels, and may be able to account for the pattern in the recognition and the production results. However, it seems unclear why the more frequent token [a] enhances the recognition and the production accuracy, but the less frequent token [u] enhances the discrimination and the identification accuracy. It is also unclear why the token frequency results in these different patterns.

Third, according to Torng (2000), Erickson et al (2004), and Hu (2004), laryngeal movements may exert an influence on supra-laryngeal articulators. The coordination of the laryngeal and supra-laryngeal movements may account for the vowel effect. For instance, Erickson et al (2004) found that speakers' jaw and tongue for low vowels (i.e. [ba], [pa], [ma]) are more retracted and F1 is significantly higher, when they produce low T3 in Mandarin than when producing high T1. That is, low tones may facilitate jaw and tongue positions of low vowels, and the coordination seems to be consistent to the tone-vowel interaction. It remains clear why the high vowel [u] enhances perception accuracy in discrimination and identification processes. As a result, the tone-vowel interaction, the vowels' token frequency, and the coordination of laryngeal and supra-laryngeal movements may be a cause for the vowel effect, but they cannot account for the different patterns of the current vowel effect.

5.6.2.3 The prosodic effect and the perception/production asymmetry

The results show that sandhi tones preceding low-falling prosody (LF) and low-rising prosody (LR) are more accurate than those preceding high-falling prosody (HF) in the perception results, but the pattern is almost the opposite in the production results. The analyses show that both the perception pattern (LF > HF) and the production pattern (HF > LF) are significant across the tasks. The patterns of the low-rising prosody condition are more complicated (discrimination: LF > LR > HF, identification: LF, LR > HF, recognition: LF > LR, HF, production: LR, HF > LF). The findings indicate that participants perceive sandhi tones preceding low-falling prosody significantly more accurately than those preceding high-falling prosody, but they produce sandhi tones preceding high-falling prosody more accurately than those preceding low-falling prosody. As to the patterns of the low-rising prosody condition, they tend to behave as those of the high-falling prosody condition. In other words, the low-falling follower enhances perception accuracy, but reduces production accuracy. The high-falling and low-rising followers reduce perception accuracy, but enhance production accuracy. The patterns of the prosodic effect are generally correlated to the differences between perception and production processes.

The analyses of lexical familiarity (shown in section 5.4.3 above) show that the prosodic types do not exert a significant influence on participants' rating scores, indicating that the prosodic effect is less likely to result from an internal influence of lexical knowledge. High-falling prosody and low-rising prosody are not significantly more familiar than low-falling prosody, and not the other way around, either. The findings show that the prosodic effect exhibits a perception-production asymmetry and can be attributed to non-lexical knowledge of the three following tones. The non-lexical knowledge may refer to tonal co-articulation (Peng 1997; Xu 2004), token frequency and type frequency, and following tones' pitch height and pitch contour (Chao 1968; Zhang & Lai 2010). The three potential non-lexical factors are discussed as follows.

First of all, according to tonal co-articulation, preceding tones' offset pitch height varies with following tones' onset pitch height (Jiang 2003; Peng 1997; Xu 2004), and following tones consisting of non-high onset pitch (i.e. low-falling tone and low-rising tone) may facilitate both sandhi tones' tonal modifications. As so the low-rising tone sandhi, the tonal modification from low-rising tone to low-level tone leads to offset-pitch lowering. As to the high-checked tone sandhi, the tonal modification from high-checked tone to low-checked tone leads to overall-pitch lowering. Both the offset-pitch lowering and the overall-pitch lowering may benefit from such tonal co-articulation. In addition, according to the perceptual compensation for co-articulation (Mann 1980), the contextual factor (i.e. being followed by low tones) may also enhance perceptual accuracy of low sandhi tones to some extent. For instance, Peng (1997:393) found that low-falling tone's perception accuracy is higher when preceding another low-falling tone (about 48.95%) than when preceding high-level tone (23.95%) and mid-level tone (about 27.11%) in Taiwan Southern Min. The effect of tonal co-articulation is hypothesized as a potential cause for the prosodic effect in (33b) above. It seems able to account for higher perception accuracy in those stimuli with sandhi tones preceding low-falling prosody and low-rising prosody, but it is unclear why production accuracy is significantly lower in those stimuli with sandhi tones preceding low-falling tone. It is also unclear why the effect of tonal co-articulation exhibits a perception-production asymmetry.

Second, the three following neighbors' token frequency may also be responsible for the prosodic effect. According to Hsu (2009:48), Hai-lu Hakka's high-level tone has a wider occurrence distribution than the low-rising tone and low-falling tone, i.e. high-level tone: 20.68% > low-falling tone: 16.86%, low-rising tone: 12.71%. The lower token frequency may account for the lower production accuracy in those stimuli with sandhi tones preceding low-falling tone, but it is unclear why the perception accuracy is the highest in those stimuli under the same prosodic condition. The frequency factor cannot account for the pattern of perception results, either. It is unclear why the perception accuracy is the lowest in those stimuli with sandhi tones preceding the most frequent prosodic type, i.e. high-level tone. As a result, token frequency may not be a crucial cause for the prosodic effect.

Third, the prosodic effect may result from the three prosodic types' intrinsic pitch height and pitch contour. Although the application of Hai-lu Hakka tone sandhi is not determined by tone types, following tones' intrinsic pitch height and pitch contour may exert a different influence on processing patterns of sandhi tones. Taking Mandarin T3 sandhi and half T3 sandhi (Chao 1968; Zhang & Lai 2010) for example, T3 becomes a low-rising-tone-like variant before another T3, whereas it changes to a low-falling-tone-like variant elsewhere (i.e. before T1, T2 and T4). The Mandarin cases indicate that the prosodic types' intrinsic pitch height and pitch contour may result in different T3 variants. T3's particular patterns may result from its longest vowel duration and/or its lowest pitch height in Mandarin's tonal system. The lowest pitch tends to coincide with glottalization which requires more articulatory efforts, and the additional articulatory efforts may reduce production accuracy to some extent. Since Hai-lu Hakka's low-falling tone has the lowest pitch height, the additional articulatory efforts may induce the lowest production accuracy in the low-falling prosody. The additional articulatory efforts are not required in perception processes, and hence the prosodic effect exhibits a perception-production asymmetry. As a result, the additional articulatory efforts of lower pitch height and the perceptual compensation for co-articulation may be the crucial cause for the prosodic effect.

5.6.2.4 Summary of the phonetic/phonological effects

In general, the current findings indicate that the three kinds of phonetic/phonological factors, i.e. the sandhi types, the vowel types, and the prosodic types, exert a consistent influence on each process of Hai-lu Hakka tone sandhi. Since they are not correlated to participants' lexical familiarity ratings, they are derived from the influence of non-lexical knowledge. That is the sandhi effect may result from sandhi tones' intrinsic pitch height and pitch contour; it is unclear what gives rise to the vowel effect although it may result from tone-vowel interaction and frequency variables; the prosodic effect may result from perceptual compensation for co-articulation and lower pitch's additional articulatory efforts. However, the three phonetic/phonological effects exhibit less consistent patterns across the tasks. Their patterns are correlated to the perception-production asymmetry and the degrees of lexical access. The less consistent patterns may result from different subordinate influences of the same phonetic/phonological factors, and these subordinate influences depend on different speech processes. Taking the sandhi effect for example, the sandhi effect may result from a subordinate influence of pitch height and pitch contour. Hai-lu Hakka speakers are more likely to keep faithful the pitch height in production, and to keep faithful the pitch contour in perception (Yeh & Lin 2015). In other words, the phonetic/phonological effects' less consistent patterns are attributed to their different subordinate influences which are conditioned by processing strategies required for different speech processes. Although the phonetic/phonological effects' patterns may not always conform to the predictions based on a specific subordinate influence, they are generally significant. As a result, these asymmetric patterns do not contradict the phonetic/phonological effects, and the current findings still support the phonetic/phonological hypothesis.

5.6.3 The interaction hypothesis

As shown in the fifth and sixth rows of Table 5.25 above, the current results generally support the interaction hypothesis (33c) that predicts an additional influence of phonetic/phonological factors on novel words in speech processing of Hai-lu Hakka tone sandhi. The results show that (i) the sandhi types exert an additional influence on novel words in the production results, but not in the perception results (i.e. the perception-production asymmetry); (ii) the vowel types exert an additional influence on novel words in the recognition and the production results, but not in the discrimination and the identification results (i.e. different degrees of lexical access); and (iii) the prosodic types exert an additional influence on novel words in the identification and the production results, but not in the discrimination and the recognition results. These findings indicate that the interaction patterns are not commonly shared by the three phonetic/phonological factors in general, and the interaction effect is more common in the production results than in the perception results. Although the additional influences of phonetic/phonological factors may occur across the tasks, except for the slightly significant influences in the discrimination results, they seem to be correlated to processing factors, such as the perception-production asymmetry and the different degrees of lexical access. These findings are further discussed in each phonetic/phonological factor as follows.

5.6.3.1 The interaction effect of sandhi types

The analyses show that there is a significant interaction between sandhi types and lexical types (only L_2) in the production results, but not in the perception results. The findings indicate that the sandhi types exert an additional influence on the lexical contrast between novel words and less frequency words in production processes, but no additional influence on any lexical contrast in perception processes. The production tendency for sandhi types (i.e. low-rising tone sandhi > high-checked tone sandhi) is more significant in novel words than in less frequent words (less significant between novel words and frequent words), but the perception tendency is evenly distributed across the lexical types. The additional sandhi effect indicates an asymmetry between perception and production processes. According to the analyses of lexical familiarity (shown in section 5.4.3 above) showing that the interaction between sandhi types and lexical types is not correlated to participants' rating scores, the additional influence is not likely to result from an internal influence of lexical knowledge. It is instead derived from participants' strategies to process novel words with a restricted access to lexical knowledge. In other words, participants are more likely to apply phonetic/phonological knowledge of sandhi types in producing tone sandhi in novel words. The findings generally support the interaction hypothesis, and indicate the influence of processing factors (i.e. the perception-production asymmetry) on the interaction between sandhi types and lexical types.

5.6.3.2 The interaction effect of vowel types

The analyses show that there is a significant interaction between vowel types and lexical types in the recognition and the production results, but not in the discrimination and the identification results. The findings indicate that the vowel types exert an additional influence on the lexical contrast between novel words and actual words (and between frequent words and less frequent words) in recognition and production processes, but no additional influence on any lexical contrast in discrimination and identification processes. The recognition and production tendency for vowel types (i.e. low vowels > high vowels) is more significant in novel words than in actual words, but the discrimination and identification tendency is evenly distributed across the lexical types. The additional vowel effect indicates a pattern conditioned by different degrees of lexical access. According to the analyses of lexical familiarity (shown in section 5.4.3 above) showing that the interaction between vowel types and lexical types is not correlated to participants' rating scores, the additional influence is not likely to result from an internal influence of lexical knowledge. It can be attributed to participants' different strategies to process novel words with a restricted access to lexical knowledge. In other words, participants are more likely to apply phonetic/phonological knowledge of vowel types in recognizing sandhi tones' lexical meanings and producing tone sandhi in novel words. The findings generally support the interaction hypothesis, and indicate the influence of processing factors (i.e. different degrees of lexical access) on the interaction between vowel types and lexical types.

5.6.3.3 The interaction effect of prosodic types

The analyses show that there is a significant interaction between prosodic types (only P_1) and lexical types (only L_2) in the identification results, a significant interaction between prosodic types (only P_2) and lexical types (only L_1) in the production results, but no significant interaction in the discrimination and the recognition results. The findings indicate that the prosodic types exert an additional influence on the lexical contrast between novel words and actual words (frequent or less frequent words) in identification and production processes, but no additional influence on any lexical contrast in discrimination and recognition processes. Both the production tendency (i.e. high-falling prosody > low-falling prosody) and the perception tendency for prosodic types (i.e. low-falling prosody > high-falling prosody) are more significant in novel words than in actual words, but it is unclear how the additional prosodic effect is correlated to the task types and any other processing factor. According to the analyses of lexical familiarity (shown in section 5.4.3 above) showing that the interaction between prosodic types and lexical types is not correlated to participants' rating scores, the additional influence is not likely to result from an internal influence of lexical knowledge. It may be derived from participants' strategies to process novel words with a restricted access to lexical knowledge. In other words, participants are more likely to apply phonetic/phonological knowledge of prosodic types in identifying sandhi tones' types and tin producing tone sandhi in novel words. The findings generally support the interaction hypothesis, and indicate the influence of some processing factors on the interaction between prosodic types and lexical types.

5.6.3.4 Summary of the interaction effects

To sum up, the current findings indicate that the three kinds of phonetic/phonological factors, i.e. the sandhi types, the vowel types, and the prosodic types, exert an additional influence on novel words in each process of Hai-lu Hakka's tone sandhi, which is currently defined as the interaction effect. The interaction effect generally doesn't seem to be a common occurrence, and seems more common in production than in perception processes. Since these factors are not correlated to participants' lexical familiarity ratings, they are subject to an influence of some processing factors. That is, the additional sandhi influence only takes place in the production results, which demonstrates an asymmetry between perception and production processes. The additional vowel influence only takes place in the recognition and the production results, which demonstrates a pattern conditioned by the different degrees of lexical access. The additional prosodic influence only takes place in the identification and the production results, which seems correlated to some unknown processing factors. The patterns of these additional phonetic/phonological influences are consistent with those processing factors found in each phonetic/phonological effect, except for the additional prosodic influence. Although these additional influences are correlated to each phonetic/phonological effect, they may not necessarily stem from the significant phonetic/phonological influences. For instance, the sandhi effect is not significant in the production results, but it is found to exert an additional influence on novel words in the same condition. The vowel effect is significant in the discrimination and the identification results, but it is found not to exert an additional influence accordingly. In general, these findings support the interaction hypothesis, and indicate two potential issues that need to be further investigated. First, the interaction effects may be correlated to some processing factors similar to those found in the phonetic/phonological effect. Second, it is unclear why the interaction effect is more likely to occur in the production results than in perception results.

5.6.4 The processing hypothesis

As shown in the seventh and eighth rows of Table 5.25 above, the current results generally support the processing hypothesis (33d) that predicts the influence of processing factors (i.e. the perception-production asymmetry and different degrees of lexical access) on lexical and phonetic/phonological effects in speech processing of Hai-lu Hakka tone sandhi. The results show that (i) the significant degrees of the lexical effect are correlated to the difference between discrimination/identification results and recognition/production results; (ii) the patterns of the sandhi effect are correlated to the difference between perception and production results; (iii) the patterns of the vowel effect are correlated to the difference between discrimination/identification results and recognition/production results; and (iv) the patterns of the prosodic effect are correlated to the differences between perception and production results. In addition, the results for interaction analyses show that (v) the additional influences of sandhi types exhibit a difference between perception and production results; (vi) the additional influences of vowel types exhibit a difference between discrimination/identification and recognition/production results; (vii) the additional influences of prosodic types exhibit a difference between discrimination/recognition and identification/production results; (viii) the patterns of the interaction effect exhibit a difference between perception and production results. As argued in section 5.4 above, the difference between perception and production results indicates the perception-production asymmetry (Boersma 1998; Flemming 2004), and the difference between discrimination/recognition and identification/production results are derived from the degrees of lexical access (Polka 1991; Werker & Tees 1984). In other words, these findings suggest the crucial role played by two processing factors, i.e. the perception-production asymmetry and different degrees of lexical access, in speech processing of Hai-lu Hakka tone sandhi.

The two potential processing factors are further discussed as follows.

5.6.4.1 The degrees of lexical access

The degrees of lexical access refer to how likely an acoustic input may activate participants' access to lexical memory. The more likely the lexical access is to be activated, the more significant the lexical effect is. In other words, the lexical effect is not only determined by different lexical types, such as words types and lexical frequency/familiarity, but also conditioned by different degrees of lexical access. The lexical types and the degrees of lexical access are correlated to some extent. For instance, as assumed previously, frequent/familiar words are more likely to activate participants' access to lexical memory than less frequent/familiar words. The more word-like the novel words are, the more likely they will be able to activate lexical access. However, the degrees of lexical access may also be correlated to factors other than lexical types, such as task types and additional methodological manipulations. As argued by Polka (1991) and Werker & Tees (1984), task types and additional manipulations may affect participants' processing strategies which require an access to different kinds of knowledge. For instance, the discrimination and identification formats are less likely to activate lexical access, so they are conventionally designed to target non-lexical knowledge. As to the recognition and production formats, they are more likely to be lexically oriented. The difference task types are arguably correlated to the different degrees of lexical access. As a result, the degrees of lexical access may restrict the effect of lexical types to varying degrees, as demonstrated currently.

The degrees of lexical access not only restrict the lexical effect to varying degrees, but also modify the patterns of the vowel effect. As mentioned in section 5.6.2 above, low vowels are found to enhance recognition and production accuracy as predicted, but to modulate discrimination and identification accuracy. It is reasonable for the degrees of lexical access to exert a varying influence on the lexical effect, but it remains unclear how lexical access affect the patterns of the vowel effect. There is one potential account for lexical access on the vowel effect, comparing to the sandhi and the prosodic effects demonstrating the perception-production asymmetry. That is, the sandhi effect and the prosodic effect are derived from contextual influences, but the vowel effect is not. These contextual changes are less likely to change stimuli's lexical meanings, while the vowel changes are more likely to. For instance, [fu13] means 'bitter,' and its low-level variant [fu22] may still mean 'bitter' as in the compound [fu22-kwa51] 'bitter-melon'. When the [fu13] changes the high vowel [u] into the low-vowel [a] as [fa13], the word basically changes its lexical meanings, too. [fa13] means 'to draw (a picture),' and it no longer means 'bitter' in any case. In other words, the effect of vowel types may be correlated to lexical influences, and hence the pattern of the vowel effect may vary with the degrees of lexical access. The issue needs to be further investigated.

5.6.4.2 The perception-production asymmetry

The asymmetry between perception and production indicates how phonetic/phonological factors play a different role in the two processes. As deduced from Boersma's (1998) functional model, Hayes's (1999) phonetic grounding, and Flemming's (2004) dispersion theory of phonological contrasts, perception and production processes are conflicting forces that shape phonological grammars in the opposite manner: to maximize perceptual distinctiveness and to minimize articulatory efforts. The account of conflicting forces seems able to explain the sandhi and the prosodic effects' opposite patterns in the perception and the production results and the patterns of the interaction effect. As indicated above, the sandhi effect exhibits a production pattern that low-rising tone sandhi is more productive than high-checked tone sandhi, but the pattern is opposite to the perception one indicating that high-checked tone sandhi is more perceptually accurate than low-rising tone sandhi. Similarly, the prosodic effect exhibits a production pattern that tone sandhi before high-falling prosody is more productive than before low-falling prosody, but the pattern is opposite to the perception one indicating that tone sandhi before low-falling prosody is more perceptually accurate than before high-falling prosody. As to the interaction effect's occurrence pattern, the additional phonetic/phonological influences are more likely to occur in the production results than in the perception ones.

Although the account of opposite forces seems to support the perception-production asymmetry, it remains unclear what subordinate phonetic/phonological factors are responsible for the different patterns of these effects. According to Zhang & Lai (2010) and Zhang et al (2011), the sandhi effect is hypothesized to derive from sandhi tones' token frequency and each prosodic position's durational preference. The frequency and duration factors can account for the production pattern of the sandhi effect, but it is unclear how the two factors can explain that the more frequent low-rising tone sandhi is less perceptually distinctive. It is also unclear why low-rising tone sandhi's underlying and surface forms that are longer in vowel duration are less perceptually distinctive than high-checked tone sandhi's two forms that are shorter. Similarly, according to tonal co-articulation (Peng 1997; Xu 2004), the prosodic effect is hypothesized to derive from sandhi tones' co-articulation with following tones. Tonal co-articulation seems able to account for the prosodic effect's perception pattern, but it is unclear why the articulatory account is contradictory to the production pattern. These findings suggest that Hai-lu Hakka tone sandhi may derive form some articulation-based influences such as durational preference or tonal co-articulation, as hypothesized by the previous studies (Peng 1997; Xu 2004; Zhang & Lai 2010; Zhang et al 2011), but participants may apply different knowledge other than these subordinate factors to different speech processes of Hai-lu Hakka tone sandhi. For instance, as discussed in section 5.6.2 above, the asymmetric patterns of the sandhi effect may result from participants' preference for being faithful to pitch height in production and to pitch contour in perception. The prosodic effect's patterns may result from an influence of perceptual compensation for co-articulation in perception and an influence of additional articulatory efforts for lower pitch height in production. Since Hai-lu Hakka tone sandhi may be subject to articulation-based influences, these influences are more likely to exert an additional influence on production processes than perception, which may account for the occurrence pattern of the interaction effect. As a result, in order to find out what subordinate phonetic/phonological factors are responsible for the different patterns of different types of effects, it is indispensable to evaluate how different patterns are correlated to each task type as processing factors.

5.6.4.3 Summary of the processing effects

To sum up, the current results indicate that the significant levels of the lexical effect and the patterns of the phonetic/phonological effects are correlated to the degrees of lexical access and the perception-production asymmetry. The results indicate that the two processing factors affect how participants access lexical and phonetic/phonological knowledge in each speech process of Hai-lu Hakka tone sandhi. As discussed above, the two processing factors were argued previously to be processing strategies that affect participants' access to different linguistic knowledge (Polka 1991; Werker & Tees 1984) and to be conflicting forces that shape phonological patterns in the opposite manner (Boersma 1998; Flemming 2004). They are not trivial, but were ignored previously for the methodological reason since most previous studies did not conduct more than one type of task formats. As indicated currently, although Hai-lu Hakka tone sandhi seems to result from some articulation-based influences, participants' processing strategies are not restricted to these articulatory factors. They may apply different kinds of knowledge to process Hai-lu Hakka tone sandhi in each task, and the different knowledge applied may result in different patterns for each task. Since the two processing factors may affect participants' access to lexical and phonetic/phonological knowledge, it is also plausible for them to affect the interaction between the two kinds of knowledge. In general, the current findings provide some evidence for the processing hypothesis, but the exact effects of the two processing factors need to be further investigated. In order to verify the potential role of processing factors, it is indispensable to consider each linguistic effect and its pattern in each task type, and then to find out an account for the correlation between the pattern and the task. The current findings demonstrate the correlation, but it is not confirmed yet what subordinate phonetic/phonological factors are responsible for the different patterns of different types of effects in each task.

5.6.5 The psychological-reality and the phonetic-naturalness issues

As shown in the last four rows of Table 5.25 above, the current results generally support the two additional hypotheses (34a & 34b) on the psychological-reality and phonetic-naturalness issues for speech processing of Hai-lu Hakka's tone sandhi. The additional analyses show that (i) the application rates of Hai-lu Hakka tone sandhi are significantly higher in actual words than in novel words. In addition, (ii) the application rates of actual words are mostly higher than the 75% standard of children's tonal acquisition, except for some less frequent words, and the application rates of novel words are consistently lower than the 75% standard. The findings indicate that Hai-lu Hakka tone sandhi is bound to actual words based on the standard of children's tonal acquisition, which is argued against the psychological reality or phonological productivity of tone sandhi. In other words, Hai-lu Hakka's tone sandhi, as well as Mandarin's T3 sandhi and Taiwan Southern Min's tonal circle, are not fully productive phonologically, and hence does not seem to be psychologically real. The additional analyses also show that (iii) the application rates of low-rising tone sandhi (i.e. duration-shortening and phonetically natural) are significantly higher than those of high-checked tone sandhi (i.e. less phonetically motivated), especially to novel words. The finding indicates that phonetic grounding, such as duration-shortening in non-final position, enhances tone sandhi rules' production processes in Hai-lu Hakka as well as in Mandarin and Taiwan Southern Min. In general, the current results provide additional cross-linguistic evidence for the psychological-reality issue (Hsieh 1976; Wang 1995; Zhang et al 2011; and many others) and the phonetic-naturalness issue (Zhang & Lai 2010; Zhang et al 2011).

5.6.5.1 The psychological-reality hypothesis

The analysis for the psychological-reality hypothesis indicates that Hai-lu Hakka's tone sandhi is bound to actual words, and is less likely to be automatically applied to novel words. The finding calls for one of two potential explanations, (i) the allomorph account and (ii) the opacity account, which were previously proposed to account for the low application rates of Taiwan Southern Min's tonal circle by Tsay & Myers (1996) and Zhang et al (2011) respectively. According to Tsay & Myers' (1996) allomorph account, sandhi tones' underlying and surface forms are both stored in lexical memory, and are retrieved accordingly in each prosodic position. Since novel words were not previously stored in lexical memory, they cannot be retrieved accordingly to process tone sandhi in time, which then leads to lower application rates of tone sandhi to novel words than to actual words. The allomorph account suggests that Hai-lu Hakka's tone sandhi is a lexical rule, instead of a fully productive post-lexical rule driven by phonological reasons. According to Zhang et al's (2011) opacity account, some rules are phonologically opaque, since their underlying and surface forms both appear as surface structure in the same prosodic context. The phonological opacity makes it difficult to retrieve a corresponding form as a surface structure in each context, resulting in lower application rates. Hai-lu Hakka tone sandhi is phonologically opaque in that sandhi tones' underlying form may occur as surface structures in sandhi position for being part of various exceptions or being overridden by two emphasis rules demonstrating patterns opposite to sandhi rules. The opacity account suggests that Hai-lu Hakka tone sandhi is a post-lexical rule as previously assumed, but its variations in degrees (i.e. application rates) are correlated to its variations in kinds (i.e. exceptions and other patterns). It is unclear which account the current findings support, but the current findings do demonstrate that Hai-lu

Hakka tone sandhi exhibits variations not only in kinds, but also in degrees and that the application rates of Hai-lu Hakka tone sandhi are conditioned by various lexical and phonetic/phonological factors.

5.6.5.2 The phonetic-naturalness hypothesis

The analysis for the phonetic-naturalness hypothesis indicates that Hai-lu Hakka's low-rising tone sandhi is more productive than high-checked tone sandhi. According to Zhang & Lai (2010) and Zhang et al (2011), it is phonetically natural for durational properties to be shorter in non-final position (i.e. the sandhi context) and low-rising tone sandhi causes sandhi tones' vowel duration to shorten. As to the high-checked tone sandhi, it is irrelevant to duration-shortening and does not seem to have phonetic bases. The finding supports that phonetic grounding such as duration-shortening in non-final position enhances production processes of Hai-lu Hakka tone sandhi. However, as mentioned earlier in section 5.6.2, the durational properties are not the only linguistic correlate that contrasts the two sandhi patterns, and there could be some other subordinate attributes, such as token/type frequency, pitch height and pitch contour, and syllable structures, conspiring to result in the difference. The current findings cannot be fully accounted for by the influence of frequency factors and durational properties, since the two kinds of factors are unable to account for the perception pattern in which high-checked tone sandhi is more perceptually distinctive than low-rising tone sandhi. In general, it remains unclear exactly which attributes account for the sandhi effect, but it is reasonable to claim that the effect of sandhi types lead to some variations as in the application rates of Hai-lu Hakka tone sandhi, which indicates the crucial effect of sandhi types based on phonetic consideration.

5.7 Conclusion: general discussion, research questions, and implications

The current results generally confirm the predictions based on the theory as well as the previous findings of Mandarin and Taiwan Southern Min tone sandhi, except for some less significant results of lexical influences and less consistent patterns of phonetic/phonological influences. The differences are suggested to be correlated to processing factors that were previously proposed as processing strategies (Polka 1991; Werker & Tees 1984) and conflicting forces of phonological grammars (Boersma 1998; Flemming 2004; Hayes 1999), but were not taken seriously due to methodological restrictions. These findings are discussed in detail by each hypothesis above, and are further interpreted accordingly as follows. The first step is to interpret the four research hypotheses and the two additional hypotheses in speech processing of Hai-lu Hakka tone sandhi, and then to answer the four research questions based on the experimental findings. To conclude this chapter, the current findings bring up some implications for the general theory of tonal phonetics and phonology, Hai-lu Hakka tone sandhi, and models of speech processing.

5.7.1 General discussion on all hypotheses

As summarized in Table 5.25 above, the current results generally substantiate all these hypotheses. As to the lexical hypothesis and the phonological-productivity hypothesis, the current findings indicate that the lexical types cause Hai-lu Hakka tone sandhi to induce variations as shown in the different degrees of accuracy rates. The lexical effect exhibits a consistent pattern (frequent words > less frequent words > novel words) across task types, but is less significant due to a minimal degree of lexical access provided by discrimination and identification processes. As to the phonetic/phonological hypothesis and the phonetic-naturalness hypothesis, the current findings indicate that the sandhi types, the sandhi tones' vowel types, and the sandhi tones' prosodic types also cause Hai-lu Hakka tone sandhi to induce variations as shown in the different degrees of accuracy rates. These phonetic/phonological effects are significant more or less across task types, but exhibit a less consistent pattern among different tasks. The sandhi effect and the prosodic effect exhibit the perception-production asymmetry, and the vowel effect exhibits a difference correlated to different degrees of lexical access. In general, the two hypotheses suggest that variations may be inherently influenced by lexical and phonetic/phonological factors. The variations not only arise from different degrees of accuracy rates, but also occur as different patterns induced by different phonetic/phonological effects.

As to the interaction hypothesis, the current findings indicate that the phonetic/phonological factors exert a more significant influence on novel words than on actual words. The interaction effect is generally not prevalent in speech processing of Hai-lu Hakka tone sandhi, but is more likely to occur in production processes than perception processes, which indicates the perception-production asymmetry. The interaction hypothesis suggests that difficulties in lexical retrieval (i.e. less likely to retrieve novel words) lead participants to resort to phonetic/phonological knowledge. The lexical retrieval/access affects participants' access to phonetic/phonological knowledge. The less likely the lexical access is to be activated, the more likely the phonetic/phonological knowledge is resorted to. That is, participants may resort to phonetic/phonological knowledge to compensate difficulties in lexical retrieval, which leads to a shift in processing strategies. The strategic shift also seems to be responsible for variations as shown in the varying accuracy rates of Hai-lu Hakka tone sandhi application.

As to the processing hypothesis, the current findings indicate that the design of task types lead participants to access lexical and phonetic/phonological knowledge in different manners. The task types elicit different processing strategies that contrast (i) different degrees of lexical access and (ii) the difference between perception and production processes. The former exert an influence on the lexical and the vowel effects, whereas the latter is correlated to the sandhi and the prosodic effects as well as the interaction between lexical and phonetic/phonological factors. The processing hypothesis suggests that processing strategies/factors affect participants' access to lexical and phonetic/phonological knowledge, and the strategic shift in each task format is also responsible for variations.

In general, these hypotheses suggest that variations in speech processing of Hai-lu Hakka tone sandhi include a quantitative difference as the different degrees of accuracy rates and a qualitative difference as the different patterns induced by the phonetic/phonological effects. They may be inherently influenced by lexical and phonetic/phonological factors, and may also arise from an intrinsic shift in processing strategies conditioned by the accessibility of lexical knowledge and the design of task types. The common occurrence of variations poses a challenge for a post-lexical account for Hai-lu Hakka tone sandhi. As mentioned earlier in section 3.1.3.2 above, the post-lexical account considers tone sandhi to be automatically productive, but it is certainly not the case in Hai-lu Hakka. The current findings suggest that Hai-lu Hakka tone sandhi is lexically bound, which calls for two potential explanations, the allomorph account and the opacity account, proposed by Tsai & Myers (1996) and Zhang et al (2011) respectively to account for the lower application rates of Taiwan Southern Min's tonal circle.

5.7.2 Four research questions on Hai-lu Hakka tone sandhi

As discussed above, the current results verify all the hypotheses, and provide positive answers to four research questions concerning the effects of lexical and phonetic/phonological factors and the interaction between the two kinds of factors. As to the first research question on lexical effects, the results show that lexical factors, including word types and lexical frequency/familiarity, cause Hai-lu Hakka speakers to process tone sandhi in different manners. For instance, Hai-lu Hakka participants process tone sandhi in actual words more accurately than in novel words. As to the second research question on phonetic/phonological effects, the results indicate that phonetic/phonological factors, including sandhi types, vowel types, and prosodic types, cause Hai-lu Hakka speakers to process tone sandhi in different manners. For instance, Hai-lu Hakka participants perceive sandhi tones before low-falling prosody more accurately than before high-falling prosody. As to the third research question on the interaction between lexical and phonetic/phonological factors, the results indicate that the two kinds of factors interact with each other to cause Hai-lu Hakka speakers to process tone sandhi in different manners. For instance, the sandhi types exert an additional influence on Hai-lu Hakka tone sandhi in novel words than in actual words. As to the fourth research question on the effects of two potential processing factors, the results indicate that degrees of lexical access and the perception/production asymmetry cause Hai-lu Hakka speakers to process tone sandhi in different manners. For instance, participants perceive high-checked tone sandhi more accurately than low-rising tone sandhi across three perception tasks, whereas they produce low-rising tone sandhi more accurately than high-checked tone sandhi.

5.7.3 Implications

In general, the current findings suggest three implications for Hai-lu Hakka tone sandhi and models of speech processing. First, Hai-lu Hakka's tone sandhi rules exhibit different degrees of variations as indicated by the findings that the application rates of tone sandhi vary with different lexical and phonetic/phonological factors. Those variations induced by lexical factors suggest that Hai-lu Hakka's tone sandhi rules are not automatically applicable to novel words, and hence are not phonologically productive or psychologically real. The lower application rates have thus have implications for the classification issue that considers tone sandhi to be fully productive as post-lexical rules. Second, although Hai-lu Hakka's tone sandhi rules are different from those in Mandarin and Taiwan Southern Min, these languages' sandhi patterns all tend to be lexically bound. The lower productivity of Hai-lu Hakka tone sandhi may be attributed to different kinds of variations found in Hai-lu Hakka, i.e. various exceptions to tone sandhi and overriding influences from emphasis rules. It is important to further investigate the influences of these various exceptions and the prevalent emphasis rules which were barely studied by the literature. Third, the current findings show that the lexical effect exhibits a more consistent pattern than the phonetic/phonological effects. The phonetic/phonological effects may exert an additional influence when the participants have difficulty in lexical access. In other words, lexical factors play a more consistent and efficient role than phonetic/phonological factors in speech processing of Hai-lu Hakka tone sandhi, suggesting that a lexically-based model is a more favorable approach to speech processing.

CHAPTER SIX

CONCLUSION

This dissertation examines two cases of tonal variations in Hai-lu Hakka: pitch variations of two falling tones and sandhi variations of two tonal rules, and supports the crucial role variations play in tonal processing. This chapter summarizes the experimental results to answer the two research questions, and discusses the lexical and phonetic/phonological effects on tonal processing. In general, this dissertation makes three contributions. First, the current findings demonstrate that variations are a common occurrence in all processes. It is problematic to strictly relate variations to phonetic processes and invariance to phonological processes. Second, Hai-lu Hakka's tonal modifications present some interesting patterns such as tonal confusion, the interaction of lexical and phonetic/phonological factors, and the perception-production asymmetry. Third, the current findings show that lexical influences exhibit a more consistent pattern than phonetic/phonological influences, suggesting that a lexically-based model is a more favorable approach to speech processing. To sum up, this dissertation suggests that some tonal contrasts may confuse L1 speakers, especially those between phonetically similar categories, and that the application of tone sandhi not only varies with different morpho-syntactic structures, but also varies with different phonetic/phonological and lexical factors.

6.0 Summary of all results and findings

The results of two experiments above are summarized according to each hypothesis below. As shown in the second and third rows of Table 6.1, the results indicate that both lexical and phonetic/phonological factors exert an influence on Hai-lu Hakka's contrast of two falling tones and the application of two sandhi rules. In experiment 1 on pitch variations of two falling tones, the lexical effect indicates that participants chose more high-falling responses in lexical results than in tonal results, suggesting that participants perceive the tonal contrast with non-lexical and lexical responses in different manners. The phonetic/phonological effects indicate that participants' contrast of two falling tones is susceptible to onset-pitch and overall-pitch variations, but is less susceptible to offset-pitch variations. That is, the higher the tonal variants' onset pitch and overall pitch, the more likely they will be perceived as high-falling tone. As to the offset pitch variations, they generally do not contrast two falling tones, except for the changes from the ambiguous pitch register to high pitch register in lexical processing. In experiment 2 on sandhi variations of two tone sandhi rules, the lexical effect indicates that participants' accuracy rates of tone sandhi are higher for frequent words than for less frequent words and novel words. The phonetic/phonological effects indicate that participants' accuracy rates of tone sandhi are susceptible to sandhi types, sandhi tones' vowel types and the following tones' prosodic types, but the patterns vary with each task. As to the sandhi types, the accuracy rates of high-checked tone sandhi are higher than those of low-rising tone sandhi in the perception results, but the pattern is reversed in the production results. As to the sandhi tones' vowel types, the accuracy rates are higher for high vowels than low vowels in the discrimination and identification results, but the opposite pattern occurs in the recognition and production results. As to the prosodic types, the accuracy rates are higher to low-falling prosody than to high-falling prosody in the perception results, but the reversed pattern occurs in the production results. The findings of lexical and phonetic/phonological effects generally substantiate the lexical hypothesis and the phonetic/phonological hypothesis.

Table 6.1 Summary of current findings for pitch variations of two falling tones and phonological variations of two sandhi rules in Hai-lu Hakka.

	Experiment 1 Pitch variations of 2 falling tones (i.e. high-falling & low-falling)	Experiment 2 Sandhi variations of 2 tonal rules (i.e. low-rising & high-checked)
Lexical Hypothesis	The frequency rates of high-falling responses are higher in lexical results than in tonal results, suggesting an effect of word types.	The accuracy rates of frequent words are higher than those of less frequent words and novel words (N), i.e. F > LF > N.
Phonetic Phonological Hypothesis	Onset-pitch and overall-pitch variations, but not offset-pitch variations, exert an influence on the tonal contrast.	Sandhi types, vowel types, and prosodic types exert an influence on tone sandhi processing, but their patterns vary across task types.
Interaction Hypothesis	(i) Pitch variations play a more significant role in tonal processing than in lexical processing. (ii) Lexical factors exert a more significant influence on ambiguous pitch variations.	Phonetic/phonological factors exert an additional or enhanced influence on novel words rather than on actual words.
Processing Hypothesis		Lexical and phonetic/phonological factors play a different role in each process (i.e. task) of tone sandhi.

As shown in the fourth row of Table 6.1, the results indicate that each of the two kinds of factors not only exerts an influence by itself, but also interacts with each other to exert an additional influence (i.e. interaction effect) on speech processing of Hai-lu Hakka two falling tones and two tone sandhi rules. The interaction effect indicates that participants may apply various degrees of phonetic/phonological knowledge to stimuli of different lexical types. For instance, in experiment 1, pitch variations are more likely to affect the tonal contrast in tonal processing (non-words) than in lexical processing (actual words). In experiment 2, phonetic/phonological factors are more likely to affect the processing of tone sandhi in novel words than in actual words. In addition to the different roles of phonetic/phonological factors in non-word and word processing, lexical factors may exert an influence to various degrees on pitch variations of different kinds. For instance, the results show that ambiguous offset-pitch variations are more likely to be perceived as high-falling responses in lexical processing than in tonal processing, which indicates a more significant lexical effect on ambiguous pitch variations. These findings support the interaction hypothesis.

These findings above are essential to this dissertation's general research questions on lexical effects, phonetic/phonological effects, and the potential interaction between the two kinds of effects. In addition, the results also indicate the influence of processing factors. As shown in the sixth row of Table 6.1, the results of experiment 2 show that lexical and phonetic/phonological factors may play a different role in different processes of Hai-lu Hakka tone sandhi (i.e. the processing effect). The processing effect indicates that (i) lexical effects' significant levels and vowel effects' patterns are correlated to different degrees of lexical access, (ii) sandhi effects and prosodic effects' patterns are correlated to the asymmetry between perception and production processes, and (iii) the interaction effects' occurrence patterns are also correlated to the perception-production asymmetry. These additional findings support the processing hypothesis.

6.1 The dissertation's research questions

As discussed above, the experimental findings generally support the lexical hypothesis, the phonetic/phonological hypothesis, and the interaction hypothesis. The additional findings also support the hypotheses on processing variables. As summarized in Table 6.2 below, these findings mostly provide positive answers to the research questions, indicating that various kinds of factors exert an influence on Hai-lu Hakka's contrast of falling tones and tone sandhi application. These various hypotheses consistently suggest that variations arise inherently from the influence of lexical and phonetic/phonological factors. Since the lexical and phonetic/phonological influences are found to vary with interaction and processing factors, the interaction and processing factors are also responsible for variations to some extent. In other words, variations are a common occurrence derived from multiple factors during tonal processing, and they play a crucial role in the contrast of two falling tones and the application of tone sandhi in Hai-lu Hakka.

Table 6.2 The answers to the two research questions.

	The research question #1 (the distinctiveness issue): Does the contrast of falling tones vary with different factors?	
Lexical Effect	Does the tonal contrast vary with any lexical factors?	**Yes**
Phonetic/ Phonological Effect	Does the tonal contrast vary with onset-pitch variations?	**Yes**
	Does the tonal contrast vary with offset-pitch variations?	**No**, but…
	Does the tonal contrast vary with overall-pitch variations?	**Yes**
Interaction Effect	Does the tonal contrast vary according to the interaction between lexical and phonetic/phonological factors?	**Yes**
	The research question #2 (the productivity issue): Does the application of tone sandhi vary with different factors?	
Lexical Effect	Does the application of tone sandhi vary with any lexical factors?	**Yes**, but…
Phonetic/ Phonological Effect	Does the application of tone sandhi vary with sandhi types?	**Yes**, but…
	Does the application of tone sandhi vary with sandhi tones' vowel types?	**Yes**, but…
	Does the application of tone sandhi vary with sandhi tones' following prosodic types?	**Yes**, but…
Interaction Effect	Does the application of tone sandhi vary with interaction between lexical and phonetic/phonological factors?	**Yes**, but…
Processing Effect	Do the lexical and phonetic/phonological effects on the application of tone sandhi vary with different degrees of lexical access?	**Yes**
	Do the lexical and phonetic/phonological effects on the application of tone sandhi vary with an asymmetry between perception and production processes?	**Yes**

6.1.1 The distinctiveness issue

As shown in Table 6.2 above, the results indicate that the tonal contrast varies with different lexical and phonetic/phonological factors, except for offset-pitch variations. Offset-pitch variations generally do not affect the tonal contrast, but the ambiguous group (i.e. Tone-42, Tone-43) may play a role in lexical processing. The findings indicate two cases in which perceptual confusion between high-falling tone and low-falling tone may occur. First, when onset-pitch height varies to a mid-high pitch register (i.e. 4 on the 5-point scale), the tonal contrast tends to be confusing to L1 speakers. Second, when the overall-pitch height varies to a high or mid-high pitch register, the tonal contrasting is also confusing. In other words, some tonal contrasts, especially those between phonetically similar categories (e.g.

high-falling tone and low-falling tone), are not as distinctive as assumed previously in that they may lead to tonal confusion under the influence of pitch variations in connected speech. The findings of interaction effects indicate that lexical factors may play a more significant role in processing of phonetically ambiguous variations, suggesting that lexical knowledge may be the remedy for tonal confusion. When there is some difficulty in lexical access, pitch variations are more likely to result in tonal confusion.

6.1.2 The productivity issue

As shown in Table 6.2 above, the results indicate that the application of tone sandhi varies with different lexical and phonetic/phonological factors, and these various factors play a different role in each task. For instance, the lexical effect is more significant in lexical recognition and production results than in tonal discrimination and identification results, and the sandhi and prosodic effects exhibit opposite patterns between perception and production tasks. These various factors give rise to different degrees of variations in the application of tone sandhi. In other words, tone sandhi rules are not fully productive as assumed previously in that they not only vary with different morpho-syntactic structures, but also vary with different lexical and phonetic/phonological factors.

6.2 The dissertation's implications and contributions

The findings suggest some implications for tonal modifications, Hai-lu Hakka tonology, and speech processing models. First, it is problematic to relate tonal modifications/rules to different processing levels/linguistic derivations. Second, Hai-lu Hakka exhibits some specific issues such as perceptual confusion and a perception-production asymmetry in tonal processing. Third, an exemplar-based processing model that argues for a non-derivational and lexically-driven account is a more reasonable approach to speech processing. These implications for tonal modifications, Hai-lu Hakka tonology, and speech processing are further discussed as follows.

6.2.1 Implications for tonal modifications

As discussed earlier in section 3.1, previous studies (Gu 2005; Shen 1992; Tsay & Myers 1996; Xu 2004) tended to relate each kind of tonal modifications to different levels of linguistic derivations/causes. The conventional approaches tend to classify different tonal changes by variations (i.e. variation vs. invariance) and their influences on speech processing (i.e. trivial vs. crucial). The current findings suggest that variations arise inherently from an extensive and substantial influence of linguistic and processing factors, and both continuous and categorical variations play a crucial role in the contrast of falling tones and the application of tone sandhi. The common occurrence and the crucial role of variations challenge the conventional classification that considers phonetically-driven changes (e.g. continuous pitch-height variations) to be trivial and less distinctive, and considers phonologically-driven changes (e.g. tone sandhi) to be categorical and invariant. It is problematic to strictly relate variations to phonetic processes and invariance to phonological ones, indicating the classification issue for tonal modifications/variations. The implication for the conventional distinction between phonetics and phonology does not necessarily dismiss the existence of an invariant core in linguistic grammars.

6.2.1.1 The classification issue

The classification issue is a long-standing issue for a derivational approach that assumes an interface between phonetics and phonology. Ohala (1990) identified the term interface in two senses: (i) some point where two different speech domains (physical and psychological) meet and (ii) an area where two largely autonomous disciplines can cooperate. The interface account suggests that the two domains/disciplines apply as independent processes/derivations which justify a derivational approach to tonal modifications presumably induced by various phonetic and phonological factors. Ohala (1990) argued against this conception, since the interface account gives rise to some controversial issues. One of the controversial issues is a circularity argument that interprets linguistic derivations as both processing levels and knowledge/factors, and then defines different knowledge/factors by processing levels (i.e. variation vs. invariance). In other words, the classification issue may arise from the circular argument rather than tonal modifications per se. Since it is problematic to relate tonal modifications to processing levels, it is also questionable to classify each kind of tonal modifications based on variation vs. invariance. It is more reasonable to define different tonal modifications by some independent criteria.

6.2.1.2 The potential criteria

According to Chen (2000: 27), there are two potential criteria that may define each tonal modification in a less paradoxical manner. As shown in Table 6.3 below, the two criteria are the degree of perceptibility and whether or not an additional meaning is involved. As indicated by Chen (2000: 27), tonal modifications induced by co-articulation are less perceptible to unaided ear than those induced by tone sandhi. Those modifications serving as inflectional and derivational devices (i.e. tone change/morpho-phonological rule) tend to carry an additional meaning. That is, the tonal modifications induced by co-articulation are less perceptible in general and rarely carry an additional meaning, but they can be more perceptible in some contexts for the sake of perceptual compensation for co-articulation. The tonal modifications induced by tone sandhi are more perceptible in general and less likely to carry an additional meaning, but they can be confused as other tonal categories due to similar phonetic realizations.. The tonal modifications induced by morpho-phonological reasons are generally more perceptible, and more likely to carry an additional meaning. In addition, Sole (2007) and Yeh & Huang (2011) proposed to use speech rates and focus intonation respectively to examine different phonetic and phonological influences. As argued by Sole (2007), phonological influences (i.e. controlled properties) exhibit an algorithmic relation to speech rates and some other independent processes, but not phonetic influences (i.e.

mechanical properties). In general, these criteria seem to be a better approach to defining each tonal modification.

Table 6.3 Classification criteria for tonal modifications.

	Tonal co-articulation	Tone sandhi	Morpho-phono. rule
Perceptibility	less	more	more
Meaning	no	no	yes

6.2.2 Implications for Hai-lu Hakka tonology

Hai-lu Hakka was less studied previously. As mentioned earlier in section 1.2.2 and chapter 2, its tonal phonetics and phonology tend to be analogized to other Hakka dialects or Chinese languages. The current finings uncover some specific issues such as tonal confusion in the falling-tone contrast and a perception-production asymmetry in the application of tone sandhi, indicating a need to carefully examine less-studied languages like Hai-lu Hakka. The two tonal cases are further discussed as follows.

6.2.2.1 Two falling tones and the tonal contrast

As illustrated in Table 6.4 below, the summary indicates three patterns that may contrast Hai-lu Hakka's falling tones. First, those tonal variations with non-high onset pitch (i.e. Tone-31 and Tone-32) tend to be perceived as low-falling responses. Second, those tonal variations with mid-high onset pitch (i.e. Tone-41, Tone-42, Tone-43, and Tone-44) tend to be perceived as either low-falling responses or ambiguous responses. The low-falling responses tend to occur in those tonal variations with 130-Hz and 140-Hz onset pitch height, while the ambiguous responses tend to occur in those with 150-Hz and 160-Hz onset pitch height. Although these pitch variations correspond to the same tonal category (e.g. Tone-42, Tone-43), they play a different role in the tonal contrast. Third, those tonal variations with high onset pitch (i.e. Tone-52 and Tone-53) tend to perceived as high-falling responses. However, they may sound like ambiguous responses, as the high-onset-pitch variations become higher (than 120 Hz) in offset pitch (i.e. Tone-54). The three patterns suggest that onset-pitch variations play a crucial role in the tonal contrast. Although offset-pitch variations may not be as important as onset-pitch variations, they may make ambiguous those high-onset-pitch variations, especially as offset pitch varies up to a mid-high pitch register (i.e. 130 to 160 Hz). As a result, pitch variations of different kinds, especially onset pitch variations, may result in perceptual confusion between high-falling tone and low-falling tone.

Table 6.4 Summary of Hai-lu Hakka participants' responses to nine normalized falling-tone variations, including Tone-31, Tone-32, Tone-41, Tone-42, Tone-43, Tone-44, Tone-52, Tone-53, and Tone-54.

P. scales	Tone-31 Tone-32	Tone-41, Tone-42, Tone-43, and Tone-44		Tone-52 Tone-53	Tone-54
Onset p.	100 to 120 Hz	130, 140 Hz	150, 160 Hz	170 to 190 Hz	190 to 210 Hz
Offset p.	60 to 90 Hz	60 to 130 Hz	60 to 150 Hz	90 to 120 Hz	130 to 150 Hz
Responses	low-falling	low-falling	ambiguous	high-falling	ambiguous

As indicated by Peng (1997), Jiang (2003), and Xu (2004), pitch variations may arise from an influence of various contextual factors, such as adjacent tones, prosodic position, and prosodic boundaries. For instance, a preceding tone's offset pitch varies with a following tone's onset pith, which gives rise to offset-pitch variations to different degrees. The common occurrence of pitch variations in connected speech may result in perceptual confusion, and then may lead to communication difficulties. This dissertation has found that lexical factors may exert a compensation influence on ambiguous variations. Lexical knowledge can then serve a remedy for potential cases of tonal confusion and for potential communication difficulties. However, tonal confusion is predicted to be more and more common in Hai-lu Hakka. As indicated by Yeh & Lin (2013, 2015) and Yeh & Lu (2013), Hai-lu Hakka has recently undergone language attrition to a large extent, especially among young generations, and language attrition exerts an impairing effect on young speakers' lexical knowledge. Since language attrition limits their lexical access, young speaker may not be able to exert a compensation effect from lexical knowledge on ambiguous variations. As a result, it is essential to pay special attention to the potential influence of pitch variations on tonal confusion between two falling tones in Hai-lu Hakka.

6.2.2.2 Tone sandhi and the patterns

Hai-lu Hakka participants' productivity results are shown below in terms of lexical types and sandhi types. As illustrated in Table 6.5 below, those stimuli made of frequent words are significantly more productive than those made of less frequent words and novel words, and those made of novel words are the least productive. The application rates of frequent-word and less-frequent-word stimuli are higher than a 90% and a 75% standard of phonological acquisition respectively, whereas those of novel-word stimuli are consistently lower than both standards. The findings suggest the crucial role played by lexical types in the application of Hai-lu Hakka tone sandhi. In addition, the productivity results indicate that those stimuli made of low-rising tone sandhi are more productive than those made of high-checked tone sandhi. Although the difference is significant, the application rates of both sandhi rules are lower than the 75% standard of phonological acquisition. The findings suggest that sandhi types play a crucial role in the application of Hai-lu Hakka tone sandhi, but the sandhi effect seems to be less essential than the lexical one. In general, the application rates of Hai-lu Hakka's sandhi rules vary with lexical types and sandhi types, and are more likely to be lexically bound or not phonologically productive.

Table 6.5 Hai-lu Hakka's productivity results in lexical types and sandhi types.

Factors	Results	Mean (average)	Max (highest)	Min (lowest)	Standard deviation
Lexical types	Frequent words (F)	93.41%	100.00%	77.08%	6.53%
	Less frequent (LF)	78.76%	93.75%	54.17%	11.16%
	Novel words (N)	34.61%	62.50%	10.42%	15.37%
Sandhi types	Low-rising (LR)	69.76%	87.50%	55.56%	9.44%
	High-checked (HC)	68.10%	93.06%	44.44%	12.36%

As mentioned in chapter 2 above, Hai-lu Hakka's lower application rates of tone sandhi, especially to novel words, may be correlated to the negative influence of various tone-sandhi exceptions or morpho-phonological patterns. As illustrated in Figure 6.1 below, two of Hai-lu Hakka's morpho-phonological patterns, (c) and (d), happen to be opposite to the two sandhi patterns, (a) and (b). The two morpho-phonological rules were previously proposed to be particular to double or triple adjectival reduplication (Gu 2005), but they are not limited to those morphological structures. They may also occur in non-final position for the emphasis on a specifier in each phrasal structure, and their occurrence may coincide with tone sandhi's contexts. Under the appropriate conditions, they can override the sandhi patterns, and turn sandhi tones Tone-22 and Tone-5 to rising tone and high-checked tone respectively, which happen to be tone sandhi's underlying forms. In other words, the two morpho-phonological rules and tone sandhi may conspire to make surface tones sound like underlying patterns. The surface patterns derived from the conspiracy may sound like exceptions to tone sandhi. The conspiracy and the exceptions lead to an opacity issue that a phonological rule's underlying and surface forms both occur in the same context. As argued by Zhang et al (2011), phonological opacity may account for lower application rates of Southern Min's tonal circle. The opacity issue can be argued to be responsible for Hai-lu Hakka's lower application rates of tone sandhi, even though Hai-lu Hakka's sandhi patterns are not as complex as Southern Min's tonal circle.

(a) Tone-13→ Tone-22 (b) Tone-5→ Tone2	(c) Non-rising tones→ Tone-13 (d) Tone-2→ Tone-5	(a)+(c) Tone-13→ Tone-13 (b)+(d) Tone-5→ Tone-5
tone sandhi rules	morpho-phonological rules (for an emphasis)	conspiracy or exceptions

Figure 6.1 Hai-lu Hakka's tone sandhi rules, morpho-phonological rules, and exceptions to tone sandhi.

The opacity issue may also account for the moderate effect of sandhi types. As mentioned above, although the application rates of low-rising tone sandhi are higher than those of high-checked tone sandhi, the application rates of sandhi rules are both lower than the 75% standard of phonological acquisition. The difference seems to be trivial comparing to Zhang et al's (2011) findings in Taiwan Southern Min. As argued by Zhang et al (2011), low-rising tone sandhi in Southern Min is the only phonologically transparent rule, which makes it less opaque phonologically than any other tone sandhi. The less phonologically opaque the tone sandhi is, the higher the productivity of the tone sandhi will be. However, Hai-lu Hakka's sandhi rules are both phonologically opaque due to the morpho-phonological alternations of emphasis rules. The influence of phonological opacity may reduce the difference induced by the sandhi effect. As a result, the moderate effect of sandhi types may be correlated to the opacity issue in Hai-lu Hakka. These findings imply a potential influence of tone-sandhi exceptions (induced by focus/emphasis rules) on the application of tone sandhi in Hai-lu Hakka. It is crucial to revisit those exceptions to tone sandhi by investigating how they are correlated to Hai-lu Hakka's morpho-phonological patterns and variability of tone sandhi in general.

To sum up, with respect to Hai-lu Hakka's tonal phonetics and phonology, the current findings imply the presence of tonal confusion for Hai-lu Hakka's contrast of two falling tones and phonological opacity for Hai-lu Hakka tone sandhi. Hai-lu Hakka's two falling tones tend to be less contrastive in connected speech, especially as contextual factors change falling tones' onset pitch to the ambiguous pitch register (i.e. mid-high, about 150 to 160 Hz). Hai-lu Hakka tone sandhi may not be as productive as assumed previously due to phonological opacity derived from various exceptions or focus/emphasis rules. Although these findings are generally similar to those demonstrated in Mandarin and Southern Min by Yeh & Lin (2011, 2012), Zhang & Lai (2010), and Zhang et al (2011), Hai-lu Hakka's falling tones and tone sandhi exhibit some different patterns. For instance, Hai-lu Hakka participants are less tolerable of high-falling variations, and the effect of sandhi types is moderate. These differences call for a further investigation of Hai-lu Hakka's tonal phonetics and phonology. Hai-lu Hakka has been less studied, and has recently been undergoing a dramatic process of language attrition. It may put Hai-lu Hakka in jeopardy by paralleling Hai-lu Hakka's tonal patterns to those in other Chinese languages/dialects directly without considering their differences. In order to protect this endangered language from language loss, it is crucial to focus on Hai-lu Hakka's own tonal patterns.

6.2.3 Implications for speech processing

As discussed above, the current findings not only imply the classification issue for different kinds of tonal modifications, but also point to the potential cases of tonal confusion and phonological opacity for Hai-lu Hakka falling tones and tone sandhi respectively. Although the current experiments were not set up specifically to evaluate competing processing models, the findings turn out to raise the level issue and the representation issue crucial to various proposals for speech processing.

Table 6.6 Comparisons of the functional model, the direct-realist model, and the exemplar model by the level issue and the representation issue.

	Functional model	Direct-realist model	Exemplar model
Proponents	Boersma (1998)	Best (1995), Fowler (1986)	Pierrehumbert (2001, 2003)
Similarities			
Processing mechanisms	sensor-motor and language systems	sensor-motor and language systems	language and sensor-motor systems
Processing strategies	mostly bottom-up and some top-down	mostly bottom-up and some top-down	mostly top-down and some bottom-up
The level issue			
Processing levels	distinctive and hierarchical	less distinctive, parallel	less distinctive, network
Relations of phonetics and phonology	interface	trivial interface or no interface	trivial interface or no interface
	stochastic	algorithmic	probabilistic
Variations	trivial, phonological	crucial, phonetic	crucial, multiple kinds
The representation issue			
Grammars and effects	perceptual, articulatory, & lexical influences	articulatory, and some lexical influences	lexical, and some perceptual & articulatory influences
Processing representations	abstract, perceptual generalizations	concrete, articulatory gestures	less abstract, phonetic and lexical details
	perceptually-driven	production-driven	lexically-based

6.2.3.1 The level issue

As illustrated in Table 6.6 above, the level issue includes three subset criteria: processing levels, relations between phonetics and phonology, and degrees of variations. The three criteria are relevant to the level issue in a conventional/derivational sense that phonetics and phonology are considered to be distinctive levels of linguistic derivations. Phonetics (i.e. a physical level) refers to a continuous and gradient process that leads to variations, whereas phonology (i.e. a psychological level) refers to a distinct and categorical process that transforms variations into invariance. Such a distinction regards variations as a crucial criterion for distinguishing the two processing levels. In general, the three criteria simply differentiate two kinds of models: a nearly-derivational approach and a non-derivational approach. The former refers to the functional model (Boersma 1998), and the latter refers to the direct-realist model (Best 1995, Fowler 1986) and the exemplar model (Pierrehumbert

2001, 2003).

The functional model (Boersma 1998:143) generally inherited a derivational (not generative) basis that assumes some transitions in between various levels of abstract representations (i.e. perceptual input, perceptual specification, and perceptual output). Although Boersma (1998) argued for a direct engagement of phonetic factors in phonological processes, phonetic variations were considered to be trivial unless they are responsible for different phonological patterns. As to the direct-realist model and the exemplar model, no transition is necessary for any distinct level of abstractions or there is simply no abstraction at all. Since phonetic and phonological factors were argued to be processed in an algorithmic/probabilistic manner, variations were considered to be common and crucial. In other words, the three models all seem to agree with the presence of variations of different kinds (at least phonetic and phonological), but they assumed a different role of phonetic variations in speech processing, i.e. trivial or crucial.

As demonstrated by Hai-lu Hakka's contrast of falling tones in Table 6.4 above, the findings suggest a crucial role of phonetic variations in speech processing. As to the results of those stimuli with ambiguous (i.e. in a mid-high register) onset pitch, they were consistently normalized as the same categories, such as Tone-41, Tone-42, Tone-43, and Tone-44, but they may sound distinct based on different phonetic details, especially those onset-pitch variations. These findings indicate that phonetic variations such as those onset-pitch and offset-pitch details may play a crucial role in speech processing, even if they are not responsible for a different phonological pattern. In other words, the current findings are more likely to support a model that dispenses with distinct levels of derivations, for instance, the direct-realist model and the exemplar model.

6.2.3.2 The representation issue

As illustrated in Table 6.6 above, the representation issue includes two subset criteria:

grammars and effects, and processing representations. The former indicates the origin of phonological grammars, and the latter explains how grammars are represented in a language system. As to the origin of grammars, the three models generally agreed that there are two kinds: one from sensor-motor tendencies (perception-driven or production-driven) and the other from paradigmatic preferences (lexically-driven). For instance, Boersma (1998) proposed perception, production, and internal lexicon as three components of phonological grammars. Best (1995) essentially argued for articulation-driven phonology, but also incorporated some lexical specifics into the direct-realist model. These proposals of grammars and effects seem to be less distinguishable among the three models. As to the representations of grammars, there seem to be more contrastive arguments for the three models. For instance, Boersma (1998) proposed perceptual generalizations as processing fundaments; Best (1995) considered grammars to be represented by articulatory gestures; and Pierrehumbert (2001, 2003) argued for lexical exemplars instead.

The current findings show (i) a more consistent pattern of lexical influences (than phonetic/phonological influences) and (ii) an asymmetry between perception and production patterns. These two particular findings are argued to favor a lexically-based approach to speech processing, i.e. the exemplar-based model, for three reasons. First, the perception-production asymmetry indicates that phonetic/phonological influences exhibit opposite patterns between perception and production processes. As to the perception-driven model and the production-driven model, i.e. the functional model and the direct-realist model, it seems paradoxical to derive opposite patterns from the same kind of representations. Since perception and production forces can be conflicting in some cases, it brings forth a fundamental issue as to why the different processes should be represented in the same manner. As to the lexically-based model, i.e. the exemplar-based model, it is less controversial to derive the opposite patterns from the influence of different exemplars or different phonetic/phonological attributes integrated in a given exemplar. Second, the fact that phonetic/phonological influences exhibit opposite patterns in different processes, but lexical influences do not, suggesting that lexical influences reveal a more consistent pattern across different processes than phonetic/phonological influences. The more consistent pattern makes it more likely for lexical attributes to be processed as fundamental representations. Third, phonetic/phonological factors tend to be distorted by contextual influences, and then phonetic ambiguity may arise to various degrees. As suggested by the interaction hypothesis, lexical factors may exert an additional influence to compensate for phonetic ambiguity induced by contextual factors. Since contextual influences are extensive and substantial in connected speech, the additional influence from lexical factors seems to be common across the board. In other words, lexical influences seem to be more crucial than phonetic/phonological ones in connected speech, which makes it more likely for lexical influences to be processed as fundamental representations. In general, these findings better support a processing model that considers lexical influences to be fundamental in speech processing. Although the three models all include lexical influences as well as perception and production forces, only the exemplar-based model considers lexical factors to be processing fundaments. As a result, these current findings may favor the exemplar-based model of speech processing.

To sum up, by contrasting the competing speech processing models in terms of the two controversial issues on processing levels and representations, the current findings suggest no transition from variations to invariance for processing levels, and a more fundamental role of lexical factors for processing representations, which seems to support Pierrehumbert's (2001, 2003) proposals as the more reasonable model for speech processing. Pierrehumbert's (2001, 2003) exemplar-based model proposed a stochastic relation between phonetic and phonological attributes, which dispenses with transitions and derivations from one to the other. These phonetic and phonological attributes derived from perception and production forces are stored as details/generalizations in a network system called exemplars. Since the exemplar is organized and processed on a basis of sounds/meanings, lexical influences seem to be more crucial to speech processing. The model seems able to account for the current findings, including a common occurrence of variations induced by various lexical and phonetic/phonological influences, a more consistent pattern of lexical influences, and the asymmetry between perception and production patterns. In other words, the current findings seem to favor Pierrehumbert's (2001, 2003) exemplar-based model.

6.3 Concluding remarks

This dissertation investigates speech processing of Hai-lu Hakka falling tones and tone sandhi by focusing on various lexical and phonetic/phonological influences and their patterns. The experimental results show that Hai-lu Hakka's contrast of falling tones varies with both lexical and phonetic/phonological factors, especially onset-pitch height, and Hai-lu Hakka's processing of tone sandhi also varies with both kinds of factors. The findings indicate that the contrast of two falling tones is not as distinctive as assumed previously, and the application of tone sandhi is not as productive as assumed previously either. Since both continuous and categorical variations play a crucial role in tonal processing, it is problematic to parallel different kinds of tonal modifications to different levels of linguistic derivations. The findings also suggest the presence of tonal confusion between two falling tones and the potential influence of phonological opacity on Hai-lu Hakka tone sandhi. In addition, the current findings demonstrate (i) a more consistent pattern of lexical influences and (ii) an asymmetry between perception and production patterns, suggesting a more crucial role of lexical influences in speech processing. Therefore, the current findings seem to favor an exemplar-based model that argues for non-derivational and lexically-driven account for speech processing.

This dissertation also reveals four methodological limitations that need to be carefully considered and further investigated by future studies. First, the two experiments set up a limited amount of stimuli, especially the experiment on tone sandhi. Since there seem to be a considerable amount of variations and exceptions to Hai-lu Hakka's tone sandhi, more stimuli are needed to better investigate and demonstrate these different tonal patterns. Second, Hai-lu Hakka was barely studied previously, and the descriptions and assumptions of its tonal patterns tend to be analogized to other Chinese languages/dialects without further evidence. This problem brings forth some methodological issues such as (i) the additional tonal training for the participants to compare Hai-lu Hakka's tones to Mandarin's tonal labels and (ii) frequency variables that were deduced from Hai-lu Hakka's dictionary entries rather than a valid speech corpus. Third, in the falling-tone experiment, more than half of the stimuli were perceived as ambiguous variations. These ambiguous variations not only sound like either falling tone (high or low), but also sound similar to high-level tone in some cases, as reported by some participants. In other words, pitch perturbations may also be responsible for tonal confusion between falling tones and level tones, as found by Yeh & Lin (2013, 2015) and Yeh & Lu (2013). Fourth, in the tone-sandhi experiment, the production results show that some participants produce some novel-word stimuli as actual words by repairing some phonotactic features/rules. For instance, novel-word stimuli [hu13] were sometimes produced as actual words [fu13]. Although the results do not contradict the current findings of the primacy of lexical influences, they seem to raise potential concerns on the experimental set up for the stimuli and the criteria for calculating production accuracy. These methodological issues need to be further considered in future studies.

In conclusion, despite some methodological limitations, the dissertation makes several contributions to Hai-lu Hakka tonal phonetics and phonology as well as the theory in general. First, relating phonetic modifications/processes to variations and phonological modifications/processes to invariance is called into questions. Second, the findings uncover specific issues such as tonal confusion and a perception-production asymmetry in Hai-lu Hakka tonal phonetics and phonology, supporting the crucial need to carefully examine a less-studied language like Hai-lu Hakka. Third, the findings indicate a more crucial role of lexical influences in tonal processing, suggesting that an exemplar-based processing model that argues for a non-derivational and lexically-driven account is a more reasonable approach to speech processing.

APPENDICES

APPENDIX A

Table 7.1 The stimulus list of the tonal and the lexical tasks in Chapter 4.

Trials	Stimuli	Tonal responses	Lexical responses
001/031/061/091	#1-100-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
002/032/062/092	#8-160-130	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
003/033/063/093	#3-120-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
004/034/064/094	#3-160-80	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
005/035/065/095	#6-170-110	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
006/036/066/096	#6-150-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
007/037/067/097	#10-210-150	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
008/038/068/098	#8-170-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
009/039/069/099	#3-140-80	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
010/040/070/100	#10-190-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
011/041/071/101	#1-120-60	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
012/042/072/102	#8-190-130	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
013/043/073/103	#2-160-70	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
014/044/074/104	#4-150-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
015/045/075/105	#9-160-140	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
016/046/076/106	#6-160-110	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
017/047/077/107	#4-160-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
018/048/078/108	#4-130-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
019/049/079/109	#1-160-60	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
020/050/080/110	#2-110-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
021/051/081/111	#10-160-150	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
022/052/082/112	#5-160-100	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
023/053/083/113	#7-160-120	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
024/054/084/114	#5-140-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
025/055/085/115	#5-160-100	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
026/056/086/116	#7-160-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
027/057/087/117	#7-180-120	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
028/058/088/118	#9-180-90	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
029/059/089/119	#9-200-140	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’
030/069/090/120	#2-130-70	Tone-53 or Tone-31	無知‘not know’ or 皇帝 ‘emperor’

APPENDIX B

Table 7.2 The stimulus list of the AXB discrimination task in Chapter 5.

Words	Rules	Tones	Vowels	Prosody	Trials
Frequent	Rising	Rising	High	High-falling	fu13-fu53, fu13-fu53,fu22-fu53/ fu13-fu53, fu22-fu53, fu22-fu53
				Low-falling	fu13-fu31 ,fu13-fu31, fu22-fu31/ fu13-fu31 ,fu22-fu31, fu22-fu31
				Low-rising	fu13-fu13 ,fu13-fu13, fu22-fu13/ fu13-fu13 ,fu22-fu13, fu22-fu13
			Low	High-falling	rha13-fu53, rha13-fu53, rha22-fu53/ rha13-fu53, rha22-fu53, rha22-fu53
				Low-falling	rha13-fu31, rha13-fu31, rha22-fu31/ rha13-fu31, rha22-fu31, rha22-fu31
				Low-rising	rha13-fu13, rha13-fu13, rha22-fu13/ rha13-fu13, rha22-fu13, rha22-fu13
		Level	High	High-falling	fu22-fu53, fu22-fu53, fu13-fu53/ fu22-fu53, fu13-fu53, fu13-fu53
				Low-falling	fu22-fu31 ,fu22-fu31, fu13-fu31/ fu22-fu31 ,fu13-fu31, fu13-fu31
				Low-rising	fu22-fu13 ,fu22-fu13, fu13-fu13/ fu22-fu13 ,fu13-fu13, fu13-fu13
			Low	High-falling	rha22-fu53, rha22-fu53, rha13-fu53/ rha22-fu53, rha13-fu53, rha13-fu53
				Low-falling	rha22-fu31, rha22-fu31, rha13-fu31/ rha22-fu31, rha13-fu31, rha13-fu31
				Low-rising	rha22-fu13, rha22-fu13, rha13-fu13/ rha22-fu13, rha13-fu13, rha13-fu13
	Checked	High	High	High-falling	shuk5-fu53, shuk5-fu53, shuk2-fu53/ shuk5-fu53, shuk2-fu53, shuk2-fu53
				Low-falling	shuk5-fu31, shuk5-fu31, shuk2-fu31/ shuk5-fu31, shuk2-fu31, shuk2-fu31
				Low-rising	shuk5-fu13, shuk5-fu13, shuk2-fu13/ shuk5-fu13, shuk2-fu13, shuk2-fu13
			Low	High-falling	tshap5-fu53, tshap5-fu53, tshap2-fu53/ tshap5-fu53, tshap2-fu53, tshap2-fu53
				Low-falling	tshap5-fu31, tshap5-fu31, tshap2-fu31/ tshap5-fu31, tshap2-fu31, tshap2-fu31
				Low-rising	tshap5-fu13, tshap5-fu13, tshap2-fu13/ tshap5-fu13, tshap2-fu13, tshap2-fu13

Table 7.2 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials
Frequent	Checked	Low	High	High-falling	shuk2-fu53, shuk2-fu53, shuk5-fu53/ shuk2-fu53, shuk5-fu53, shuk5-fu53
				Low-falling	shuk2-fu31, shuk2-fu31, shuk5-fu31/ shuk2-fu31, shuk5-fu31, shuk5-fu31
				Low-rising	shuk2-fu13, shuk2-fu13, shuk5-fu13/ shuk2-fu13, shuk5-fu13, shuk5-fu13
			Low	High-falling	tshap2-fu53, tshap2-fu53, tshap5-fu53/ tshap2-fu53, tshap5-fu53, tshap5-fu53
				Low-falling	tshap2-fu31, tshap2-fu31, tshap5-fu31/ tshap2-fu31, tshap5-fu31, tshap5-fu31
				Low-rising	tshap2-fu13, tshap2-fu13, tshap5-fu13/ tshap2-fu13, tshap5-fu13, tshap5-fu13
Less Frequent	Rising	Rising	High	High-falling	vu13-fu53, vu13-fu53, vu22-fu53/ vu13-fu53, vu22-fu53, vu22-fu53
				Low-falling	vu13-fu31, vu13-fu31, vu22-fu31/ vu13-fu31, vu22-fu31, vu22-fu31
				Low-rising	vu13-fu13, vu13-fu13, vu22-fu13/ vu13-fu13, vu22-fu13, vu22-fu13
			Low	High-falling	sha13-fu53, sha13-fu53, sha22-fu53/ sha13-fu53, sha22-fu53, sha22-fu53
				Low-falling	sha13-fu31, sha13-fu31, sha22-fu31/ sha13-fu31, sha22-fu31, sha22-fu31
				Low-rising	sha13-fu13, sha13-fu13, sha22-fu13/ sha13-fu13, sha22-fu13, sha22-fu13
		Level	High	High-falling	vu22-fu53, vu22-fu53, vu13-fu53/ vu22-fu53, vu13-fu53, vu13-fu53
				Low-falling	vu22-fu31, vu22-fu31, vu13-fu31/ vu22-fu31, vu13-fu31, vu13-fu31
				Low-rising	vu22-fu13, vu22-fu13, vu13-fu13/ vu22-fu13, vu13-fu13, vu13-fu13
			Low	High-falling	sha22-fu53, sha22-fu53, sha13-fu53/ sha22-fu53, sha13-fu53, sha13-fu53
				Low-falling	sha22-fu31, sha22-fu31, sha13-fu31/ sha22-fu31, sha13-fu31, sha13-fu31
				Low-rising	sha22-fu13, sha22-fu13, sha13-fu13/ sha22-fu13, sha13-fu13, sha13-fu13

Table 7.2 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials
Less Frequent	Checked	High	High	High-falling	fuk5-fu53, fuk5-fu53, fuk2-fu53/ fuk5-fu53, fuk5-fu53, fuk2-fu53
				Low-falling	fuk5-fu31, fuk5-fu31, fuk2-fu31/ fuk5-fu31, fuk5-fu31, fuk2-fu31
				Low-rising	fuk5-fu13, fuk5-fu13, fuk2-fu13/ fuk5-fu13, fuk5-fu13, fuk2-fu13
			Low	High-falling	sap5-fu53, sap5-fu53, sap2-fu53/ sap5-fu53, sap2-fu53, sap2-fu53
				Low-falling	sap5-fu31, sap5-fu31, sap2-fu31/ sap5-fu31, sap2-fu31, sap2-fu31
				Low-rising	sap5-fu13, sap5-fu13, sap2-fu13/ sap5-fu13, sap2-fu13, sap2-fu13
		Low	High	High-falling	fuk2-fu53, fuk2-fu53, fuk5-fu53/ fuk2-fu53, fuk5-fu53, fuk5-fu53
				Low-falling	fuk2-fu31, fuk2-fu31, fuk5-fu31/ fuk2-fu31, fuk5-fu31, fuk5-fu31
				Low-rising	fuk2-fu13, fuk2-fu13, fuk5-fu13/ fuk2-fu13, fuk5-fu13, fuk5-fu13
			Low	High-falling	sap2-fu53, sap2-fu53, sap5-fu53/ sap2-fu53, sap5-fu53, sap5-fu53
				Low-falling	sap2-fu31, sap2-fu31, sap5-fu31/ sap2-fu31, sap5-fu31, sap5-fu31
				Low-rising	sap2-fu13, sap2-fu13, sap5-fu13/ sap2-fu13, sap5-fu13, sap5-fu13
Non-words	Rising	Rising	High	High-falling	hu13-fu53, hu13-fu53, hu22-fu53/ hu13-fu53, hu22-fu53, hu22-fu53
				Low-falling	hu13-fu31, hu13-fu31, hu22-fu31/ hu13-fu31, hu22-fu31, hu22-fu31
				Low-rising	hu13-fu13, hu13-fu13, hu22-fu13/ hu13-fu13, hu22-fu13, hu22-fu13
			Low	High-falling	zha13-fu53, zha13-fu53, zha22-fu53/ zha13-fu53, zha22-fu53, zha22-fu53
				Low-falling	zha13-fu31, zha13-fu31, zha22-fu31/ zha13-fu31, zha22-fu31, zha22-fu31
				Low-rising	zha13-fu13, zha13-fu13, zha22-fu13/ zha13-fu13, zha22-fu13, zha22-fu13

Table 7.2 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials
Non-words	Rising	Level	High	High-falling	hu22-fu53, hu22-fu53, hu13-fu53/ hu22-fu53, hu13-fu53, hu13-fu53
				Low-falling	hu22-fu31, hu22-fu31, hu13-fu31/ hu22-fu31, hu13-fu31, hu13-fu31
				Low-rising	hu22-fu13, hu22-fu13, hu13-fu13/ hu22-fu13, hu13-fu13, hu13-fu13
			Low	High-falling	zha22-fu53, zha22-fu53, zha13-fu53/ zha22-fu53, zha13-fu53, zha13-fu53
				Low-falling	zha22-fu31, zha22-fu31, zha13-fu31/ zha22-fu31, zha13-fu31, zha13-fu31
				Low-rising	zha22-fu13, zha22-fu13, zha13-fu13/ zha22-fu13, zha13-fu13, zha13-fu13
	Checked	High	High	High-falling	huk5-fu53, huk5-fu53, huk2-fu53/ huk5-fu53, huk2-fu53, huk2-fu53
				Low-falling	huk5-fu31, huk5-fu31, huk2-fu31/ huk5-fu31, huk2-fu31, huk2-fu31
				Low-rising	huk5-fu13, huk5-fu13, huk2-fu13/ huk5-fu13, huk2-fu13, huk2-fu13
			Low	High-falling	vap5-fu53, vap5-fu53, vap2-fu53/ vap5-fu53, vap2-fu53, vap2-fu53
				Low-falling	vap5-fu31, vap5-fu31, vap2-fu31/ vap5-fu31, vap2-fu31, vap2-fu31
				Low-rising	vap5-fu13, vap5-fu13, vap2-fu13/ vap5-fu13, vap2-fu13, vap2-fu13
		Low	High	High-falling	huk2-fu53, huk2-fu53, huk5-fu53/ huk2-fu53, huk5-fu53, huk5-fu53
				Low-falling	huk2-fu31, huk2-fu31, huk5-fu31/ huk2-fu31, huk5-fu31, huk5-fu31
				Low-rising	huk2-fu13, huk2-fu13, huk5-fu13/ huk2-fu13, huk5-fu13, huk5-fu13
			Low	High-falling	vap2-fu53, vap2-fu53, vap5-fu53/ vap2-fu53, vap5-fu53, vap5-fu53
				Low-falling	vap2-fu31, vap2-fu31, vap5-fu31/ vap2-fu31, vap5-fu31, vap5-fu31
				Low-rising	vap2-fu13, vap2-fu13, vap5-fu13/ vap2-fu13, vap5-fu13, vap5-fu13

APPENDIX C

Table 7.3 The stimulus list in the identification (IDN) and lexical tasks (LEX) in Chapter 5.

Words	Rules	Tones	Vowels	Prosody	Trials	Responses (IDN or LEX)
Frequent	Rising	Rising	High	High-falling	fu13-fu53	Tone-22/13 or 褲/苦
				Low-falling	fu13-fu31	Tone-22/13 or 褲/苦
				Low-rising	fu13-fu13	Tone-22/13 or 褲/苦
			Low	High-falling	rha13-fu53	Tone-22/13 or 抓/夜
				Low-falling	rha13-fu31	Tone-22/13 or 抓/夜
				Low-rising	rha13-fu13	Tone-22/13 or 抓/夜
		Level	High	High-falling	fu22-fu53	Tone-22/13 or 褲/苦
				Low-falling	fu22-fu31	Tone-22/13 or 褲/苦
				Low-rising	fu22-fu13	Tone-22/13 or 褲/苦
			Low	High-falling	rha22-fu53	Tone-22/13 or 抓/夜
				Low-falling	rha22-fu31	Tone-22/13 or 抓/夜
				Low-rising	rha22-fu13	Tone-22/13 or 抓/夜
	Checked	High	High	High-falling	shuk5-fu53	Tone-5/2 or 叔/熟
				Low-falling	shuk5-fu31	Tone-5/2 or 叔/熟
				Low-rising	shuk5-fu13	Tone-5/2 or 叔/熟
			Low	High-falling	tshap5-fu53	Tone-5/2 or 插/雜
				Low-falling	tshap5-fu31	Tone-5/2 or 插/雜
				Low-rising	tshap5-fu13	Tone-5/2 or 插/雜
		Low	High	High-falling	shuk2-fu53	Tone-5/2 or 叔/熟
				Low-falling	shuk2-fu31	Tone-5/2 or 叔/熟
				Low-rising	shuk2-fu13	Tone-5/2 or 叔/熟
			Low	High-falling	tshap2-fu53	Tone-5/2 or 插/雜
				Low-falling	tshap2-fu31	Tone-5/2 or 插/雜
				Low-rising	tshap2-fu13	Tone-5/2 or 插/雜

Table 7.3 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials	Responses (IDN or LEX)
Less Frequent	Rising	Rising	High	High-falling	vu13-fu53	Tone-22/13 or 武/芋
				Low-falling	vu13-fu31	Tone-22/13 or 武/芋
				Low-rising	vu13-fu13	Tone-22/13 or 武/芋
			Low	High-falling	sha13-fu53	Tone-22/13 or 捨/社
				Low-falling	sha13-fu31	Tone-22/13 or 捨/社
				Low-rising	sha13-fu13	Tone-22/13 or 捨/社
		Level	High	High-falling	vu22-fu53	Tone-22/13 or 武/芋
				Low-falling	vu22-fu31	Tone-22/13 or 武/芋
				Low-rising	vu22-fu13	Tone-22/13 or 武/芋
			Low	High-falling	sha22-fu53	Tone-22/13 or 捨/社
				Low-falling	sha22-fu31	Tone-22/13 or 捨/社
				Low-rising	sha22-fu13	Tone-22/13 or 捨/社
Less Frequent	Checked	High	High	High-falling	fuk5-fu53	Tone-5/2 or 福/服
				Low-falling	fuk5-fu31	Tone-5/2 or 福/服
				Low-rising	fuk5-fu13	Tone-5/2 or 福/服
			Low	High-falling	sap5-fu53	Tone-5/2 or 圾/煠
				Low-falling	sap5-fu31	Tone-5/2 or 圾/煠
				Low-rising	sap5-fu13	Tone-5/2 or 圾/煠
		Low	High	High-falling	fuk2-fu53	Tone-5/2 or 福/服
				Low-falling	fuk2-fu31	Tone-5/2 or 福/服
				Low-rising	fuk2-fu13	Tone-5/2 or 福/服
			Low	High-falling	sap2-fu53	Tone-5/2 or 圾/煠
				Low-falling	sap2-fu31	Tone-5/2 or 圾/煠
				Low-rising	sap2-fu13	Tone-5/2 or 圾/煠

Table 7.3 (cont’d).

Words	Rules	Tones	Vowels	Prosody	Trials	Responses (IDN or LEX)
Non-words	Rising	Rising	High	High-falling	hu13-fu53	Tone-22/13 or ⿰虫戔/⿰虫寧
				Low-falling	hu13-fu31	Tone-22/13 or ⿰虫戔/⿰虫寧
				Low-rising	hu13-fu13	Tone-22/13 or ⿰虫戔/⿰虫寧
			Low	High-falling	zha13-fu53	Tone-22/13 or ⿰魚戔/⿰魚彖
				Low-falling	zha13-fu31	Tone-22/13 or ⿰魚戔/⿰魚彖
				Low-rising	zha13-fu13	Tone-22/13 or ⿰魚戔/⿰魚彖
		Level	High	High-falling	hu22-fu53	Tone-22/13 or ⿰虫戔/⿰虫寧
				Low-falling	hu22-fu31	Tone-22/13 or ⿰虫戔/⿰虫寧
				Low-rising	hu22-fu13	Tone-22/13 or ⿰虫戔/⿰虫寧
			Low	High-falling	zha22-fu53	Tone-22/13 or ⿰魚戔/⿰魚彖
				Low-falling	zha22-fu31	Tone-22/13 or ⿰魚戔/⿰魚彖
				Low-rising	zha22-fu13	Tone-22/13 or ⿰魚戔/⿰魚彖
	Checked	High	High	High-falling	huk5-fu53	Tone-5/2 or ⿱戔鳥/鶩
				Low-falling	huk5-fu31	Tone-5/2 or ⿱戔鳥/鶩
				Low-rising	huk5-fu13	Tone-5/2 or ⿱戔鳥/鶩
			Low	High-falling	vap5-fu53	Tone-5/2 or ⿰犭蚩/⿰犭差
				Low-falling	vap5-fu31	Tone-5/2 or ⿰犭蚩/⿰犭差
				Low-rising	vap5-fu13	Tone-5/2 or ⿰犭蚩/⿰犭差
		Low	High	High-falling	huk2-fu53	Tone-5/2 or ⿱戔鳥/鶩
				Low-falling	huk2-fu31	Tone-5/2 or ⿱戔鳥/鶩
				Low-rising	huk2-fu13	Tone-5/2 or ⿱戔鳥/鶩
			Low	High-falling	vap2-fu53	Tone-5/2 or ⿰犭蚩/⿰犭差
				Low-falling	vap2-fu31	Tone-5/2 or ⿰犭蚩/⿰犭差
				Low-rising	vap2-fu13	Tone-5/2 or ⿰犭蚩/⿰犭差

APPENDIX D

Table 7.4 The stimulus list of the production task in Chapter 5.

Words	Rules	Tones	Vowels	Prosody	Trials
Frequent	Rising	Rising	High	High-falling	手肘
Frequent	Rising	Rising	High	Low-falling	手帕
Frequent	Rising	Rising	High	Low-rising	手指
Frequent	Rising	Rising	Low	High-falling	打斷
Frequent	Rising	Rising	Low	Low-falling	打扮
Frequent	Rising	Rising	Low	Low-rising	打賭
Frequent	Rising	Level	High	High-falling	樹下
Frequent	Rising	Level	High	Low-falling	樹奶
Frequent	Rising	Level	High	Low-rising	樹頂
Frequent	Rising	Level	Low	High-falling	夜班
Frequent	Rising	Level	Low	Low-falling	夜市
Frequent	Rising	Level	Low	Low-rising	夜景
Frequent	Checked	High	High	High-falling	屋尾
Frequent	Checked	High	High	Low-falling	屋稅
Frequent	Checked	High	High	Low-rising	屋頂
Frequent	Checked	High	Low	High-falling	摘花
Frequent	Checked	High	Low	Low-falling	摘菜
Frequent	Checked	High	Low	Low-rising	摘草
Frequent	Checked	Low	High	High-falling	佛經
Frequent	Checked	Low	High	Low-falling	佛教
Frequent	Checked	Low	High	Low-rising	佛祖
Frequent	Checked	Low	Low	High-falling	白毛
Frequent	Checked	Low	Low	Low-falling	白菜
Frequent	Checked	Low	Low	Low-rising	白點

Table 7.4 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials
Less Frequent	Rising	Rising	High	High-falling	祖先
				Low-falling	祖墓
				Low-rising	祖產
			Low	High-falling	假心
				Low-falling	假貨
				Low-rising	假死
		Level	High	High-falling	芋(頭)冰
				Low-falling	芋奶
				Low-rising	芋餅
			Low	High-falling	社里
				Low-falling	社會
				Low-rising	社長
Less Frequent	Checked	High	High	High-falling	穀倉
				Low-falling	穀串
				Low-rising	穀米
			Low	High-falling	隔間
				Low-falling	隔暗
				Low-rising	隔水
		Low	High	High-falling	複加
				Low-falling	複印
				Low-rising	複診
			Low	High-falling	麥膏
				Low-falling	麥穗
				Low-rising	麥片
Non-words	Rising	Rising	High	High-falling	**hu13**-fu53
				Low-falling	**hu13**-pa31
				Low-rising	**hu13**-mi13
			Low	High-falling	**ha13**-ton53
				Low-falling	**ha13**-mu31
				Low-rising	**ha13**-fu13
		Level	High	High-falling	**hu22**-mo53
				Low-falling	**hu22**-zo31
				Low-rising	**hu22**-du13
			Low	High-falling	**sa22**-san53
				Low-falling	**sa22**-sui31
				Low-rising	**sa22**-dang13

Table 7.4 (cont'd).

Words	Rules	Tones	Vowels	Prosody	Trials
Non-words	Checked	High	High	High-falling	**huk5**-li53
				Low-falling	**huk5**-am31
				Low-rising	**huk5**-fu13
			Low	High-falling	**fak5**-sian53
				Low-falling	**fak5**-ji31
				Low-rising	**fak5**-mi13
		Low	High	High-falling	**huk2**-san53
				Low-falling	**huk2**-fu31
				Low-rising	**huk2**-shui13
			Low	High-falling	**k^{h}ak2**-sim53
				Low-falling	**k^{h}ak2**-zo31
				Low-rising	**k^{h}ak2**-du13

Words		Rules	Tones	Vowels	Prosody	Trials
Control Trials (Non-Sandhi)	Frequent	Rising	High	High	Word-final	右手
				Low	Word-final	追打
			Low	High	Word-final	榕樹
				Low	Word-final	今夜
		Checked	High	High	Word-final	新屋
				Low	Word-final	未摘
			Low	High	Word-final	神佛
				Low	Word-final	黑白
	Less Frequent	Rising	High	High	Word-final	媽祖
				Low	Word-final	做假
			Low	High	Word-final	山芋
				Low	Word-final	旅社
		Checked	High	High	Word-final	五穀
				Low	Word-final	分隔
			Low	High	Word-final	繁複
				Low	Word-final	大麥
	Non-words	Rising	High	High	Word-final	fu31-**hu13**
				Low	Word-final	sian53-**ha13**
			Low	High	Word-final	fu53-**hu22**
				Low	Word-final	go53-**sa22**
		Checked	High	High	Word-final	beng53-**huk5**
				Low	Word-final	ging53-**fak5**
			Low	High	Word-final	mang55-**huk2**
				Low	Word-final	fan55-**k^{h}ak2**

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