國立交通大學

外國語文學系外國文學與語言學碩士班

碩士論文

中文聲調協同發音之重探

Revisiting Mandarin Tonal Coarticulation

研 究 生：黃慧婷

指導教授：賴郁雯　教授

中華民國一百零二年七月

中文聲調協同發音之重探
Revisting Mandarin Tonal Coarticulation

研究生：黃慧婷　　Student：Hui-Ting Huang

指導教授：賴郁雯　　Advisor：Yuwen Lai

國立交通大學

外國語文學系外國文學與語言學碩士班

碩士論文

A Thesis
Submitted to Department of Foreign Languages and Literatures
College of Humanities and Social Sciences
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Master
in

Foreign Languages and Literatures

July 2013

Hsinchu, Taiwan, Republic of China

中華民國一百零二年七月

中文聲調協同發音之重探

學生：黃慧婷　　　　指導教授：賴郁雯

國立交通大學外國語文學系外國文學與語言學碩士班

摘　　要

本篇論文主要探討中文聲調協同發音之現象。文中包含兩大主旨: (1) 重新檢視文獻中對於中文聲調協同發音不一致的結果。(2)檢視中介子音內含的不同的發音方式是否對中文聲調協同發音產生影響。為了解決文獻中許多不一致的結果，本篇論文所採用的實驗設計極為縝密，包含了較密集的基頻測量點以及精確的基頻差異計算。聲調協同發音將透過順向作用及逆向作用這兩種方向來檢視。實驗結果顯示，無論是在影響範圍或影響程度上，順向作用都較估優勢。在中文的聲調協同發音中，最容易受順向作用影響的聲調是四聲，而最容易受逆向作用影響的則是二聲。聲調協同發音的觸發並非因為某種特定的相鄰聲調而產生，而是因為相鄰聲調中最靠近影響目標的基頻數值高低所造成的。中文的順向作用皆為同化現象，逆向作用中卻包含了異化現象。本文另外也檢視了中介子音的發音方式對聲調的影響。結果顯示，屬於同類型(響音類或鈍音類)的子音，彼此之間對聲調的影響較為相似。

關鍵字: 聲調，協同發音，基頻，順向作用，逆向作用

Revisitiing Mandarin Tonal Coarticulation

student：Hui-Ting Huang Advisors：Dr.Yuwen Lai

Graduate Institute of Foreign Literatures & Linguistics
National Chiao Tung University

ABSTRACT

The present study is about tonal coarticulation in Mandarin. Two major aims are included: (1) To re-examine some conflicting results in Mandarin tonal coarticulation from previous studies (2) To exemplify whether intervening consonants with different manners of articulation affect tonal coarticulation. In order to resolve the inconsistency from previous results, in this study a rigorous experimental design was developed with detailed measurements and precise computation of F_0 variation. Tonal coarticulation is examined through two directional effects: carryover effect and anticipatory effect. The results show that carryover effect is more prevailing than anticipatory effect on both temporal extent and magnitude. Tone 4 is more susceptible to carryover effect and Tone 2 is to anticipatory effect. Triggers in tonal coarticulation must be defined by specific tonal values adjacent to target tones rather than the entire neighboring tones. All carryover effects are assimilation while anticipatory effects contain dissimilation. The present study also investigates the influence on tones from different manners of articulation of consonants. Sonorant consonants like liquid and nasal have similar F_0 variation on tones, and the effects of obstruent consonants such as stop, fricative and affricate are also close to each other.

Keywords: tone, coarticulation, Fundamental Frequency (F_0), carryover effect, anticipatory effect

誌謝

謝謝身邊所有的人，論文終於完成了。碩班三年，也在這一刻劃下句點了。

謝謝這三年來在交大外文所裡每一位教過我的老師，以及每一堂我所上過的課。如果不是因為這些課的訓練及累積，最後一年在進行所有跟論文相關的研究時，也許會走得更艱辛。也要謝謝以前一起待在研究室的學長姐們，有前人的經驗傳承，這三年才可以順利的前進，少走很多的冤枉路。

能走到這一步，當然要謝謝我的指導教授賴郁雯老師。寫論文實在不是一件容易的事，從大海撈針般的尋找題目、擬定論文方向、實驗設計和執行、一直到最後把論文有條理地寫出來，都需要很多的摸索和學習。謝謝指導教授在這一路上所給予的提點和訓練，讓我最終能夠完成這本論文。另外也要感謝曾經在資格考和學位考試時擔任口委的盧郁安老師、劉秀雪老師和張詠翔老師。口委老師們對我的問題與論文的不足都能夠給予我明確的建議、或是提供我其他值得參考的資料，讓我的論文內容可以更加完善。而且很幸運的，無論是資格考或是學位考試時，口委老師們對我都很親切，讓我在論文的這兩大關卡中，也能夠少面對一些無形的壓力。

能夠完成三年的研究所學業，也要謝謝在這段期間內擔任過系所助理的雅玲、旅櫻、佩吟和思怡。三年來，無論是在課務或是其他的工讀機會上，總是受到助理很多很多的關心與照顧，也因為接觸的機會很多，漸漸的都跟助理們變成可以談心的好朋友。在系辦閒聊打屁的時光不僅很愉快，更重要的是，它為我在系館的生活增添了許多樂趣和休閒成分。

最後，最想感謝的是這三年來一直在身邊的朋友們。包括所上的朋友、大學時期的死黨，還有社團的夥伴，因為有這些人，這三年過得一點也不孤單。做研究和寫論文的時期其實是很煩躁又很鬱悶的，但是因為有這些人陪著，大家一起在各自的領域努力、一起放鬆玩耍、再一起找回繼續前進的動力。因為有這樣的相互扶持，我們才能一路走到現在。

謝謝這一路上所有的人!謝謝!

Content

Figure Content

Table Content

1. Introduction

“Coarticulation, refers to the phenomenon that speech sounds are usually produced with some articulatory overlap. That is, in the production of a sequence of sounds, the articulatory maneuvers for one sound typically overlap a preceding or following sound.” (Reetz & Jongman, 2009) Coarticulation is not limited to segments, but also between segments and suprasegmental cues. Each of the phenomena will be thoroughly reviewed.

In tonal languages, adjacent tones will affect each other as well. Such influence is known as ‘tonal coarticulation.’ Tonal coarticulation has been examined in tonal languages such as Vietnamese (Han & Kim, 1974; Brunelle, 2009), Thai (Gandour et al., 1992b,1992c &1994; Potisuk et al., 1996) and Mandarin Chinese (Shen, 1990; Lin & Yan, 1992; Xu, 1993, 1994 & 1997). As Shen (1990), Lin & Yan (1992) and Xu (1993, 1994 & 1997) have examined the tonal coarticulation in Mandarin, some important issues was proposed such as the directionality of influence, the extent being affected and the tones related to greater coarticulatory effects. However, some of their findings are controversial to each other. These researches will be reviewed in detail in the following chapter.

The main purpose of the present study is to resolve those confounding results in previous studies through examining the F_0 variation resulted from tonal coarticulation. The main issues addressed here include:

1) The affected extent and magnitude of two directions in tonal coarticulation
2) The target and the possible trigger of two directions in tonal coarticulation
3) The influence from intervening obstruents on tonal coarticulation

These research goals will be reached by conducting two experiments – 1) in the first experiment, tri-syllabic stimuli were adopted to exemplify the effects from both directions on the middle target tone. 2) In the second experiment, disyllabic words intervened by consonants with different manners of articulation (MOA) were chosen to investigate the MOA influence on adjacent tones.

In order to get clear pictures on the inconsistency from previous studies, the present study was designed in a more refined way that contains following advantages:

- Careful control of the stimuli to exemplify coarticulatory effects from two directions
- A detailed measurements on F_0 contour of each target tone
- A precise comparison to define the F_0 variation caused by tonal coarticulation

More details of this study and the discussion on results from both experiments will be addressed accordingly in following chapters.

2. Literature Review

Studies related to coarticulation are reviewed in this chapter. The definition of coarticulation is interpreted in section 2.1 with classification of coarticulation illustrated with examples. Section 2.2 addresses tonal coarticulation in tonal languages such as Vietnamese, Thai and Mandarin Chinese. Section 2.3 reviews the relationship between consonantal qualities and coarticulation. A brief summary of coarticulation is given in section 2.4. Finally, section 2.5 sketches the frame of the present research.

2.1 Coarticulation

As mentioned in the first chapter, it is widely known that speech sounds rarely occur in isolation but are articulated in a continuous fashion. Part of the reason why neighboring sounds affect each other is due to fast speaking rate. In English, normal conversation is produced at a rate of 10 to 20 segments per second. That is, a segment can be pronounced in 100 milliseconds on the average. However, it is impossible for articulators to reach the precise positions of each segment and fully produce all properties in such a short time. Consequently, the articulators might move only half way toward the target position, or still reach the target with longer time by overlapping the duration of other sounds (MacKay, 1987; Singh & Singh, 2006). As a result, in connected speech, some sounds or segments cannot completely reach their target values and some will be altered due to the features or characteristics spreading from their neighboring sounds or segments. The process that adjacent segments affect each other in speech is called ‘coarticulation’ (Daniloff & Hammarberg, 1973; MacKay, 1987; Ladefoged, 1993, 2001; Laver, 1994; Ball & Rahilly, 1999; Kühnert & Nolan, 1999; Roach, 2001; Kent & Read, 2002; Ashby & Maidment, 2005;

Flemming, 2008; Reetz & Jongman, 2009).

2.1.1 Classification

Coarticulation could be defined in several different ways. Roach (2001) proposed that there are three types of coarticulation based upon what elements get varied: voice, place and manner of articulation. In terms of “voice”, a voiced segment might become voiceless because of its adjacent voiceless segment, and vice versa. In other cases, the places and manner of neighboring segments could affect each other . He mentioned in English if the word ‘that’ /ðæ t/ is followed by ‘boy’ /bɔɪ/, it will pronounced as /ðæ p/ but it will become /ðæ k/ when followed by ‘girl’ /ɡɜːl/. In this example, the word-final alveolar consonant /t/ is altered to have the same place of articulation with its following consonant. The coarticulation of manner could be found in cases such as in the sentence ‘Get some of that soap’, the pronunciation of ‘Get some’ becomes /ges sʌm/ instead of the underlying /get sʌm/. Roach’s (2001) classification is explicit and widely accepted, however limited to the coarticulation occur only in segments but not suprasgmental features.

Ball & Rahilly (1999) proposed to classify coarticulation as 1) influential directions, 2) affected aspects of articulation, and 3) the extent changed by coarticulation. In terms of influential directions, there are carryover and anticipatory. Carryover coarticulation happens when a previous segment affects its following segment. Anticipatory coarticulation, on the opposite, refers to the effect that a following segment influences its preceding segment.

The coarticulation defined through affected aspects of articulation contains all types of different articulators varied due to coarticulation. Vocal organs like lips, tongue, velum and larynx are possibly affected due to coarticulation. To be more specific, the tongue variation can be further separated into actions of the tip, the blade and the dorsum which are all possible to be affected. The variation of velum also comprises three distinctions between oral, nasal and nasalized aspects. And for variation on larynx, types of phonatory activity and its time in articulation are contained as well.

Lastly, they categorize coarticulation in terms of their functions, which refers to the changed element (an allophone or a phoneme) and the extent being coarticulated. They claimed the coarticulation contains only one varied allophone is ‘allophonic similitude’; and the type containing one varied phoneme is called ‘‘phonemic assimilation’. However, coarticulation is not restricted to two adjacent segment but may spread across several segments, the whole word or even a string of words. Therefore, they further defined the term ‘allophonic feature spread’ for the type of coarticulation in which only allophonical segments changed, while ‘segment harmony’ for the type including a series of altered phonemes. This view is controversial for most researchers (MacKay, 1987; Singh & Singh, 2006) defined ‘coarticulation’ as minor phonetic variations, which only contain changes in the allophonic situations. Nonetheless, their first two classifications (directionality and articulatory aspects) are widely accepted by many researchers. The issue of directionality is most relevant to the present study and will be illustrated further with specific examples.

Carryover coarticulation

Carryover coarticulation happens when the preceding segment influences following segment(s). In other words, the feature/property of the earlier segment will prolong into the later-occurring segment(s). Thus the term ‘carryover’ are also known as ‘perseverative’, ‘retentive’, ‘progressive’ or ‘left-to-right’. (Roach, 2001; Ball & Rahilly, 1999; Reetz & Jongman, 2009; Kent & Read, 2002; Laver, 1994)

The spread of nasalization progressively can be seen as an example of carryover coarticulation. In the word ‘no’ /nõ/, the vocalic segment is nasalized due to the influence of its previous nasal element (Kent & Read, 2002). The pronunciation of plural suffix in English also provides a great example of voicing coarticulation. The plural form of ‘cat’ /kæ t/ is ‘cats’ /kæ ts/, in which the pronunciation of ‘-s’ remains as voiceless /s/, while the same plural form of ‘dog’ /dɒɡ/ (in British pronunciation) will be ‘dogs’ /dɒgz/, with the final segment changed into a voiced /z/ because of its preceding voiced segment /ɡ/ (Roach, 2001). The variation of the place of articulators can also result from carryover effect. In the word ‘eke’ /ik̟/, the articulation of /k̟/ is further forward because of the influence of its preceding front vowel /i/, while the articulation of /k̠/ in the RP pronunciation of ‘arc’ /ɑk̠/ is comparatively back due to the influence of its preceding back vowel /ɑ/ (Laver, 1994).

Anticipatory coarticulation

Opposite to the carryover effect, in anticipatory coarticulation, the preceding segment(s) take on the properties from its following segment. That is, the feature/property of the latter-occurring segment is produced in advance during the earlier segment(s). The effect is also known as ‘regressive’ and ‘right-to-left’ coarticulation.(Roach, 2001; Ball & Rahilly, 1999; Reetz & Jongman, 2009; Kent & Read, 2002; Laver, 1994)

Vowel nasalization provides a good example of anticipatory coarticulation. In the common be-verb ‘am’ /æ̃m/ the vowel /æ / becomes nasalized because it is directly followed by a nasal consonant and thus gets influenced (Kent & Read, 2002). The word ‘zoom’ /z^{w}um/ is also an example of anticipatory coarticulation. In this case, the lip position of the segment /z/ is protruded because of the influence from its following segment - the rounded vowel /u/ (Laver, 1994). Another anticipatory example is the lip-shape in the word ‘see-saw’ /siː-sɔː/. The same segments /s/ in this word will be altered differently when preceding two vowels with different features. The first /s/ located before /iː/ becomes fronted with lips spreading, while the second /s/ preceding /ɔː/ is further back with the lip rounded (Roach, 2001). Similar lip rounding can also be found in the word ‘stew’ /stu/, in which the lip rounding feature is originally embedded in the round vowel /u/, but it undergoes the anticipatory effect and hence influences across two segments on the preceding /t/ as well as the initial segment /s/ (Kent & Read, 2002).

Bi-directional coarticulation

Either anticipatory effect or carryover effect interpreted above is a single directional coarticulation. Nonetheless both directions of coarticulation can operate at the same time (Daniloff & Hammarberg, 1973; MacKay, 1987).

Two kinds of phenomenon can be treated as having both directions act simultaneously: 1) a particular sound influences both its preceding and following sounds; 2) a sound located in the middle get affected by both its preceding and following sounds. The English word ‘spoon’ is a great example for the first type. The canonical pronunciation of segments /s/, /p/ and /n/ do not contain any lip-rounding feature, while only the vowel /u/ does. When the word ‘spoon’ is produced, lip protrusion can be observed in all segments of this word. That is, the lip protrusion feature spread both ways- anticipatory effects on the preceding segments /s/ and /p/ and also carryover effect on the following segment /n/ (Daniloff & Hammarberg, 1973). As appose to the “outward” coarticulation, it’s also possible for segments to be influenced by preceding and following segments simultaneously, which MacKay (1987) described as ‘double accommodation’. In the word ‘shear’ /ʃɪɹ/, the vowel is found to be rounded because both its preceding /ʃ/ and following /ɹ/ are rounded. Another example comes from word pairs like ‘man’, ‘mat’ and ‘tan’. Even though all vowels in these words are nasalized, the nasalization of the vowel in ‘man’ is greater than vowels in other two words, which is caused by the double effects of two nasal consonants from both left and right (MacKay, 1987).

2.1.2 Coarticulation between segments and suprasegmental cues

The above-mentioned researches have mostly focused on the coarticulation on the level of segments. In addition to the coarticulation between segments, coarticulation also happens between segment and suprasegmental cues. Early studies observed that the intrinsic height of vowels have effects on fundamental frequency (F_0, which is an important cue of pitch in suprasegmental properties). Intrinsic high vowels are produced with higher F_0 and vice versa. This phenomenon is proven extensively across diverse languages such as American English (Black, 1949; House & Fairbanks, 1953; Lehiste & Peterson, 1961; Peterson & Barney, 1952), Danish (Peterson, 1976), French (Di Cristo & Chafcouloff, 1976), Korean (Kim, 1968) and so on (Hombert, 1978). In addition, the voicing feature of consonants also influences F_0 of the following vowel. Lehiste (1976) pointed out that the F_0 of syllable nuclei will be altered by its preceding consonants. To be more specific, higher F_0 is associated with a previous voiceless consonant, and especially when it is voiceless fricative since there will be a highest peak right after the consonant. On the other hand, the F_0 of syllable nuclei rises slowly without such peak when occurring after the voiced consonant. Similar consequences are found by House & Fairbanks (1953), Lehiste & Peterson (1961), Mohr (1968), Chang (1973), Lea (1973), Hombert (1975) and Löfqvist (1975).

2.2 Tonal coarticulation

In tonal languages, different kinds of pitch inlaid in words differentiate the meanings of words. More than half of the languages in the world are tonal, including many Asian, African or American languages (MacKay, 1987; Ball & Rahilly, 1999; Ladefoged, 2001; Ashby & Maidment, 2005). Similar to the segments, tones in natural speech also affect each other. In the literature of tonal coarticulation, the effect of carryover or anticipatory direction has been the most discussed issue. It had been generally assented that there is directional asymmetry in tonal coarticulation: carryover effect occurs predominantly in tonal coarticulation (Hyman & Schuh, 1974; Hyman, 2007; Ladefoged, 2001; Flemming, 2008). We'll first review studies done on other tonal languages and narrow done our discussion to studies in Mandarin tonal coarticulation.

2.2.1 Tonal coarticulation in Vietnamese & Thai

Han & Kim (1974) investigated the tonal coarticulation between six tones in Vietnamese. They adopted disyllabic real words covering all 36 possible tonal combinations (6x6) and asked four speakers (two males and two females) to record these stimuli. Their results indicated that tones are indeed affected by its tonal environment. Moreover, both the tonal contour and height are changed under tonal coarticulation especially more by carryover effect. Coarticulatory assimilation was found in this study. That is, the F_0 of a tone will become higher when adjacent to tones with high overall pitch, but get lower F_0 when adjacent to tones with low overall pitch. Moreover, tonal onset, offset and the overall tone height get affected in tonal coarticulation.

Brunelle (2009) conducted a comparative study of Northern and Southern Vietnamese (abbreviated as NVN and SVN) on tonal coarticulation. Six tones in NVN and five tones in SVN were included. The tokens used were disyllabic non-words with the same segmental string /i ma/ under all tonal combinations. Five native speakers of NVN and six of SVN participated in the experiment. It is observed that both carryover and anticipatory effects have function in coarticulation but carryover effect is more dominant. Also, both carryover and anticipatory coarticulation in Vietnamese are assimilation. The target tone is always affected to be more like its adjacent tones.

Gandour and collegues conducted a series of experiments to examine tonal coarticulation in Thai (Gandour et al., 1992b, 1992c, 1994). In the first preliminary study (Gandour et al., 1992b), three tonal pairs of disyllabic noun-verb phrases were utilized to test carryover effect on the second tone (the 1st pair: Falling-Low vs. Mid-Low; the 2nd pair: Falling-Mid vs. Low-Mid; the 3rd pair: High-Rising vs. Rising-Rising). All the disyllabic phrases were constructed in the way that the initial consonant of the second syllables were all plosives. They showed that coarticulatory extent differs according to the preceding tones, but carryover effect is minimal on either F_0 height or slope in this study. This conclusion is contrary to most findings from other research. Gandour et al. explained that such minimal carryover effect might resulted from the intervening plosives (with complete obstruction in the supraglottal cavity) or from the incomplete tonal combinations of stimuli. This is the first research which discuss the possibility of segments may block the coarticulation on the suprasegmental level. The present study is partly motivated by the notion.

In order to exemplify from an opposite direction, Gandour et al. conducted another study to verify anticipatory effect on falling tone (Gandour et al., 1992c). Five disyllabic noun compounds were used as stimuli, containing a stable falling tone at the first syllable and five different tones beginning with a velar stop at the second syllable. Contrary to the minimal carryover effect found in the previous study, the anticipatory effect on falling tone is quite clear. Both of the F_0 height and slope are considerably affected but with different extent: the height is affected through the whole syllable, while the influence on the slope is limited in the terminal portion of the syllable. The most interesting thing is that the offset of the target tone (Falling tone), which contains a relatively low offset, gets raised before the Low and Rising tones whose onsets are low, and gets lowered before another Falling tone which has a high onset. Gandour et al. explained this anticipatory dissimilation through the vocal fold adjustment. According to them, "because of vocal fold dynamics, one may speculate it is easier in some articulatory sense to move from an even higher F_0 to an extremely low F_0." They also proposed that the intervening stop consonant is also a possible factor which influences the coarticulation. However, the anticipatory effect was exemplified only on falling tone, which is quite limited.

Both researches reviewed above share the same drawback that not all possible tonal combinations in Thai were included. Therefore, a full picture of tonal coarticulation is not available to get. In a follow-up study Gandour et al. (1994) used two-tone sequences containing all 25 possible combinations of five tones in Thai. All tokens were produced in a quadri-syllabic frame: the first and the last words were constant mid tones, and the two words in the middle were the target two-tone sequences. Ten male speakers recorded the tokens for investigation. According to the results, carryover effect influences tones on both F_0 height and the slope, and it also has larger influential extent than anticipatory effect. In terms of F_0 height, only Rising tone is not affected by carryover effect, while Low tone and Falling tone do not undergo anticipatory effect. And in terms of slope, carryover effect functions on Mid tone and Low tone, while no tone shows any anticipatory effect at all. In addition, carryover effect can influence the following syllable about 75% of its duration on height and no more than 50% on slope, while anticipatory influences the preceding syllable about 50% of its duration on height and has no effect on slope.

In addition to the coarticulatory outcomes, Gandour and colleagues further proposed that the different voicing states of the intervening consonants should be an important factor in tonal coarticulation. They explained that the obstruction of voiceless consonants may break the continuity between tones of two syllables. Thus, tonal coarticulation might be interfered by intervening voiceless consonants. That is, the qualities of intervening consonants are possible to affect tonal coarticulation. Similar ideas about the relationship between consonantal qualities and tonal coarticulation will be further discussed in section 2.3. However, such claim was made according to the results of unbalanced stimulus setting, i.e., Gandour et al. (1994) did not include voiced intervening segments in the target sequence.

Potisuk et al.(1996) also investigated the carryover and anticipatory effect in Thai. Tri-syllabic tonal sequences were selected with the middle syllable as the target. The three- tone-sequences with 125 possible combinations of the five Thai tones were put in a quadri-syllabic frame with a final word with fixed Low tone added to the target. To avoid voiceless consonants from inhibiting the coarticulation, which was found in Gandour et al. (1994), all four words in the frame began and ended with a sonorant, thus the sentences remains voiced throughout the string. Six speakers including three males and three females participated in the study. According to the results, Potisuk et al. (1996) proposed that in Thai, carryover effect is much greater than anticipatory effect as more tones undergo carryover influences on both height and slope, while anticipatory effect influences only some tones on height but not slope. In terms of the temporal extent, the scope of carryover effect, which can extend to 70% of the duration of the following syllable on both height and slope, is much greater than anticipatory effect, which affects merely 30% of the preceding tone and only on height. Their results also indicated that in Thai tonal coarticulation, all tones are altered by carryover assimilation while only Rising and High tones (whose pitch range in the terminal portion is upper) are affected by anticipatory dissimilation - the higher F_0 offset get raised by following lower onset. To explain such dissimilation, Potisuk et al. argued that the raising effect was made to enhance the perceptual separation to counter the overall declination of the utterance

2.2.2 Tonal coarticulation in Mandarin

To examine the coarticulatory effects in Mandarin, Shen (1990) chose tri-syllabic non-words /pa pa pa/ as stimuli. All tokens were repeated twice by two female speakers. Three measurements including the onset, the offset and the turning point were conducted. Based on the data, Shen (1990) argued that carryover and anticipatory effects happen simultaneously and both directions are equally dominant. In terms of the extent, Shen claimed that both affect the whole adjacent tones. What's more, it was found that when carryover effects occur, Tone 1 and Tone 2 (tones with high offsets) often raise the following tones. And in terms of anticipatory effect, Tone 4 and Tone 1 (tones with high onsets) tend to raise the preceding tone. Assimilation was found in both carryover and anticipatory effects. However, the contrary phenomenon, which showed a dissimilation effect, that Tone 1 and Tone 2 are higher when preceding mid-onset tones (Tone 2 and Tone 3) than when preceding high-onset tones (Tone 4 and Tone 1) was not fully explained by Shen.

Lin & Yan (1992) adopted quadri-syllable real phrases under 256 tonal combinations (4x4x4x4) to evaluate tonal coarticulation in Mandarin. Recordings of a trained phonetician were analyzed. The onset, the offset and turning points of the tonal contour were measured. Their results indicated that effects from both directions do not function simultaneously. Carryover effect can affect the following tonal onset but not the offset. And anticipatory effect can affect the preceding offset but not the onset. Furthermore, their study showed that Tone 1, Tone 2 and Tone 3 are significantly influenced under carryover effects, and Tone 4, on the other hand, gets affected under anticipatory effect markedly.

Xu also conducted a series of experiments on Mandarin tonal coarticulation (1993, 1994 and 1997). In the first research, Xu (1993) examined target tones in compatible and conflicting contexts. Xu devided tones into two values- high and low. If a tone occurs when both of the values of its onset and offset are similar to their adjacent tonal values, it is in a compatible context (compatible combinations included: T1-T4-T3, T1-T4-T2, T2-T4-T2, T2-T4-T3, T3-T2-T1, T3-T2-T4, T4-T2-T4 and T4-T2-T1). On the contrary, when both onset and offset have different values from their adjacent tonal values, this tone is under a conflicting context (conflicting combinations were: T1-T2-T3, T1-T2-T2, T2-T2-T2, T2-T2-T3, T3-T4-T1, T3-T4-T4, T4-T4-T4, and T4-T4-T1). Trisyllabic real words were used in this study with the second syllable being either rising tone or falling tone. Each target syllable was under compatible or conflicting contexts. 16 possible combinations listed above were included as materials. Five native speakers including three males and two females were recorded. The analysis was focused on the duration, the mean F_0 and the slope of contour of the target tone. According to his results, in both compatible and conflicting contexts, carryover effect has a greater influence than anticipatory effect. In addition, both rising tone and falling tone have steeper slope in compatible context. Surprisingly, according to his results, the direction of a rising tone in conflicting context could even change into falling tone.

The studies of Shen (1990), Lin & Yan (1992) and Xu (1993) share some similar pitfalls. Firstly, all of them contained too few speakers and data. Secondly, too less measured points were included in their research, which is hard to monitor the extent of coarticulation. Thus both Lin & Yan (1992) and Xu (1993) did not propose any exact coarticulatory extent. Thirdly, the stimuli used in these studies could be more well-controlled. The intervening voiceless /p/ adopted in Shen’s (1990) could probablely eliminate or even block the tonal coarticulation (cf. Gandour et al. 1994). And in the studies of Lin & Yan (1992) and Xu (1993), real phrases were used as tokens. These phrases may sound natural but the possible perturbation effects from segments to tones could not be eliminated. Moreover, Xu's (1993) study only contained parts of the possible tonal combinations which makes it impossible to discuss all tonal contexts and get a full picture of the coarticulation phenomenon. Last but not least, all of these studies did not contain any canonical form. Without a comparable standard, it is hard to define how tones changed by tonal coarticulation.

Xu (1994) later chose disyllabic tonal sequences /ma ma/ to further inspect coarticulatory effects. Sixteen possible tonal combinations were recorded by four male speakers. Monosyllabic /ma/ with four tones were recorded as the canonical forms. On each vowel, ten points of F_0 were measured. According to his results, Xu proposed that carryover effect has the largest extent on Tone 1 and Tone 2. On the other hand, the extent from anticipatory effect is largest on Tone 1, followed by Tone 2 and Tone 4, while Tone 3 is not affected by anticipatory effect. Moreover, there is a asymmetry between two directions: carryover effect tends to assimilate neighboring tones (when next to high tone, get high), while anticipatory effect is more likely to dissimilate a preceding tone by having its F_0 raised by a following low onset. Based on this observation, Xu proposed a new in this research: When tones are produced with variation due to tonal coarticulation, the key factor is the immediately adjacent tonal value rather than the entire neighboring tone.

Xu conducted another research in 1997, using the same disyllabic /ma ma/ sequences with 16 tonal combinations, however, different from the study in 1994, each token was measured by its duration, the maximum F_0, the minimum F_0 and five points in F_0 contour (the point at the beginning, one quarter, midpoint, three quarters, and the end). Eight male native speakers of Beijing Mandarin recorded the materials for analysis. For the purpose of comparison, monosyllabic /ma/ with four different tones were also produced in isolation to be the standard form which represent the canonical form not affected by adjacent tones. Carryover effect was found to have greater magnitude than anticipatory effect in this study. Also, the carryover effect on the following tone from the preceding tone can extend over two-thirds or even the entire following tone. Tone 1 and Tone 2 (tones with high offset) were affected to the greatest extent by carryover effect, whereas Tone 2 and Tone 4 are affected to a greater extent under the influence of anticipatory effect. Tone 3, when located at the second syllable, tends to influence preceding tones the most. The anticipatory dissimilation found in the result is that a following low onset raises its preceding F_0 rather than lower it. The asymmetry between the two directions was found in Xu(1994) and confirmed by this study again: assimilation happens in carryover effect and dissimilation happens in anticipatory effect.

Although both studies of Xu (1994 & 1997) included more measurements of the data and compared the data with the canonical form, but it is still not adequate to get the complete picture of tonal coarticulation in Mandarin. The extent of carryover was proposed, but which tones are much easier triggers of carryover effect was not mentioned. In terms of the anticipatory effect, target and trigger tones were provided but not the temporal extent.

2.3 Consonantal qualities and coarticulation

As mentioned in section 2.2, Gandour et al. (1994) proposed that different qualities of intervening consonants are likely to affect the tonal coarticulation. Though this notion was proposed, rare studies can be found to exemplify how intervening consonants affect the tonal coarticulation. Most of related literature discussed only the consonantal qualities and coarticulation between segments or between segment and suprasegmental cue. Most reviews were related to two kinds of consonantal qualities: the place of articulation (POA) and voicing.

The relation between POA and segmental coarticulation was exemplified to investigate whether a given segment could block coarticulatory effects from its adjacent segments. Bladon and Al-Bamerni (1976) first proposed the idea of ‘coarticulatory resistance (CR)’. Later the CR conception was further developed into the concept of ‘degree of articulatory constraint (DAC)’ by Recasens et al. (1984b, 1985, 1987, 1997 & 2009). According to Recasens, the DAC concerns about “the degree of involvement of the speech articulators in the formation of a closure or constriction.” The speech articulator Recasens used to discuss was the tongue dorsum. That is, the more the dorsum gets involved in the constriction formation, the higher DAC will be. (Recasens, 1997&1987) Based upon the idea from CR and DAC, phonemes differ in coarticulatory resistance will have different degrees of articulatory constraint, and it will directly influence the spreading of coarticulatory effects. To be more specific, phonemes with high DAC will reduce or block coarticulation, and low DAC allows greater coarticulatory effects to happen. Recasens also assigned different degrees to consonants: dorsals including alveolopalatals /ʃ/ and /ɲ/, palatal /i/, velar /k/ and dark /l/ are maximally constrained and thus assigned with highest DAC value 3. Labial consonants like /p/ which is minimally constrained got the lowest DAC value 1. And to those consonants with intermediate degree of tongue-dorsum constraint such as alveolars /n/ and /s/ get the DAC value in between (DAC=2). Recasens provided this concept of DAC from the data of Catalan and Spanish, and his model was proved in Italian (Farnetani, 1990) and English (Fowler and Brancazio, 2000). However, these DAC-related studies only focused on how segments with different places of articulation affect the coarticulation.

In section 2.1.2, it was reviewed that Lehiste et al. (1961 & 1976) demonstrated that voicing affects the F_0 of its adjacent vowel. The similar phenomenon that the vowels after voiceless obstruents have higher F_0 than the vowels after voiced obstruents was widely discussed (Ohala, 1978; Hombert, 1978). Also, in the review of Schuh (1978), the author generalized many instances that voicing of consonants influence the tone spreading. According to his summary, high tones cannot spread through voiced obstruents in tonal languages such as Bade, Balonci (Lukas, 1969) and Zulu (Cope, 1970). While low tones cannot spread through voiceless obstruents, which could be found in Ngizim (Schuh, 1971) and Nupe (George, 1970).

2.4 Summary

It is widely known that coarticulation happens in running speech. Both segments and suprasegmental cues get mutually influenced by the phonetic properties of adjacent segments/suprasgmental features. Tones in tonal languages also have similar coarticulatory effects. Among the studies concerning tonal coarticulation, it is generally accepted that carryover effect has greater influence than anticipatory effect. Evidence could be found in Vietnamese (Han & Kim, 1974; Brunelle, 2009), Thai (Gandour et al., 1994; Potisuk et al., 1996) and Mandarin Chinese (Xu, 1993 & 1997).

There were some studies investigating Mandarin tonal coarticulation (Shen, 1990; Lin & Yan, 1992; Xu, 1993, 1994 & 1997). However, there was no general agreement on the temporal extent or the magnitude of tonal coarticulation of both directions, and the possible target and trigger tones in coarticulation were inconsistent in previous studies. Also, the studies reviewed in section 2.2.2 share some similar problems: they contained too few speakers or measurements, and their stimuli were not well-controlled in terms of the segmental environment of the target tones. A clear comparison between these reviews is shown in Table 1.

	Shen (1990)	Lin & Yan (1992)	Xu (1993)	Xu (1994)	Xu (1997)
stimuli	/pa pa pa/	σσσσ real phrases	σσσ real words	/ma ma/; canonical /ma/	/ma ma/; canonical /ma/
speaker	2 females	1 phonetician	3 males & 2 females	4 males	8 males
measurement	onset , offset, turning point	onset , offset, turning point	duration, mean F0, contour slope	10 points of F0 on vowel	duration, max & min F0, 5 points of F0
2 directions	equal & simultaneously	not simultaneously	more carryover		more carryover
extent	whole syllable	not whole syllable			C: 2/3 to whole syllable
target		C: T1 , T2 , T3 A: T4		C: T1, T2 A: T1> T2, T4	C: T1, T2 A: T2, T4
trigger	C: T1 , T2 A: T4 , T1				A: T3
assimilation dissimilaiton	all assimilation			C: assimilation A: dissimilation	C: assimilation A: dissimilation

Table 1. A comparison between reviews of Mandarin tonal coarticulation
(In the table, “C” refers to “carryover coarticulation” and “A” refers to “anticipatory coarticulation”)

In addition, it was identified that different qualities of intervening consonants will influence coarticulation. The effects from different POAs or voicing states were discussed as in 2.3. However, the influence from different manners of articulation (MOA), another crucial property of consonants, was rarely analyzed in the literature.

2.5 The present study

To examine the inconsistent results in previous studies, the first aim of the present research is to re-investigate Mandarin tonal coarticulation with a more rigorous experimental setting. A set of tri-syllabic stimuli with better-controlled segmental environment is adopted in experiment I. The target tone was surrounded by all possible tonal combinations. The measurements of F_0 at about every 10% of the tonal contour were analyzed. This experiment focuses on the F_0 variation caused by tonal coarticulation, and following coarticulatory issues will be discussed: the coarticulatory direction, the temporal extent, the magnitude, the target and the trigger in Mandarin tonal coarticulation. Although there is inconsistency between studies reviewed, it is assumed that carryover effect might tend to be greater than anticipatory effect due to the order in natural speech. And if it does, the effect should be greater on both of its extent and magnitude (the results in previous studies often included only one aspect being affected). Target and trigger involved in tonal coarticulation are not easy to predict, but better ways to explore target and trigger will be provided in this study.

In addition, the present study also aims to examine whether different manners of articulation (MOA) of the intervening consonants influence tonal coarticulation in Mandarin. As the places of articulation (POA) and the voicing states were proposed to be relevant to coarticulation by previous researchers, Exp. II is devoted to find out if there is any variation in coarticulatory effect originated from different MOAs of intervening consonants. Based on the fact that tones are produced with the vibration of vocal cords, it is assumed that an intervening voiceless consonant which stops the vibration due to the constriction might reduce the effect of tonal coarticulation. This assumption is in line with the statement in Gandour et al. (1994). Therefore, the hypothesis of the Exp. II is that consonants with MOA such as voiceless stop, fricative or affricate which involve a short break of vibration in vocal cords would reduce tonal coarticulation. On the other hand, when the intervening consonants are liquid or nasal, the extent and magnitude of coarticulation would be more distinct.

3. Methodology

3.1 Overview

The present research contains two experiments: Exp. I was designed to re-examine the directionality, the extent and the magnitude of tonal coarticulation in Mandarin. To examine both carryover and anticipatory effects, Exp. I adopts tri-syllabic tonal sequences as stimuli to evaluate the effect of the preceding and following tones on the same target tone – the tone on the second syllable. Non-words were adopted to ensure identical segmental environments for the target tone. Exp. II investigates how different MOAs of intervening consonants modulate the tonal coarticulation. All tokens in Exp. II are disyllabic real words, with the onset of second syllable varies in 5 MOAs (affricate, fricative, liquid, nasal and stop).

3.2 Participants

Ten native Mandarin male speakers were recorded in both experiments. To minimize possible F_0 variability between genders, no female is included in this study. All speakers are students of different departments in National Chiao-Tung University in Taiwan. None of the participants majors in language-related program nor has ever taken any linguistic course. The speakers' average age is 23 years old. None of them has any listening, speaking or reading problems.

The language background of speakers was carefully-controlled. All of them were born and had lived in central or southern Taiwan until entering the university which is located in northern Taiwan. They all speak Mandarin as their first language but are able to use Taiwanese to communicate. All speakers are familiar with the Zhuyin system (Bopomofo) which was adopted to denote the tokens in both experiments. All participants were paid for their participation.

3.3 Stimuli

ExperimentⅠ

The main purpose of Exp.Ⅰis to clarify the disagreement among previous studies concerning the carryover and anticipatory effects in Mandarin tonal coarticulation. To investigate the effects from both directions, tri-syllabic syllables are adopted, and the target tone is embedded in the middle syllable. Furthermore, to eliminate any possible effect from segment to tone on the coarticulation, the segment /i/ was chosen to be the target syllable. To ensure the target tone has identical segmental neighbors, the coda of the first syllable and the onset of the third syllable are always alveolar nasal /n/. We chose /tɕʰin/ to be the first syllable and /niou/ as the third syllable for they contains no tonal lexical gaps. The frame of the tri-syllabic words is / tɕʰin・i・niou/ which were produced under 64 (4x4x4) possible tonal combinations. Concerning the adoption of nonword tokens, Xu (1997) argued that the tonal coarticulation in nonsense words, although smaller in degree, has the same pattern as in real words as long as there is no pause between syllables.

In addition to the tri-syllabic tonal sequences, the monothong /i/ with four tones were also produced in isolation to serve as the canonical form of /i/ without any coarticulatory effect from other tones.

ExperimentⅡ

The second experiment was designed to investigate whether intervening consonants with different MOAs (nasal, liquid, stop, fricative and affricate) have effect on tonal coarticulation in actual occurring disyllabic words. A total of 80 tokens are included in this experiment (5 MOAs × 16 possible tonal combinations in the disyllabic words). All tokens share the same syllable structure: “$C_1V_1C_2V_2$”. Table 1 lists all the segments covered included in the tokens.

Table 2. Segments used in tokens of Experiment Ⅱ

C_1	V_1	C_2	V_2
any possible consonants without particular constraint	/i/ or /u/	Nasal	diphthong /au/
		Liquid	
		Stop	
		fricative	
		affricate	

As there was no discussion about MOA effect in the literature, whether the effect is significant or not is uncertain. Thus, real words are adopted in this experiment to exemplify tonal coarticulation with the largest degree. In Mandarin /i/ and /u/ are the most productive monothongs in terms of the number of real words they could form when combined with other consonants. Unfortunately, either one of them alone cannot compose all the tokens needed. As a result, both /i/ and /u/ are adopted for “V_1”. Since both high vowels have similar tongue height, the intrinsic F_0 difference between them was expected to be not crucial in this experiment. “C_2” was designed to contain one of the five MOAs. The diphthong /au/ was chosen to be “V_2” because it is the only vowel which can be combined with all types of MOAs and can form real words at the same time. The complete word list of Exp. II can be seen in Appendix I.

In addition, simple monothongs /i/ and /u/ as well as the diphthong /au/ were read in a sequence which is the canonical form without any influences from any neighboring consonants. The disyllabic frames /i au/ and /u au/ were recorded under the 16 tonal contexts by each speaker.

3.4 Experimental procedure

All experiments were conducted in a phonetic laboratory in National Chiao-Tung University. Speakers were instructed to follow every instruction displayed on a PC screen. Before the main experiment, speakers had to finish a practice section to get familiarized with the procedure. All tokens denoted with Zhuyin were shown on the screen at a random order, and speakers had to pronounce what they saw within a 2-second time window. Their production was recorded by a stimulus presentation system – Paradigm (by Bruno Tagliaferri, version 1.0.3.998). The main experiment was composed of Exp. I and II. Each speaker should repeat the main experiment for three times. The participants could take a break between the two experiments.

A total of 1,920 tokens were recorded for Exp. I (64 tokens * 10 speakers* 3 times) and 2400 tokens for Exp. II (80 tokens * 10 speakers* 3 times). The canonical forms were also recorded, 120 words were recorded for Exp. I (4 canonical form * 10 speakers * 3 times) and 960 words for Exp. II (32 canonical form * 10 speakers* 3 times).

3.5 Software and instruments

All experiments were conducted through the stimulus presentation software-Paradigm (by Bruno Tagliaferri, version 1.0.3.998) on a PC (ASUS CP1130). The tokens were recorded using the voice input function of Paradigm via a Microsoft LifeChat LX-3000 Headset.

The software Praat (by Paul Boersma & David Weenink, version 5.3.02) was used for the acoustic analysis, and the script “TimeNormalizedF_0 Praat script” (developed by Yi Xu, version 2.4.3) was adopted for all the F_0 analyses. The statistical analysis was done in Microsoft Excel (data organization) and SPSS (by International

Business Machines (IBM) Corporation, version 12.0.1C).

3.6 Data analysis

In Exp. I, the F_0 of the target syllable was measured whereas in Exp. II, the F_0 of both syllables were examined. To reduce any potential interference from onsets, the F_0 of all target syllables were measured on target vowels only. All the F_0 measurements were done using the TimeNormalizedF_0 Praat script developed by Xu. To avoid octave jump or false automeasurements, every single vocal pulse marking of the measured syllables were examined carefully to remove extra pulses or add missing pulses. The F_0 contours were time-normalized by the script yielding 10 points (measurement done near every 10% of the contour) for each tone.

Considering that the degree of coarticulation should be a within subject comparison, and the canonical forms should be speaker-specific, every speaker also recorded canonical forms aside from the stimuli. The F_0 values at 10 time points of 3 repetitions of canonical forms were averaged to further form a new canonical form which is specific to individual speaker. For each speaker's data, the delta F_0 is defined as the F_0 difference (at the target time point) between the F_0 measurements of the target tone and his own canonical tone.

3.7 Statistical analysis

Experiment I

Forty two-way (4x4) repeated measure ANOVAs were conducted to evaluate the effect of preceding and following tones on the delta F_0 of four different target tones (There are 10 measuring time points, hence the 40 ANOVA). The independent variables were the preceding tone (the tones of the first syllable) (4 levels) and the following tone (the tones of the third syllable) (4 levels). The dependent variable was the F_0 difference between the target tone & the norm (the delta F_0 of the target syllable) at each time point.

Experiment II

Eighty two-way (4x5) repeated measure ANOVAs were conducted to evaluate the effect of MOAs on the co-articulation. Four different tones of the target syllable and 10 measuring time points were analyzed separately. The independent variables were the tones of the preceding or the following syllable (4 levels) and the MOAs of the intervening C_2 (5 levels: nasal, liquid, stop, fricative and affricates). The dependent variable was the delta F_0 at each time point.

4. Results

4.1 Citation forms of four tones[1]

To exemplify the general pattern of four tones produced by ten speakers involved in this study, the citation form was established by averaging all records of monosyllabic /i/ of ten speakers. Figure 1 shows the F_0 contour of the citation forms of four tones. For ease of analyzing the coarticulatory extent on each tone, the contours are displayed by normalized time scale (10 measured time points for each target) instead of their actual duration. The F_0 of four tones distributed between 103.2 Hz to 156 Hz. To distinguish tonal F_0 from their height, the F_0 range of four tones was divided equally into three parts: the Low region is defined from 103.2 Hz to 120.8 Hz; the Mid region is defined from 120.8 Hz to 138.4 Hz; and the High region is defined from 138.4 Hz to 156 Hz. The onsets and offsets of four tones are assigned with different values of their height according to their location on the F_0 range, which is displayed in Table 3.

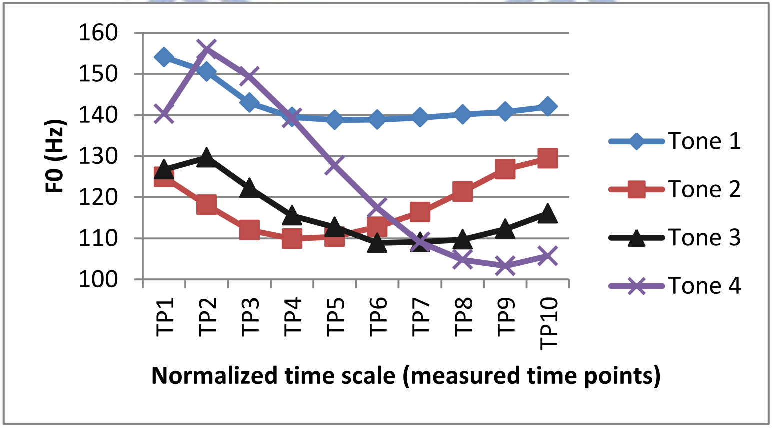

Figure 1. The citation forms of four tones (averaged by ten speakers)

---

[1] One thing has to be noted is that this citation form was established simply to get a general picture about the distribution of four tones, therefore the three F_0 regions (High, Mid, and Low) can be defined more suitable to the real F_0 distribution. In this study, all the F_0 variation caused by tonal coarticulation is compared between the F_0 of one's target tone and his own canonical form, but not the citation form listed here which is averaged by ten speakers.

Citation Tone	Onset Value	Offset Value
Tone 1	High	High
Tone 2	Mid	Mid
Tone 3	Mid	Low
Tone 4	High	Low

Table 3. The height values of onsets and offsets of four citation tones

4.2 Experiment I

For each target tone, ten two-way repeated measure ANOVAs were conducted to evaluate the effects of Preceding tones (4 levels) and Following tones (4 levels) on F_0 at the 10 measuring time points. The dependent variable is the F_0 differences between the target tone and its speaker-specific canonical form.

The results of target Tone 1 is shown in Table 4. The main effect of Preceding tone is significant across all 10 points whereas the main effect of Following tone is significant from the fifth time point (TP5) to TP10. The interaction between preceding tone and following tone is not significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 5 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each adjacent tone are further displayed in Figure 2 and Figure 3.

The results of target Tone 2 is shown in Table 6. The main effect of Preceding tone is significant across all 10 points whereas the main effect of Following tone is significant at TP1 and from TP3 to TP10. The interaction between preceding tone and following tone is not significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 7 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each adjacent tone are further displayed in Figure 4 and Figure 5.

The results of target Tone 3 is shown in Table 8. The main effect of Preceding tone is significant across all 10 points whereas the main effect of Following tone is significant from TP7 to TP10. The interaction between preceding tone and following tone is not significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 9 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each adjacent tone are further displayed in Figure 6 and Figure 7.

The results of target Tone 4 is shown in Table 10. The main effect of Preceding tone is significant across all 10 points whereas the main effect of Following tone is significant from TP5 to TP7. The interaction between preceding tone and following tone is not significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 11 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each adjacent tone are further displayed in Figure 8 and Figure 9.

To sum up, the preceding tones and the following tones of targets have different temporal extent on the middle target tones. For all four target tones, the influences from their preceding tones can extend to the whole syllable (from TP1 to TP10). However, the influences from the following tones are more limited. Only target Tone 2 gets influenced across nearly the whole syllable (the effects are significant from TP10 backward to TP3 and also at TP1). The effect on Tone 1 extends more than half of the syllable (from TP10 backward to TP5), while the effects on Tone 3 and Tone 4 are even shorter than half of the syllable (the significant effects on Tone 3 are from TP10 to TP7 and on Tone 4 are TP7 to TP5). In addition, the magnitude of delta F_0 variation caused by the preceding tones and by the following tones is different too. Generally the magnitude varied by preceding tones is much greater. For all target tones, the range between the maximum and the minimum delta F_0 caused by different preceding tones will be at least 28 Hz and even more than 60 Hz (The range of target Tone 1 is near 42 Hz, of target Tone 2 is near 29 Hz, of target Tone 3 is about 33 Hz and of target Tone 4 is about 62 Hz). On the contrary, all of the range between the maximum and the minimum delta F_0 caused by different following tones is limited under 20 Hz. (The range of target Tone 1 is about 8 Hz, of target Tone 2 is about 20 Hz, of target Tone 3 is near 17 Hz and of target Tone 4 is about 13 Hz).

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,42)=18.805	.000	*	(3,42)=17.308	.000	*	(3,42)=18.189	.000	*	(3,42)=18.881	.000	*	(3,42)=16.529	.000	*
following tone	(3,42)=.512	.676	n.s.	(3,42)=.212	.887	n.s.	(3,42)=.754	.526	n.s.	(3,42)=1.948	.137	n.s.	(3,42)=2.855	.048	*
preceding * following	(9,126)=.663	.741	n.s.	(9,126)=.675	.730	n.s.	(9,126)=.904	.524	n.s.	(9,126)=1.422	.186	n.s.	(9,126)=1.348	.219	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,42)=13.234	.000	*	(3,42)=11.561	.000	*	(3,42)=10.747	.000	*	(3,42)=11.036	.000	*	(3,42)=13.027	.000	*
following tone	(3,42)=4.423	.009	*	(3,42)=6.104	.002	*	(3,42)=7.816	.000	*	(3,42)=8.959	.000	*	(3,42)=11.338	.000	*
preceding * following	(9,126)=.964	.473	n.s.	(9,126)=.790	.626	n.s.	(9,126)=.747	.665	n.s.	(9,126)=.691	.716	n.s.	(9,126)=.522	.857	n.s.

Table 4. The ANOVA results of Experiment I **(Target - Tone1)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* -1.6 / -11.2 / -24.5 / -18.5	* 6.3 / -4.2 / -19.2 / -11.9	* 14.5 / 6.1 / -6.7 / -0.7	* 17.1 / 11.6 / 0.4 / 4.1	* 16.8 / 13.4 / 3.6 / 5.1
following tone	n.s.	n.s.	n.s.	n.s.	* 8.0 / 10.9 / 11.5 / 8.5
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	* 15.8 / 13.6 / 5.4 / 5.4	* 14.4 / 12.9 / 5.7 / 4.7	* 13.0 / 12.1 / 5.5 / 3.6	* 12.3 / 11.9 / 5.4 / 3.0	* 11.3 / 10.7 / 3.3 / 1.5
following tone	* 8.2 / 11.4 / 11.9 / 8.6	* 7.4 / 11.1 / 11.3 / 7.9	* 6.2 / 10.7 / 10.4 / 6.9	* 5.7 / 10.6 / 10.1 / 6.3	* 3.8 / 9.1 / 8.9 / 5.0

Table 5. Results for the post-hoc analysis in experiment I **(Target - Tone1)**

(The four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

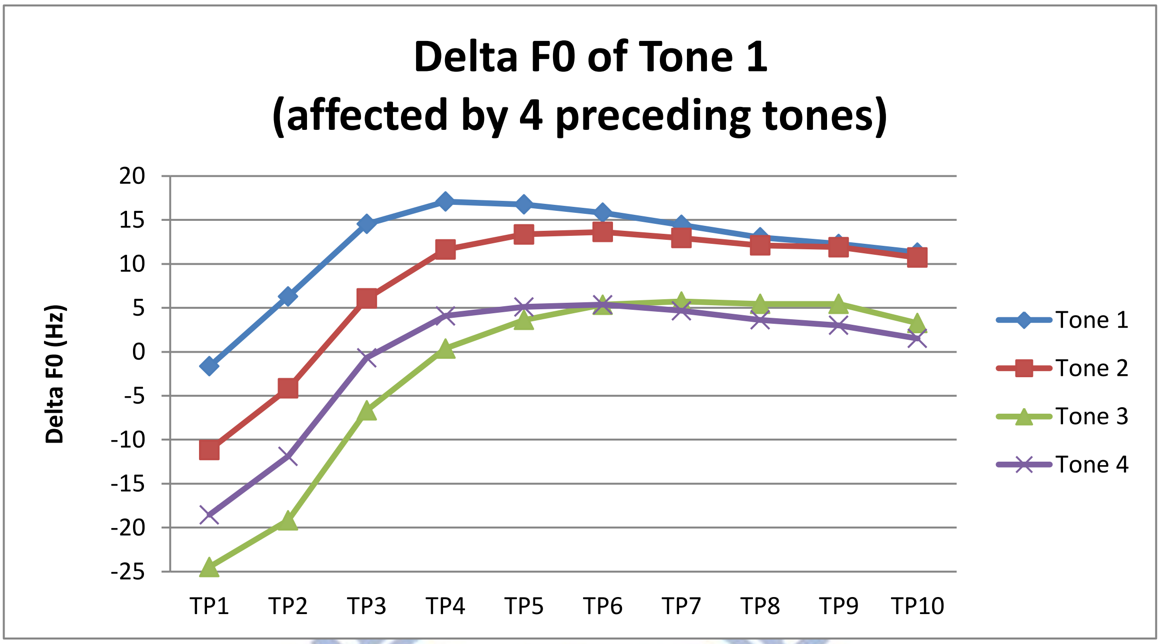

Figure 2. Contours of the delta F_0 of Tone 1 when affected by four preceding tones

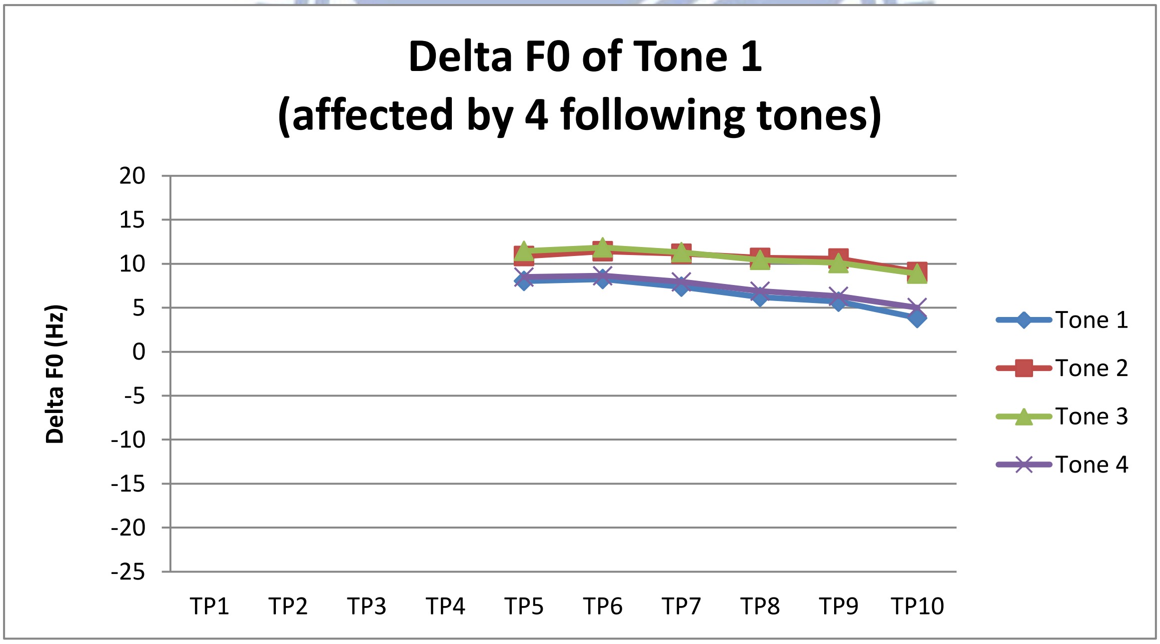

Figure 3. Contours of the delta F_0 of Tone 1 when affected by four following tones

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,81)=55.103	.000	*	(3,81)=46.018	.000	*	(3,81)=51.229	.000	*	(3,81)=61.936	.000	*	(3,81)=59.045	.000	*
following tone	(3,81)=3.728	.014	*	(3,81)=1.968	.125	n.s.	(3,81)=3.929	.011	*	(3,81)=4.865	.004	*	(3,81)=4.578	.005	*
preceding * following	(9,243)=1.014	.430	n.s.	(9,243)=.573	.819	n.s.	(9,243)=.508	.868	n.s.	(9,243)=.390	.939	n.s.	(9,243)=.279	.980	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,81)=45.410	.000	*	(3,81)=35.626	.000	*	(3,81)=28.739	.000	*	(3,81)=25.075	.000	*	(3,81)=33.042	.000	*
following tone	(3,81)=5.462	.002	*	(3,81)=7.877	.000	*	(3,81)=11.093	.000	*	(3,81)=17.231	.000	*	(3,81)=23.826	.000	*
preceding * following	(9,243)=.410	.929	n.s.	(9,243)=.389	.940	n.s.	(9,243)=.476	.890	n.s.	(9,243)=.661	.743	n.s.	(9,243)=1.137	.337	n.s.

Table 6. The ANOVA results of Experiment I **(Target – Tone2)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* 5.3 / 6.3 / -11.6 / -5.9	* 12.5 / 12.7 / -8.4 / -0.2	* 16.3 / 16.8 / -2.2 / 4.8	* 15.5 / 17.2 / 0.5 / 6.2	* 12.9 / 15.6 / 1.0 / 5.6
following tone	* -2.7 / -1.3 / 0.9 / -2.8	n.s.	* 6.8 / 8.9 / 11.3 / 8.7	* 7.9 / 10.2 / 11.9 / 9.4	* 7.3 / 9.0 / 10.7 / 8.2
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	* 9.1 / 12.2 / -0.5 / 3.3	* 4.5 / 7.9 / -3.4 / -0.5	* -0.3 / 3.5 / -6.4 / -4.6	* -4.1 / -0.3 / -8.9 / -8.2	* -3.7 / -0.4 / -9.5 / -9.2
following tone	* 4.6 / 6.3 / 8.0 / 5.2	* 0.5 / 2.8 / 4.4 / 0.9	* -4.1 / -0.7 / 0.6 / -3.7	* -8.0 / -3.5 / -2.3 / -7.6	* -8.6 / -3.8 / -2.3 / -8.2

Table 7. Results for the post-hoc analysis in experiment I **(Target – Tone2)**

(The four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

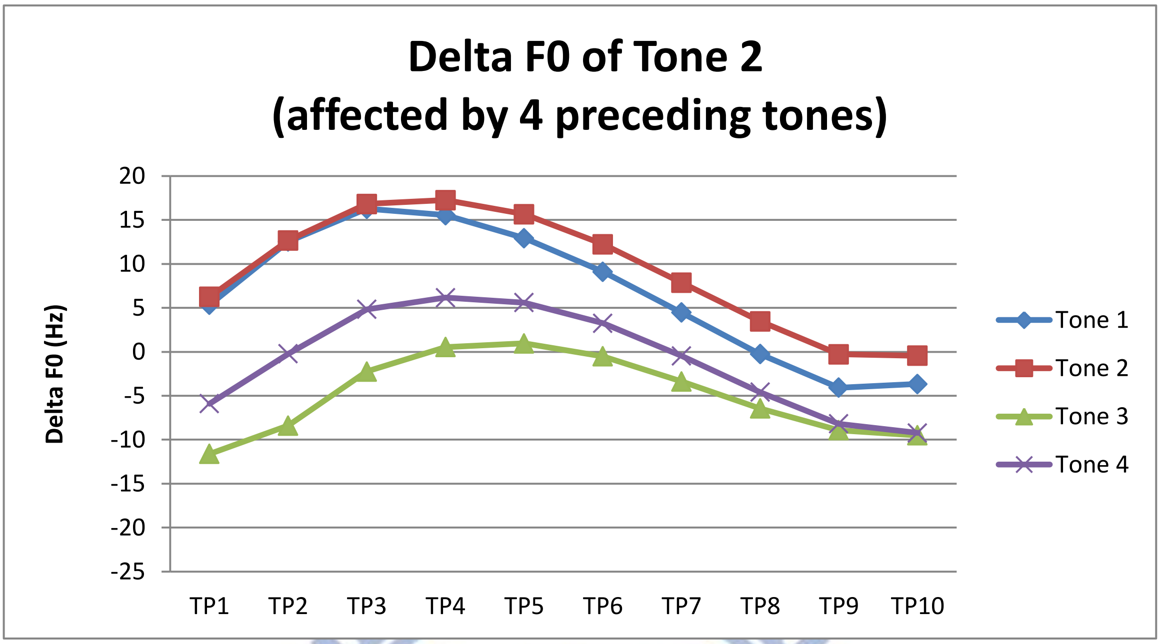

Figure 4. Contours of the delta F_0 of Tone 2 when affected by four preceding tones

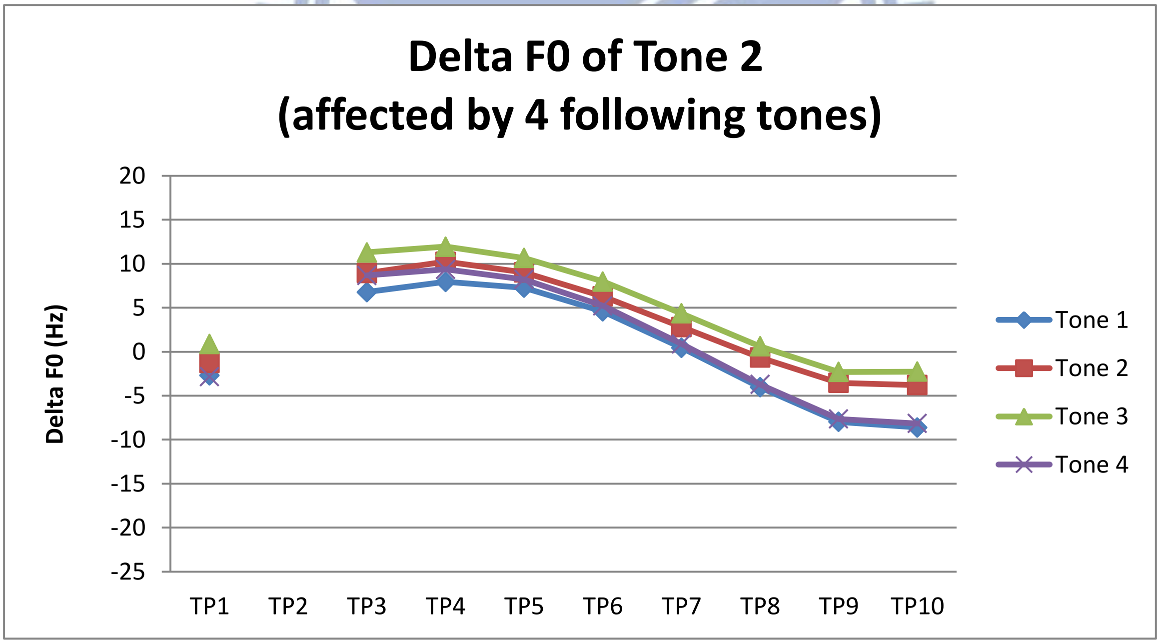

Figure 5. Contours of the delta F_0 of Tone 2 when affected by four following tones

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,66)=21.299	.000	*	(3,66)=22.303	.000	*	(3,66)=22.345	.000	*	(3,66)=20.561	.000	*	(3,66)=17.817	.000	*
following tone	(3,66)=2.317	.084	n.s.	(3,66)=.457	.713	n.s.	(3,66)=.341	.796	n.s.	(3,66)=.377	.770	n.s.	(3,66)=.524	.667	n.s.
preceding * following	(9,198)=1.606	.115	n.s.	(9,198)=1.468	.162	n.s.	(9,198)=1.140	.336	n.s.	(9,198)=1.226	.281	n.s.	(9,198)=1.618	.112	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,66)=12.789	.000	*	(3,66)=7.737	.000	*	(3,66)=4.880	.004	*	(3,66)=2.977	.038	*	(3,66)=3.702	.016	*
following tone	(3,66)=1.959	.129	n.s.	(3,66)=4.850	.004	*	(3,66)=7.533	.000	*	(3,66)=9.818	.000	*	(3,66)=10.580	.000	*
preceding * following	(9,198)=1.575	.125	n.s.	(9,198)=1.328	.224	n.s.	(9,198)=1.319	.229	n.s.	(9,198)=1.202	.296	n.s.	(9,198)=1.317	.230	n.s.

Table 8. The ANOVA results of Experiment I **(Target – Tone3)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* -3.8 / -6.3 / -13.4 / -21.6	* -1.5 / -2.2 / -11.9 / -23.3	* 3.0 / 5.3 / -3.8 / -15.0	* 5.4 / 9.9 / 2.6 / -7.5	* 4.9 / 10.0 / 4.2 / -4.5
following tone	n.s.	n.s.	n.s.	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	* 5.9 / 9.9 / 5.2 / -1.6	* 2.5 / 5.2 / 1.3 / -3.9	* -0.1 / 1.3 / -1.9 / -6.2	* -2.9 / -2.5 / -5.0 / -8.9	* -4.3 / -4.3 / -7.6 / -11.6
following tone	n.s.	* -0.7 / 1.9 / 5.5 / -1.6	* -4.3 / -1.3 / 4.6 / -5.9	* -8.2 / -5.0 / 3.6 / -9.7	* -10.6 / -7.6 / 1.7 / -11.3

Table 9. Results for the post-hoc analysis in experiment I **(Target – Tone3)**

(The four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

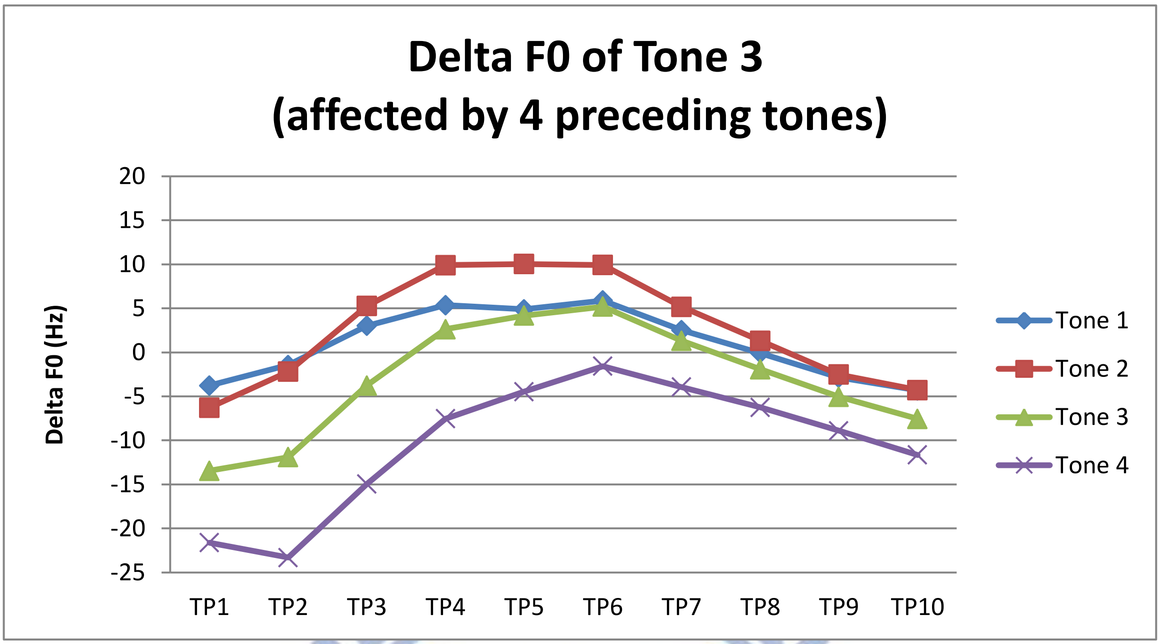

Figure 6. Contours of the delta F_0 of Tone 3 when affected by four preceding tones

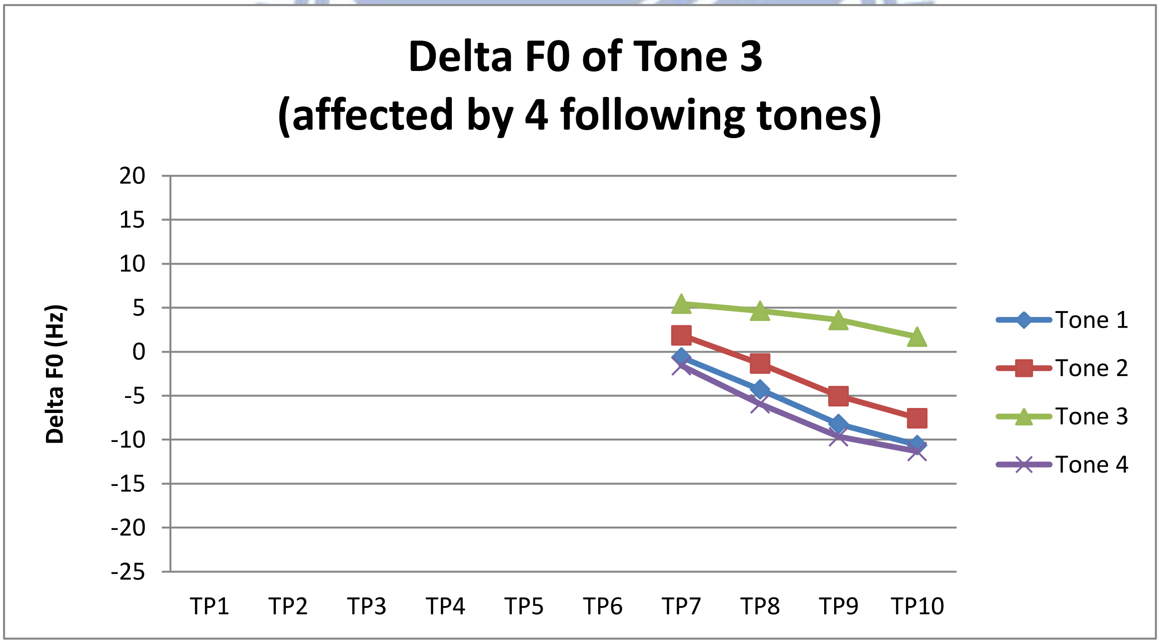

Figure 7. Contours of the delta F_0 of Tone 3 when affected by four following tones

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,69)=13.770	.000	*	(3,69)=12.802	.000	*	(3,69)=14.473	.000	*	(3,69)=17.933	.000	*	(3,69)=19.116	.000	*
following tone	(3,69)=.372	.773	n.s.	(3,69)=.152	.928	n.s.	(3,69)=.526	.666	n.s.	(3,69)=2.615	.058	n.s.	(3,69)=5.916	.001	*
preceding * following	(9,207)=1.249	.267	n.s.	(9,207)=1.517	.144	n.s.	(9,207)=1.512	.145	n.s.	(9,207)=1.616	.112	n.s.	(9,207)=1.802	.070	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,69)=19.605	.000	*	(3,69)=17.567	.000	*	(3,69)=12.732	.000	*	(3,69)=8.641	.000	*	(3,69)=11.792	.000	*
following tone	(3,69)=6.783	.000	*	(3,69)=5.145	.003	*	(3,69)=2.711	.052	n.s.	(3,69)=.755	.523	n.s.	(3,69)=2.334	.081	n.s.
preceding * following	(9,207)=1.944	.047	*	(9,207)=1.634	.107	n.s.	(9,207)=1.559	.130	n.s.	(9,207)=1.505	.148	n.s.	(9,207)=1.351	.212	n.s.

Table 10. The ANOVA results of Experiment I **(Target – Tone4)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* -0.5 / -3.6 / -13.8 / -15.3	* -5.4 / -7.8 / -21.0 / -24.4	* 6.4 / 5.8 / -6.3 / -9.1	* 18.2 / 18.9 / 8.9 / 7.7	* 27.9 / 28.9 / 21.0 / 20.5
following tone	n.s.	n.s.	n.s.	n.s.	* 22.5 / 26.0 / 26.5 / 23.3
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	* 34.0 / 34.9 / 28.5 / 28.0	* 37.0 / 37.7 / 32.1 / 31.8	* 34.7 / 35.1 / 30.4 / 30.3	* 29.8 / 29.9 / 26.3 / 26.1	* 25.0 / 24.5 / 20.3 / 20.6
following tone	* 29.4 / 32.4 / 33.5 / 30.1	* 32.8 / 35.5 / 36.7 / 33.9	n.s.	n.s.	n.s.

Table 11. Results for the post-hoc analysis in experiment I **(Target – Tone4)**

(The four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

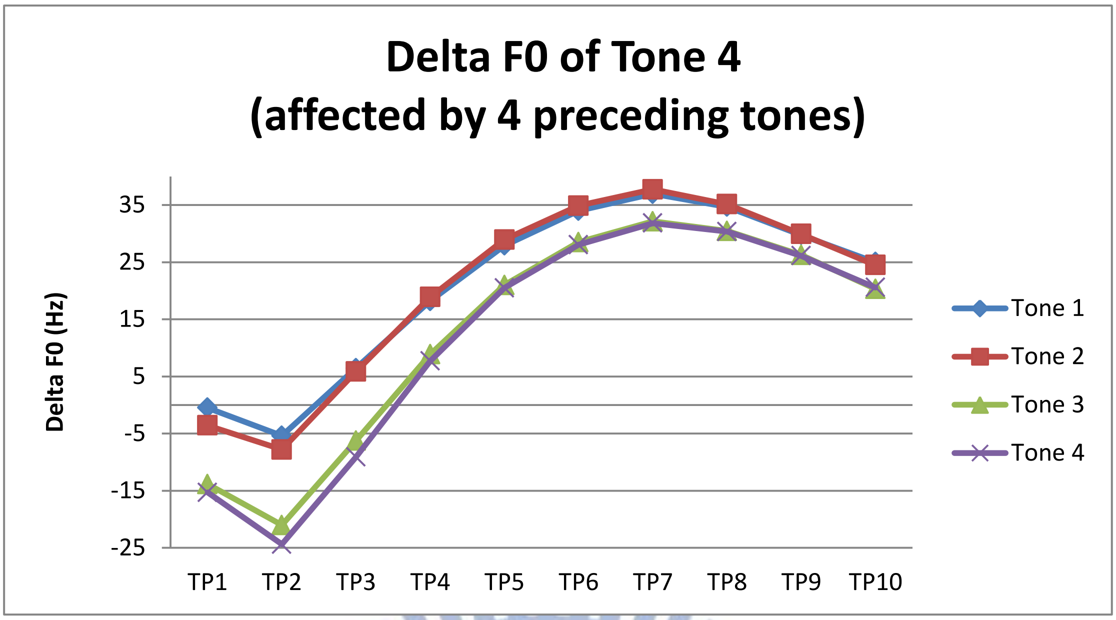

Figure 8. Contours of the delta F_0 of Tone 4 when affected by four preceding tones

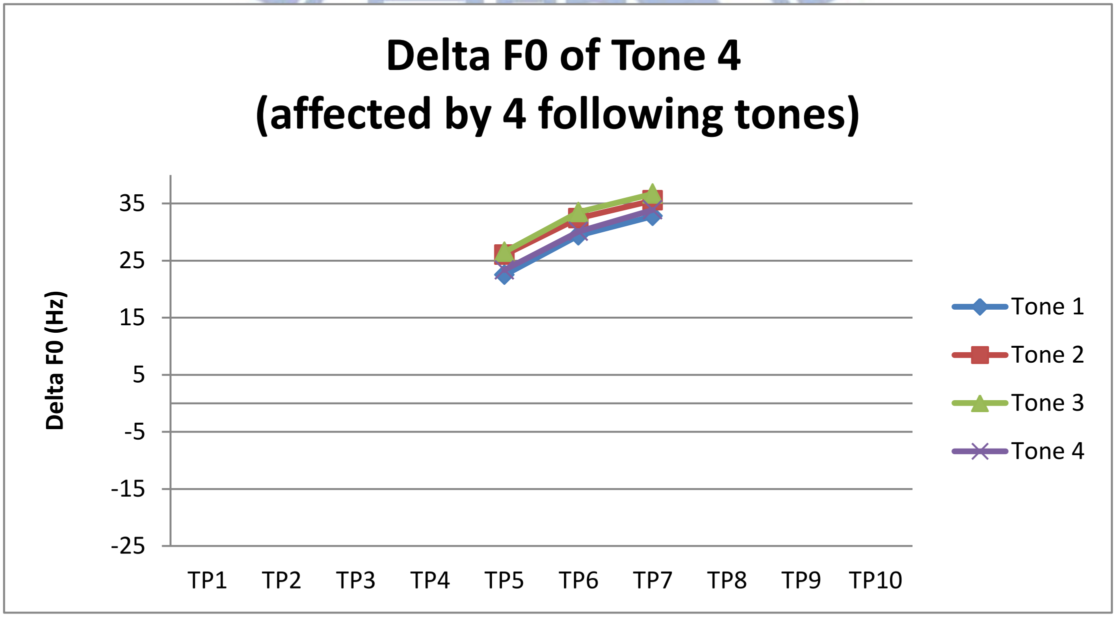

Figure 9. Contours of the delta F_0 of Tone 4 when affected by four following tones

4.3 Experiment II

MOA effects on tones of V_1

For each target tone of V_1, ten two-way repeated measure ANOVAs were conducted to evaluate the effects of Following tones (4 levels) and MOAs of the intervening C_2 (5 levels) on F_0 at the 10 measuring time points. The dependent variable is the F_0 differences between the target tone and its speaker-specific canonical form.

The results of target Tone 1 of V_1 is shown in Table 12, the main effect of Following tone is significant at TP1 and from TP3 to TP8 whereas the main effect of MOA is significant from TP3 to TP10. The interaction between following tone and MOA is not significant from TP5 to TP7. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 13 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 10 (a).

The results of target Tone 2 of V_1 is shown in Table 14, the main effect of Following tone is significant only at TP8 whereas the main effect of MOA is significant from TP9 to TP10. The interaction between following tone and MOA is significant only at TP9. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 15 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 10 (b).

The results of target Tone 3 of V_1 is shown in Table 16, the main effect of Following tone is significant only at TP2 whereas the main effect of MOA is significant from TP2 to TP4 and also TP10. The interaction between following tone and MOA is not significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 17 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 10 (c).

The results of target Tone 4 of V_1 is shown in Table 18, the main effect of Following tone is significant only at TP6 and from TP9 to TP10 whereas the main effect of MOA is significant from TP1 to TP3 and from TP8 to TP9. The interaction between following tone and MOA is significant in all 10 time points. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 19 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 10 (d).

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,48)=3.212	.031	*	(3,48)=1.401	.254	n.s.	(3,48)=2.938	.043	*	(3,48)=4.781	.005	*	(3,48)=4.450	.008	*
MOA	(4,64)=.641	.635	n.s.	(4,64)=1.173	.331	n.s.	(4,64)=3.402	.014	*	(4,64)=3.417	.014	*	(4,64)=3.244	.017	*
following tone *MOA	(12,192)=2.924	.001	*	(12,192)=4.365	.000	*	(12,192)=3.131	.000	*	(12,192)=1.936	.032	*	(12,192)=1.483	.133	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,48)=4.037	.012	*	(3,48)=4.396	.008	*	(3,48)=3.795	.016	*	(3,48)=1.473	.234	n.s.	(3,48)=1.185	.325	n.s.
MOA	(4,64)=3.566	.011	*	(4,64)=4.335	.004	*	(4,64)=5.021	.001	*	(4,64)=4.343	.004	*	(4,64)=4.081	.005	*
following tone *MOA	(12,192)=1.401	.168	n.s.	(12,192)=1.563	.105	n.s.	(12,192)=2.008	.025	*	(12,192)=2.446	.006	*	(12,192)=1.858	.042	*

Table 12. The ANOVA results of Experiment II **(V_1 Target - Tone1)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
following tone	* -0.2 / -7.8 / -0.7 / 3.5	n.s.	* 0.2 / 0.9 / 0.9 / 5.6	* 0.7 / 1.2 / 1.5 / 7.3	* 0.9 / 1.1 / 1.7 / 7.0
MOA	n.s.	n.s.	* 2.9 / 3.0 / 0.5 / 1.0 / 2.3	* 3.5 / 3.8 / 1.5 / 1.6 / 3.0	* 3.4 / 3.9 / 1.8 / 1.5 / 2.9
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
following tone	* 0.7 / 0.8 / 1.1 / 6.3	* 0.1 / 0.8 / 0.1 / 5.7	* -0.8 / 2.0 / 0.3 / 4.8	n.s.	n.s.
MOA	* 3.0 / 3.5 / 1.4 / 0.9 / 2.3	* 2.6 / 3.1 / 0.9 / 0.3 / 1.4	* 2.6 / 3.3 / 0.8 / 0.3 / 0.9	* 3.2 / 4.4 / 2.0 / 1.6 / 1.4	* 4.7 / 6.2 / 3.8 / 4.0 / 2.5

Table 13. Results for the post-hoc analysis in experiment II **(V_1 Target - Tone1)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,42)=1.967	.134	n.s.	(3,42)=.080	.970	n.s.	(3,42)=1.095	.362	n.s.	(3,42)=.592	.624	n.s.	(3,42)=.088	.966	n.s.
MOA	(4,56)=1.488	.218	n.s.	(4,56)=1.086	.372	n.s.	(4,56)=.296	.879	n.s.	(4,56)=.144	.965	n.s.	(4,56)=.364	.834	n.s.
following tone *MOA	(12,168)=0.822	.628	n.s.	(12,168)=1.188	.295	n.s.	(12,168)=.944	.505	n.s.	(12,168)=.705	.745	n.s.	(12,168)=.778	.673	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,42)=.775	.514	n.s.	(3,42)=.790	.506	n.s.	(3,42)=3.091	.037	*	(3,42)=1.103	.359	n.s.	(3,42)=1.857	.152	n.s.
MOA	(4,56)=.964	.434	n.s.	(4,56)=1.748	.151	n.s.	(4,56)=2.259	.074	n.s.	(4,56)=2.839	.033	*	(4,56)=2.821	.033	*
following tone *MOA	(12,168)=.937	.512	n.s.	(12,168)=.648	.799	n.s.	(12,168)=1.570	.105	n.s.	(12,168)=2.067	.022	*	(12,168)=1.609	.093	n.s.

Table 14. The ANOVA results of Experiment II **(V_1 Target – Tone2)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
following tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	n.s.	n.s.	n.s.	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
following tone	n.s.	n.s.	* -6.7 / -7.8 / -10.7 / -5.4	n.s.	n.s.
MOA	n.s.	n.s.	n.s.	* -7.5 / -6.4 / -8.6 / -8.6 / -6.6	* -5.1 / -3.7 / -6.6 / -5.6 / -4.3

Table 15. Results for the post-hoc analysis in experiment II **(V_1 Target – Tone2)**

(In 'following tone' column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In 'MOA' column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,33)=0.236	.870	n.s.	(3,33)=3.738	.020	*	(3,33)=1.499	.233	n.s.	(3,33)=1.491	.235	n.s.	(3,33)=2.726	.060	n.s.
MOA	(4,44)=1.499	.219	n.s.	(4,44)=5.646	.001	*	(4,44)=7.337	.000	*	(4,44)=4.000	.007	*	(4,44)=1.969	.116	n.s.
following tone *MOA	(12,132)=0.659	.788	n.s.	(12,132)=1.101	.365	n.s.	(12,132)=.962	.489	n.s.	(12,132)=.573	.861	n.s.	(12,132)=.724	.726	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,33)=1.354	.274	n.s.	(3,33)=.475	.702	n.s.	(3,33)=.890	.456	n.s.	(3,33)=.739	.536	n.s.	(3,33)=.837	.483	n.s.
MOA	(4,44)=1.623	.185	n.s.	(4,44)=1.409	.247	n.s.	(4,44)=1.240	.308	n.s.	(4,44)=1.469	.228	n.s.	(4,44)=3.582	.013	*
following tone *MOA	(12,132)=1.035	.421	n.s.	(12,132)=1.073	.388	n.s.	(12,132)=.979	.473	n.s.	(12,132)=.871	.578	n.s.	(12,132)=.737	.713	n.s.

Table 16. The ANOVA results of Experiment II **(V_1 Target – Tone3)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
following tone	n.s.	* 9.3 / 10.5 / 3.9 / 2.7	n.s.	n.s.	n.s.
MOA	n.s.	* 8.1 / 4.3 / 7.4 / 5.9 / 7.4	* 9.2 / 5.0 / 7.2 / 6.6 / 7.8	* 8.9 / 6.0 / 6.5 / 6.6 / 7.5	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
following tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	n.s.	n.s.	n.s.	n.s.	* 12.8 / 15.0 / 10.2 / 10.0 / 12.6

Table 17. Results for the post-hoc analysis in experiment II **(V_1 Target – Tone3)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,48)=1.324	.278	n.s.	(3,48)=1.908	.141	n.s.	(3,48)=2.294	.090	n.s.	(3,48)=2.482	.072	n.s.	(3,48)=2.587	.064	n.s.
MOA	(4,64)=3.355	.015	*	(4,64)=4.306	.004	*	(4,64)=3.664	.009	*	(4,64)=2.438	.056	n.s.	(4,64)=1.627	.178	n.s.
following tone *MOA	(12,192)=2.457	.005	*	(12,192)=4.804	.000	*	(12,192)=5.377	.000	*	(12,192)=3.924	.000	*	(12,192)=3.081	.001	*
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
following tone	(3,48)=2.932	.043	*	(3,48)=1.963	.132	n.s.	(3,48)=2.083	.115	n.s.	(3,48)=3.413	.025	*	(3,48)=4.237	.010	*
MOA	(4,64)=1.528	.205	n.s.	(4,64)=2.012	.103	n.s.	(4,64)=2.367	.042	*	(4,64)=2.871	.030	*	(4,64)=1.750	.150	n.s.
following tone *MOA	(12,192)=3.002	.001	*	(12,192)=3.160	.000	*	(12,192)=3.263	.000	*	(12,192)=3.014	.001	*	(12,192)=2.815	.001	*

Table 18. The ANOVA results of Experiment II **(V_1 Target – Tone4)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
following tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	* -5.8 / -4.3 / -6.5 / -4.2 / -9.3	* -12.1 / -12.1 / -11.0 / -10.2 / -15.6	* -6.1 / -6.6 / -5.0 / -3.8 / -8.5	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
following tone	* 2.4 / 5.7 / 3.6 / 1.4	n.s.	n.s.	* 6.1 / 14.2 / 11.8 / 7.4	* 5.2 / 15.5 / 11.4 / 6.5
MOA	n.s.	n.s.	* 7.9 / 7.8 / 7.8 / 10.7 / 7.7	* 9.1 / 9.7 / 9.4 / 12.1 / 9.2	n.s.

Table 19. Results for the post-hoc analysis in experiment II **(V_1 Target – Tone4)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

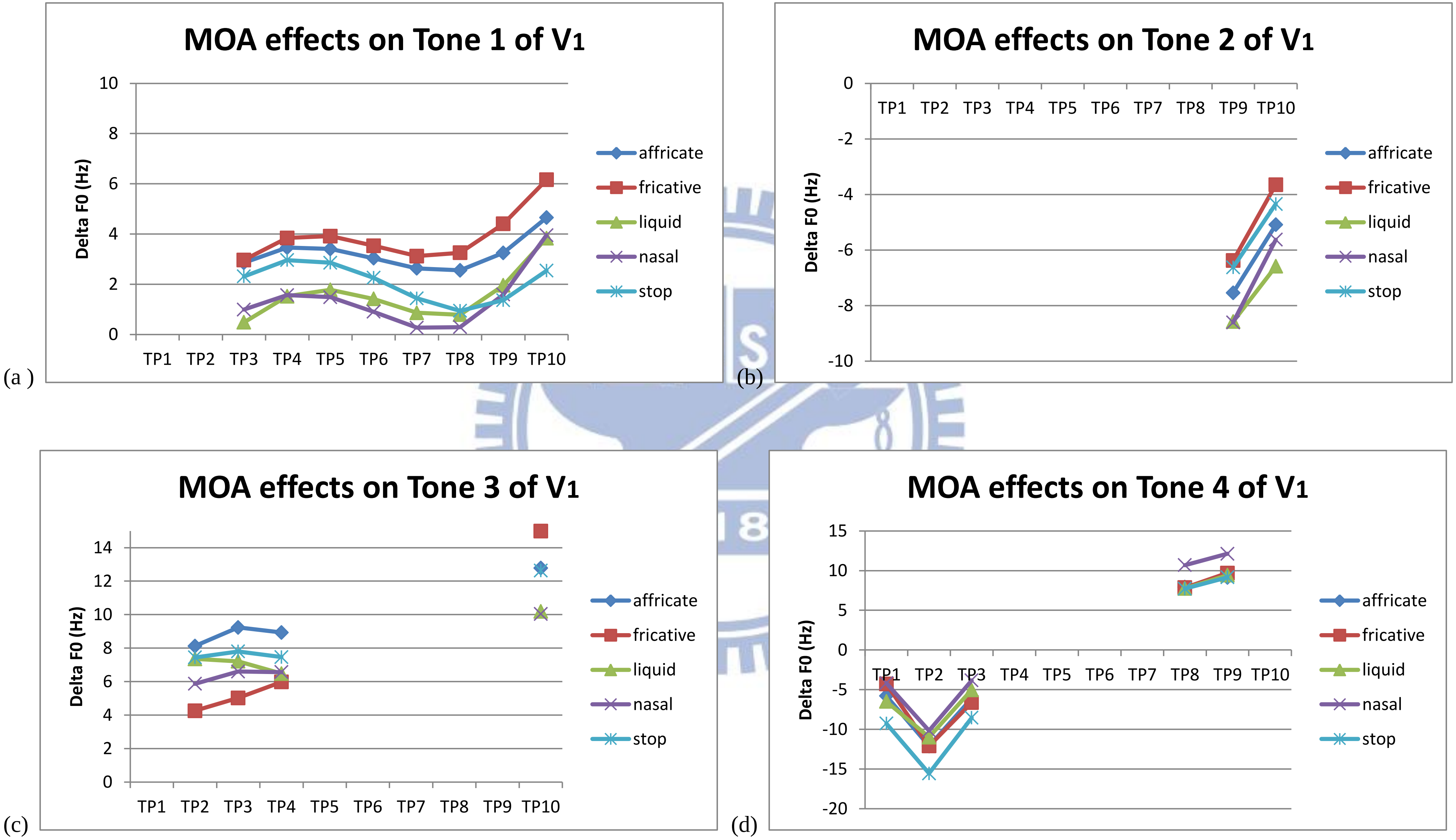

Figure 10. Contours of the delta F_0 of Tones on V_1 when affected by five MOAs

MOA effects on tones of V_2

For each target tone of V_2, ten two-way repeated measure ANOVAs were conducted to evaluate the effects of Preceding tones (4 levels) and MOAs of the intervening C_2 (5 levels) on F_0 at the 10 measuring time points. The dependent variable is the F_0 differences between the target tone and its speaker-specific canonical form.

The results of target Tone 1 of V_2 is shown in Table 20, the main effect of Preceding tone is significant from TP1 to TP2 and from TP4 to TP9 whereas the main effect of MOA is significant from TP1 to TP2. The interaction between preceding tone and MOA is not significant from TP2 to TP10. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 21 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 11 (a).

The results of target Tone 2 of V_2 is shown in Table 22, the main effect of Preceding tone is not significant across all ten time points whereas the main effect of MOA is significant from TP2 to TP5 and from TP9 to TP10. The interaction between preceding tone and MOA is not significant at TP1and from TP5 to TP10. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 23 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 11 (b).

The results of target Tone 3 of V_2 is shown in Table 24, the main effect of Preceding tone is significant from TP2 to TP4 whereas the main effect of MOA is significant only at TP3. The interaction between preceding tone and MOA is not significant from TP7 to TP10.

In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 25 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 11 (c).

The results of target Tone 4 of V_2 is shown in Table 26, the main effect of Preceding tone is significant from TP1 to TP3 whereas the main effect of MOA is significant from TP1 to TP2 and at TP6. The interaction between preceding tone and MOA is not significant from TP2 to TP7 and at TP9. In cases where the main effect is significant, Tukey post-hoc comparison was conducted for the pairwise comparison between each tone. Table 27 shows the results of all the post-hoc analysis (degree of confidence - 95%). According to the results from the post-hoc comparison, the values of mean delta F_0 caused by each MOA are further displayed in Figure 11 (d).

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,66)=18.090	.000	*	(3,66)=3.111	.032	*	(3,66)=1.499	.223	n.s.	(3,66)=3.052	.035	*	(3,66)=5.858	.001	*
MOA	(4,88)=10.670	.000	*	(4,88)=9.965	.000	*	(4,88)=1.551	.195	n.s.	(4,88)=.683	.606	n.s.	(4,88)=.923	.455	n.s.
preceding tone *MOA	(12,264)=1.992	.025	*	(12,264)=1.476	.133	n.s.	(12,264)=1.410	.161	n.s.	(12,264)=1.581	.097	n.s.	(12,264)=1.356	.187	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,66)=4.909	.004	*	(3,66)=4.616	.005	*	(3,66)=6.701	.001	*	(3,66)=3.347	.024	*	(3,66)=2.462	.070	n.s.
MOA	(4,88)=1.446	.226	n.s.	(4,88)=2.192	.076	n.s.	(4,88)=2.064	.092	n.s.	(4,88)=.979	.424	n.s.	(4,88)=.697	.596	n.s.
preceding tone *MOA	(12,264)=.997	.453	n.s.	(12,264)=1.222	.268	n.s.	(12,264)=1.709	.065	n.s.	(12,264)=1.479	.132	n.s.	(12,264)=1.369	.181	n.s.

Table 20. The ANOVA results of Experiment II **(V_2 Target - Tone1)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* 3.3 / -2.9 / 8.4 / 10.1	* 4.3 / 0.6 / 5. 5/ 5.9	n.s.	* -0.6 / -3.3 / -2.7 / -4.0	* -0.6 / -3.6 / -4.3 / -4.5
MOA	* 6.8 / 7.4 / 2.3 / 2.8 / 4.3	* 6.3 / 6.7 / 1.6 / 2.4 / 3.4	n.s.	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	* -1.0 / -3.9 / -4.4 / -4.5	* -1.4 / -4.1 / -4.4 / -5.2	* -0.1 / -4.1 / -4.4 / -5.2	* 0.0 / -4.7 / -3.2 / -4.6	n.s.
MOA	n.s.	n.s.	n.s.	n.s.	n.s.

Table 21. Results for the post-hoc analysis in experiment II **(V_2 Target - Tone1)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,30)=1.619	.206	n.s.	(3,30)=2.020	.132	n.s.	(3,30)=1.593	.212	n.s.	(3,30)=.210	.889	n.s.	(3,30)=.878	.464	n.s.
MOA	(4,40)=.845	.505	n.s.	(4,40)=2.856	.036	*	(4,40)=4.879	.003	*	(4,40)=4.645	.004	*	(4,40)=3.774	.011	*
preceding tone *MOA	(12,120)=1.550	.116	n.s.	(12,120)=3.117	.001	*	(12,120)=2.940	.001	*	(12,120)=2.258	.013	*	(12,120)=1.525	.124	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,30)=.751	.530	n.s.	(3,30)=.258	.855	n.s.	(3,30)=1.155	.343	n.s.	(3,30)=1.374	.270	n.s.	(3,30)=2.362	.091	n.s.
MOA	(4,40)=2.474	.060	n.s.	(4,40)=1.367	.263	n.s.	(4,40)=1.919	.126	n.s.	(4,40)=2.624	.049	*	(4,40)=4.170	.006	*
preceding tone *MOA	(12,120)=.854	.595	n.s.	(12,120)=.691	.757	n.s.	(12,120)=.863	.586	n.s.	(12,120)=1.154	.324	n.s.	(12,120)=1.148	.329	n.s.

Table 22. The ANOVA results of Experiment II **(V_2 Target – Tone2)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	n.s.	* 12.1 / 10.3 / 14.6 / 14.8 / 12.6	* 8.0 / 7.0 / 10.6 / 12.6 / 9.3	* 6.7 / 5.9 / 8.5 / 10.6 / 6.8	* 5.4 / 4.3 / 6.8 / 8.6 / 5.1
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	n.s.	n.s.	n.s.	* -4.3 / 0.0 / -0.3 / -2.0 / -1.6	* -9.1 / -3.6 / -4.4 / -6.1 / -4.7

Table 23. Results for the post-hoc analysis in experiment II **(V_2 Target – Tone2)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,42)=2.606	.064	n.s.	(3,42)=7.332	.000	*	(3,42)=8.621	.000	*	(3,42)=3.791	.017	*	(3,42)=1.018	.394	n.s.
MOA	(4,56)=1.287	.286	n.s.	(4,56)=1.669	.170	n.s.	(4,56)=2.534	.050	*	(4,56)=2.315	.069	n.s.	(4,56)=1.581	.192	n.s.
preceding tone *MOA	(12,168)=1.822	.048	*	(12,168)=2.618	.003	*	(12,168)=2.314	.009	*	(12,168)=2.017	.025	*	(12,168)=2.340	.008	*
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,42)=.430	.732	n.s.	(3,42)=.910	.444	n.s.	(3,42)=1.824	.157	n.s.	(3,42)=1.903	.144	n.s.	(3,42)=2.051	.121	n.s.
MOA	(4,56)=.933	.452	n.s.	(4,56)=.371	.828	n.s.	(4,56)=.232	.919	n.s.	(4,56)=.190	.943	n.s.	(4,56)=.330	.857	n.s.
preceding tone *MOA	(12,168)=2.434	.006	*	(12,168)=1.738	.063	n.s.	(12,168)=1.256	.249	n.s.	(12,168)=1.124	.344	n.s.	(12,168)=1.172	.307	n.s.

Table 24. The ANOVA results of Experiment II **(V_2 Target – Tone3)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	n.s.	* 10.3 / 14.0 / 17.2 / -3.5	* 3.7 / 6.0 / 14.2 / -5.9	* 1.4 / 2.5 / 9.2 / -3.7	n.s.
MOA	n.s.	n.s.	* 6.7 / 0.0 / 4.8 / 9.6 / 1.5	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	n.s.	n.s.	n.s.	n.s.	n.s.

Table 25. Results for the post-hoc analysis in experiment II **(V_2 Target – Tone3)**

(In ‘following tone’ column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In ‘MOA’ column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

	Time Point 1			Time Point 2			Time Point 3			Time Point 4			Time Point 5		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,48)=16.067	.000	*	(3,48)=9.506	.000	*	(3,48)=3.952	.013	*	(3,48)=1.662	.188	n.s.	(3,48)=.731	.538	n.s.
MOA	(4,64)=11.151	.000	*	(4,64)=10.099	.000	*	(4,64)=1.941	.114	n.s.	(4,64)=.565	.689	n.s.	(4,64)=1.909	.120	n.s.
preceding tone *MOA	(12,192)=2.523	.004	*	(12,192)=1.208	.280	n.s.	(12,192)=.522	.899	n.s.	(12,192)=.454	.939	n.s.	(12,192)=.663	.785	n.s.
	Time Point 6			Time Point 7			Time Point 8			Time Point 9			Time Point 10		
	F value	P value		F value	P value		F value	P value		F value	P value		F value	P value	
preceding tone	(3,48)=.620	.605	n.s.	(3,48)=.211	.888	n.s.	(3,48)=.073	.974	n.s.	(3,48)=.914	.441	n.s.	(3,48)=1.572	.208	n.s.
MOA	(4,64)=3.802	.008	*	(4,64)=2.491	.052	n.s.	(4,64)=1.618	.181	n.s.	(4,64)=1.550	.198	n.s.	(4,64)=1.504	.212	n.s.
preceding tone *MOA	(12,192)=1.372	.182	n.s.	(12,192)=1.657	.079	n.s.	(12,192)=1.830	.046	*	(12,192)=1.774	.055	n.s.	(12,192)=1.925	.034	*

Table 26. The ANOVA results of Experiment II **(V_2 Target – Tone4)**

	Time Point 1	Time Point 2	Time Point 3	Time Point 4	Time Point 5
preceding tone	* 0.7 / -3.6 / 16.2 / 6.3	* 6.1 / -0.7 / 14.4 / 5.1	* 2.4 / -2.2 / 7.2 / 1.9	n.s.	n.s.
MOA	* 7.2 / 7.4 / 2.4 / 1.5 / 6.5	* 9.4 / 9.0 / 2.9 / 2.8 / 7.1	n.s.	n.s.	n.s.
	Time Point 6	Time Point 7	Time Point 8	Time Point 9	Time Point 10
preceding tone	n.s.	n.s.	n.s.	n.s.	n.s.
MOA	* -2.0 / 1.6 / 1.2 / 2.7 / -3.1	n.s.	n.s.	n.s.	n.s.

Table 27. Results for the post-hoc analysis in experiment II **(V_2 Target – Tone4)**

(In 'following tone' column, the four numbers under the significant star refers to the mean delta F_0 caused by Tone 1 / Tone 2 / Tone 3 / Tone 4 in order.)

(In 'MOA' column, the five numbers under the significant star refers to the mean delta F_0 caused by affricate / fricative / liquid / nasal / stop in order.)

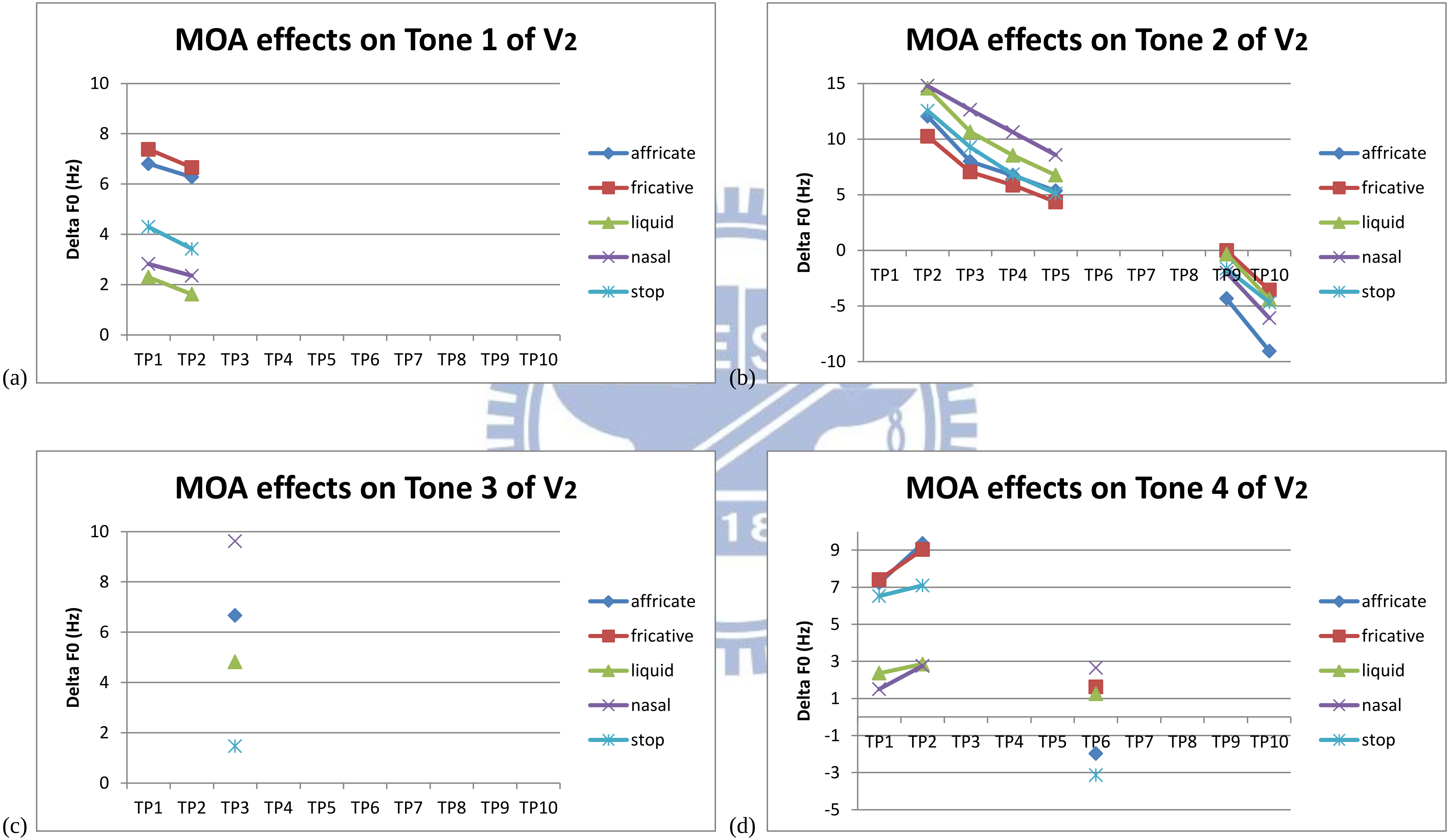

Figure 11. Contours of the delta F_0 of Tones on V_2 when affected by five MOAs

Summary of Experiment II

The result above shows that the main effect of MOA is significant in limited extent both on V_1 and V_2. Only when Tone 1 is at V_1, Tone 4 at V_1 and Tone 2 at V_2 got influenced more than half of the syllable. Besides, many of the significant effects scattered across various measured time points without continuous influence. The magnitude of MOA effect is also limited in the results. Most of the range between the maximum and the minimum delta F_0 caused by different MOAs is under 15 Hz except for Tone 4 at V_1 (the range is about 28 Hz) and Tone 2 at V_2 (the range is about 24 Hz). The most important thing is that by examining the post-hoc information, it was found out that the delta F_0 caused by five MOAs do not always show a regular pattern. That is, it is hard to organize the values of delta F_0 caused by five MOAs in a certain order. Nevertheless, something interesting is that the values of delta F_0 are likely to distribute by group: though there is no specific order, most of values caused by liquid and nasal are close to each other, and most of values caused by stop, fricative and affricate are also relatively close. Therefore, the data of delta F_0 is further merged into two groups by sonorancy: sonorants (including liquid and nasal) and obstruents (including stop, fricative and affricate). The results of sonorancy effect on both V_1 and V_2 are shown in Figure 12 and 13. To conclude, the delta F_0 caused by intervening sonorants and obstruents still show an inconsistent pattern: for target Tone 2 and Tone 4, the delta F_0 caused by sonorants is greater than obstruents at some time points, which echoes to the hypothesis of this study. However, at more time points the effects of sonorants and obstruents are totally opposite.

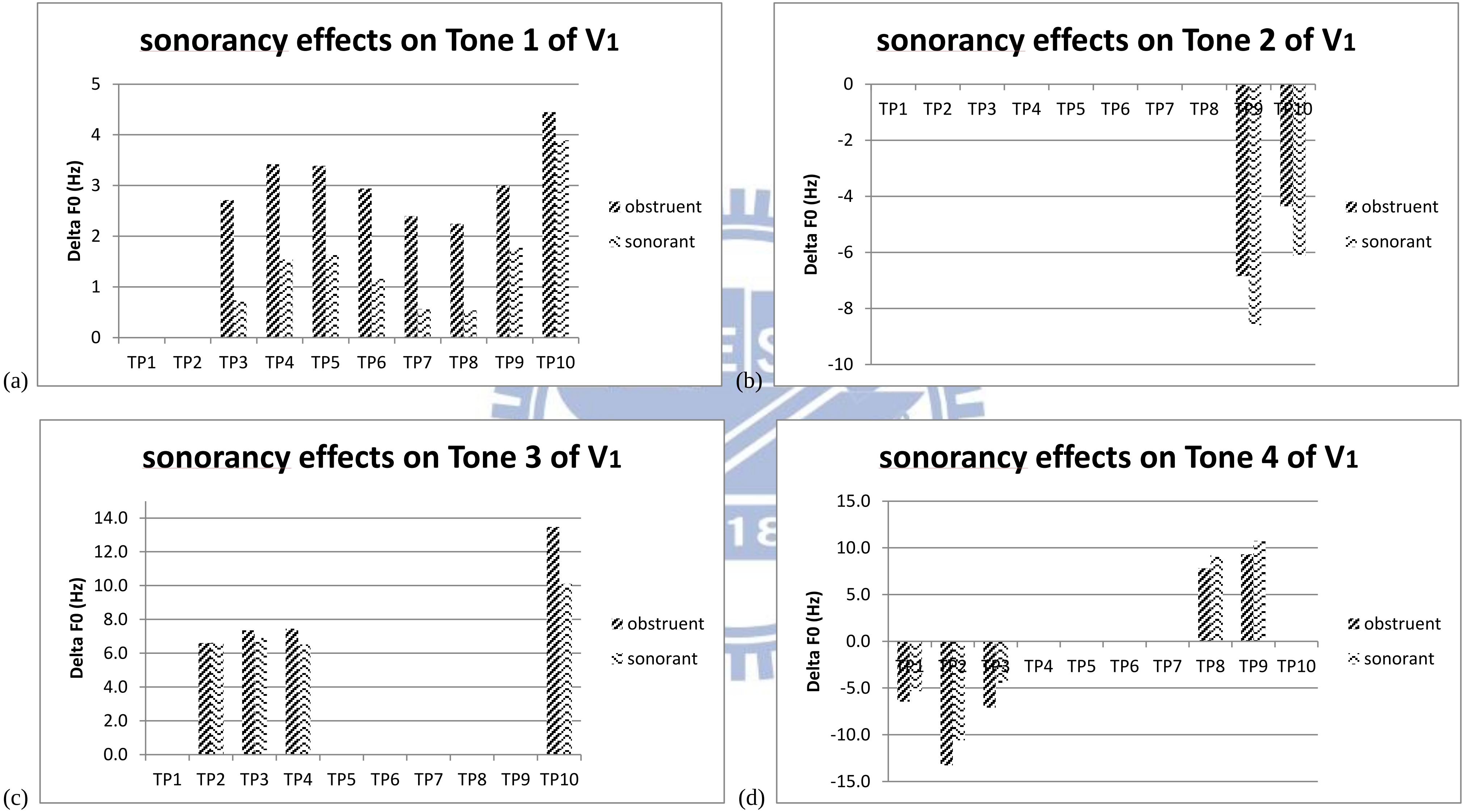

Figure 12. Comparison between the delta F_0 of Tones on V_1 when affected by sonorants and obstruents

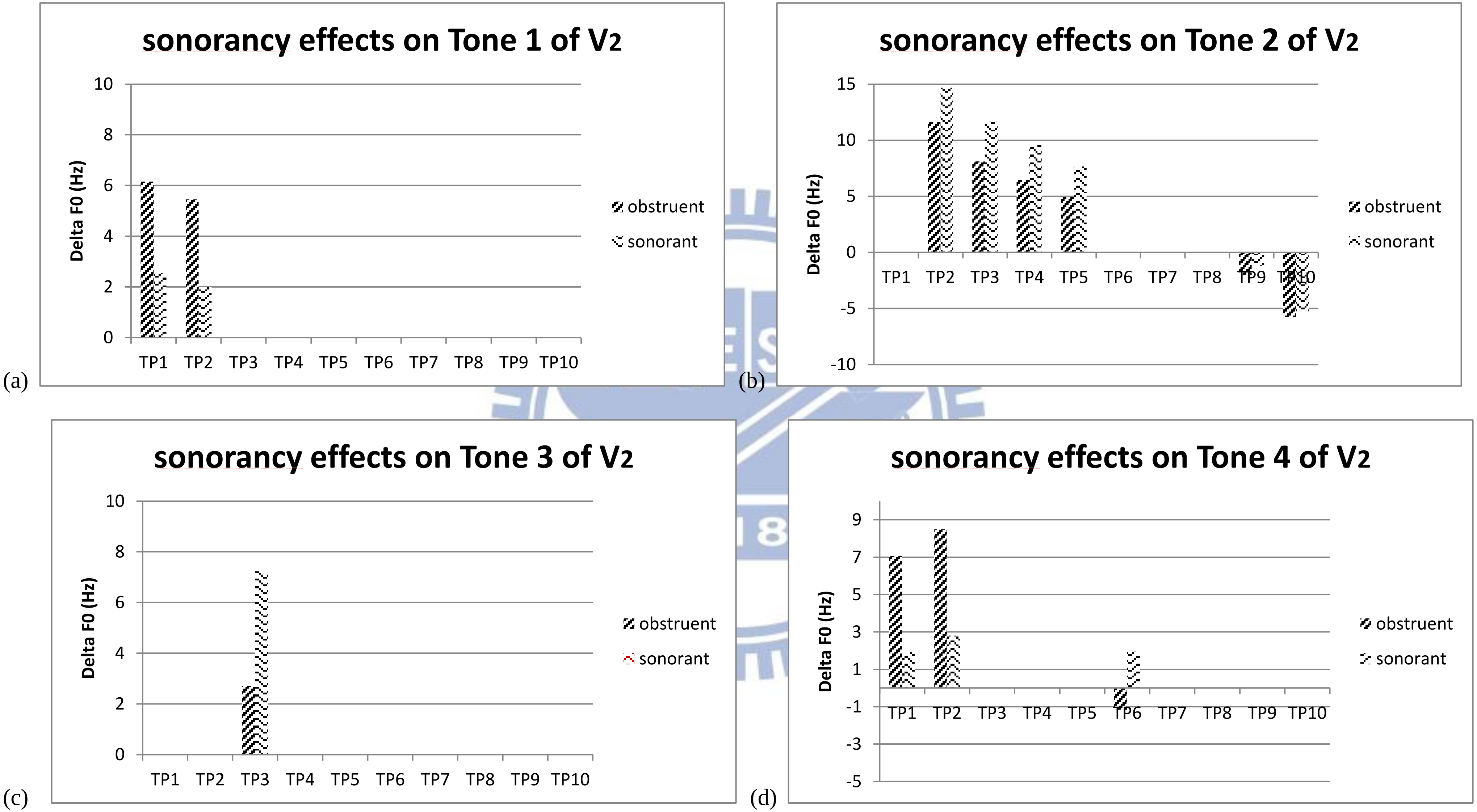

Figure 13. Comparison between the delta F_0 of Tones on V_2 when affected by sonorants and obstruents

5. Discussion

The present study contains two main experiments. Experiment I aims to re-examine the directionality, the temporal extent and the magnitude of Mandarin tonal coarticulation. Also, the target and trigger in tonal coarticulation are discussed. Trisyllabic non-words were adopted to examine the effects on the middle target from both preceding and following tones. The delta F_0 of 10 measured points between targets and the speaker-specific canonical forms were counted to compare the coarticulatory effect of each tonal context. The results show that carryover effect is more prevailing than anticipatory effect by having greater temporal extent and magnitude. This is different from the finding of Shen (1990), but agrees with Xu (1993 &1997). Moreover, this study provides a more detailed description on both target and trigger involved in tonal coarticulation. Target tones are discussed through two affected aspects: temporal extent and magnitude. Triggers, on the other hand, are discussed by examining the specific onset or offset related to coarticulatory effects.

Experiment II was designed to investigate whether different MOAs of intervening consonants has different effects on Mandarin tonal coarticulation. Disyllabic real words intervened by consonants with five MOAs were adopted as stimuli (Five MOAs are: affricate, fricative, liquid, nasal and stop). Tones of vowels in both syllables (V_1 and V_2) were examined. The delta F_0 of 10 measured points between targets and the speaker-specific canonical forms were counted to compare the coarticulatory effect. It was assumed that consonants with obstruent features like affricate, fricative or stop will reduce tonal coarticulation. Results of five MOAs do not perform regularly, and even if further analyzed by dividing the data into two groups: sonorants and obstruents, the hypothesis is not verified according to the result. No specific pattern shows that intervening obstruents tend to reduce the tonal coarticulation.

5.1 Re-examination of Mandarin Tonal coarticulation

In terms of the both directions in Mandarin tonal coarticulation, Shen (1990) proposed that both carryover and anticipatory effects are equal, while Xu (1993, 1997) argued that carryover effect is more dominant than anticipatory effect. According to the results shown in the previous chapter, for all target tones, the main effect of Preceding tone is significant across all measured time points, which indicates that the carryover effect from preceding tones can extend to the whole syllable of all target tones. However, the main effect of Following tone is significant with more limited extent. Only Tone 2 and Tone 1 got influenced significantly across more than half of the syllable. That is, the extent of the anticipatory effect from following tones is smaller. Besides, the magnitude of the delta F_0 variation caused by two directions is also different. By calculating the range between the maximum and the minimum value of delta F_0, the variation caused by the preceding tone is at least 28 Hz while the variation by the following tone is no more than 20 Hz across four target tones. This implies that the range of delta F_0 varied by carryover effect is greater than by anticipatory effect. To conclude from both aspects of temporal extent and delta F_0 magnitude, the data in this study showed that carryover effect is much more prevailing than anticipatory effect in tonal coarticulation. This echoes the statement of Xu (1993, 1997) but not Shen’s (1990). The conflicting finding from Shen’s (1990) is probably resulted from the inadequacy of her experiment. As she measured only onset, offset and the turning point (if there is any turning point), the tonal variation across the whole syllable duration is unclear. Therefore, it would be too rough to define that any difference of the target onset or offset is affected exactly by carryover effect or by anticipatory effect. Moreover, Shen's data was limited that it comes from only two speakers. If there was any speaker difference in recording, the conclusion will be more different from the way most people produced.

Tones as targets of tonal coarticulation were not consistent in previous studies. Lin & Yan (1992) proposed that Tone 1, Tone 2 and Tone 3 have greater F_0 variation under carryover effect while Tone 4 is more susceptible to anticipatory effect. Xu (1994) argued that Tone 1 and Tone 2 get more carryover effect because of the larger affected extent and Tone 1 gets most anticipatory effect. Xu (1997) also provided another statement that Tone 2 and Tone 4 are targets of anticipatory effect because their F_0 get larger variation from following tones. The problem is that not only different tones were defined as targets, but the criteria to define also diverse. In this study, tones being affected by coarticulation are examined through two aspects: the extent and the magnitude. Under carryover effect, four tones share the same affected extent as the effect extends to 10 measured time points on them equally. But four tones have different magnitude of F_0 variation. By comparing the range between their maximum and minimum delta F_0 in magnitude, the order of range is like Tone 4 > Tone 1 > Tone 3 > Tone 2 (The range of Tone 4 is about 62 Hz, of Tone 1 is about 42 Hz, of Tone 3 is about 33 Hz and of Tone 2 is about 29 Hz). This order shows that Tone 4 gets the largest F_0 variation by carryover effect. In terms of anticipatory effect, four tones have different results on extent and magnitude. The extent of anticipatory effect is under the order that Tone 2 > Tone 1 > Tone 3 > Tone 4 (9 time points of Tone 2 are affected, 6 time points of Tone1, 4 time points of Tone 3 and 3 time points of Tone 4). And the magnitude of anticipatory effect is under the order that Tone 2 > Tone 3 > Tone 4 > Tone 1(The range of Tone 2 is about 20 Hz, of Tone 3 is about 17 Hz, of Tone 4 is about 13 Hz and of Tone 1 is about 8 Hz). Therefore, Tone 2 gets varied the most both from the temporal extent and the magnitude of anticipatory effect. In conclusion, the temporal extent of carryover effect is equal across four tones, but the magnitude is largest on Tone 4. And Tone 2 is the most obvious target of anticipatory effect from both the temporal extent and the magnitude.

Tones as triggers of tonal coarticulation were discussed only by Shen (1990) and Xu (1997). Shen (1990) proposed that Tone 1 and Tone 2 trigger most carryover effects as the F_0 of their following tones has the largest variation. Tone 4 and Tone 1 are anticipatory triggers as the F_0 of their preceding tones varied the most. From Xu's (1997) results he concluded that Tone 3 is the most significant trigger for anticipatory effect since it causes more variation on its preceding tones. As the tone which causes the largest F_0 variation on its adjacent tones is taken as the trigger of tonal coarticulation, based on the results of post-hoc comparison in previous chapter, trigger tones at each time point for four target tones are listed in Table 28 and Table 29.

time point target tone	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10
Tone 1	T3	T3	T1	T1	T1	T1	T1	T1	T1	T1
Tone 2	T3	T2	T2	T2	T2	T2	T2	T3	T3	T3
Tone 3	T4	T4	T4	T2	T2	T2	T2	T4	T4	T4
Tone 4	T4	T4	T4	T2	T2	T2	T2	T2	T2	T1

Table 28. The trigger tones of carryover effect

time point target tone	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10
Tone 1	n.s.	n.s.	n.s.	n.s.	T3	T3	T3	T2	T2	T2
Tone 2	T4	n.s.	T3	T3	T3	T3	T3	T1	T1	T1
Tone 3	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	T3	T4	T4	T4
Tone 4	n.s.	n.s.	n.s.	n.s.	T3	T3	T3	n.s.	n.s.	n.s.

Table 29. The trigger tones of anticipatory effect

(The 'n.s.' refers that the anticipatory effect is not significant at that time point)

However, some problems will be found when these trigger tones are examined carefully. First, no regular pattern exists. Not only that four target tones are affected by different triggers, but even a certain target tone is affected by different triggers across ten time points. Also, if we re-inspect the data of post-hoc comparison, it will be found out that at some time points the F_0 variation caused by the 'second' trigger is very similar to the 'top' trigger, which makes the trigger in tonal coarticulation become more complicated. Therefore, it is problematic to define triggers in tonal coarticulation simply as the tones which caused largest variation on other tones. One possible way to resolve this is to narrow down the trigger to a smaller unit, which might provide more detailed information of tonal coarticulation. As Xu (1994) proposed that tonal coarticulation happens due to the tonal values adjacent to the target tones instead of the whole neighboring tones, another way is adopted to find possible triggers. That is, to exemplify those tonal values immediately next to the target tones.

For each target tone being affected by carryover effect, the results of F_0 value varied the most at each time point are examined to define which preceding offset tends to be the trigger. If the variation caused by the ‘second’ trigger is very similar to the ‘top’ trigger, both cases will be included. All of the results are presented in Table 30. To sum up, except for the final portion (TP8 to TP10) where the carryover effect is not the same on different target tones perhaps due to its far distance from the preceding trigger offset, the carryover effect is quite consistent on four target tones from TP1 to TP7. All target tones will firstly get lowered the most due to the preceding low offsets, and then from TP2, TP3 or TP4 will start to get raised the most due to the preceding high and mid offsets. Such different effects at different time points probably result from the nature of Mandarin tones. That is, instead of being level tones, Mandarin tones are contour tones which do not contain steady F_0 contours. Therefore, the change on these contour tones will not contain steady patterns, either. Besides, as the preceding low offsets lower the target tones and the preceding high and mid offsets raise them, assimilation is found in carryover coarticulation. In conclusion, under carryover assimilation, the preceding low offsets significantly lower the target tones for the time points in front, while the raising effect from preceding high and mid offsets will overwhelm it afterwards.

target Tone 1	TP1 to TP2 F_0 get lowered the most by preceding low offset (T3)	TP3 to TP10 F_0 get raised the most by preceding high and mid offset (T1 and T2)	
target Tone 2	TP1 F_0 get lowered the most by preceding low offset (T3)	TP2 to TP7 F_0 get raised the most by preceding mid and high offset (T2 and T1)	TP 8 to TP10 F_0 get lowered the most by preceding low offset (T3 and T4)
target Tone 3	TP1 to TP3 F_0 get lowered the most by preceding low offset (T4)	TP4 to TP7 F_0 get raised the most by preceding mid offset (T2)	TP 8 to TP10 F_0 get lowered the most by preceding low offset (T4)
target Tone 4	TP1 to TP3 F_0 get lowered the most by preceding low offset (T3 and T4)	TP4 to TP10 F_0 get raised the most by preceding high and mid offset (T1 and T2)	

Table 30. The preceding trigger offsets of carryover effect

target Tone 1		TP10 backward to TP5 F_0 get raised the most by following mid onset (T2 and T3)
target Tone 2	TP7 backward to TP3 F_0 get raised the most by following mid onsets (T3 and T2)	TP10 backward to TP8 F_0 get lowered the most by following high onsets (T1 and T4)
target Tone 3	at TP7 F_0 get raised the most by following mid onset (T3)	TP10 backward to TP8 F_0 get lowered the most by following high onset (T4)
target Tone 4	TP7 backward to TP5 F_0 get raised the most by following mid onsets (T3 and T2)	

Table 31. The following trigger onsets of anticipatory effect

The pattern of anticipatory effect from the following tone is very different from that of carryover effect. Table 31 shows the results of following trigger onsets of anticipatory effect by presenting the F_0 value varied the most at each time point where the anticipatory effect is significant. To sum up, in every case where the anticipatory effect is significant on target tones, it is the following mid or high onsets trigger the tonal coarticulation. Not like the situation of carryover effect in which all variation is assimilation, though following mid onsets also raise the F_0 of targets tones just like its raising effect in carryover coarticulation, following high onsets right behind the target Tone 2 and Tone 3 (tones with mid or low offsets) lowers the F_0 of targets for three time points (from TP10 backward to TP8) instead of raising it. (Although target Tone 4 also involves a low offset, the anticipatory effect on Tone 4 is not significant from TP10 backward to TP8.) Therefore, dissimilation exists in anticipatory coarticulation, and it happens to the preceding tones with mid or low offsets. When the preceding tone carries a high offset (Tone 1), it still undergoes the anticipatory assimilation from its following tonal onset.

Anticipatory dissimilation was also found in Thai (Gandour et al., 1992c; Potisuk et al., 1996) and in Mandarin (Xu, 1994 & 1997). To investigate the phenomena of anticipatory dissimilation, there should be two types included. For the first type, the following lower F_0 value raises the preceding higher F_0 value rather than lowers it. And the second type is opposite that the following higher F_0 value lowers the preceding lower F_0 value rather than raises it, just as the results shown in this study. The anticipatory dissimilation found in the studies of Gandour et al. (1992c), Potisuk et al. (1996), and Xu (1994 & 1997) belonged to the first type. Gandour et al. (1992c) discussed their results by explaining the adjustment of vocal folds. According to them, “The transition (of F_0 range) requires complex adjustments of the vocal folds. Because of vocal fold dynamics, one may speculate it is easier in some articulatory sense to move from an even higher F_0 to an extremely low F_0. This vocal fold adjustment is analogous to what happens when a semi-trailer swings wide to make a sharp right or left turn. The extra wide turn facilitates the movement from a street going in one direction to a street cutting off at a 90 degree angle. The anticipatory effects on the slope of the preceding falling tone are believed to follow as a consequence of the adjustments in height. From a given height to a fixed F_0 onset, the slope must necessarily be steeper from a higher F_0. Back to the semi-trailer analogy, the angle of the turn varies as a direct consequence of the wider swing around the corner."

However, Xu (1994) argued that the theory of Gandour et al. was too wide that both low-to-high F_0 transition and high-to-low F_0 transition should be possible. That is, according to Xu, "Not only should a high pitch target be raised by a following low pitch target, but also a low pitch target should be lowered by a following high pitch target." Since the latter situation (high-to-low F_0 transition) was not found in the results of Gandour et al. (1992c) and of Xu (1994), Xu (1994) suggested that the explanation of Gandour et al. does not suit to the fact. Therefore, Xu (1994 & 1997) provided another way to describe the anticipatory dissimilation. According to him, the 'High-Low' tonal sequence is similar to the pattern of intonation declination in which the pitch also goes from high to low. In order not to confuse both tonal pattern and declination contour, the difference between the 'High-Low' sequence must be exaggerated. According to Xu (1994), "however, due to the physical limit of the lower threshold, this exaggeration is accomplished by fully implementing the H target rather than by lowering L target." Xu's argument seems to make sense in some ways. However, even if it takes more efforts to reach a low pitch, it's still possible that the lowering effect can exist with a minor magnitude that does not extend lower than one's low threshold. The exaggeration should be possible to be completed by varying the F_0 of both targets. Moreover, since the second type of anticipatory dissimilation is found in this study, Xu's argument that Gandour et al. (1992c) had unsuitable explanation is not tenable anymore. Thus, the 'vocal fold adjustment' explanation from Gandour et al. (1992c) should be taken in again. That is, no matter the F_0 transition is from high-to-low or from low-to-high, the F_0 of the previous target will first raise or lower more to leave a greater range for easier transition to the next target F_0.

To conclude the Exp. I, in this study it is verified that carryover effect is much more prevailing than anticipatory effect from both the temporal extent and the magnitude. Tone 4 is most susceptible target to carryover effect due to the affected magnitude (all four target tones share the same temporal extent of carryover effect), and Tone 2 is most susceptible target to anticipatory effect due to both the extent and the magnitude. In terms of the trigger in tonal coarticulation, instead of the certain tone, it is the adjacent tonal offset or onset that should be taken into consideration. Preceding low offset tends to trigger carryover coarticulation on the beginning of its target tone, but after about two or three time points the effect from preceding high and mid offset will be more significant. Each kind of preceding offsets causes carryover assimilation. Anticipatory coarticulation is more complicated that it contains both assimilation and dissimilation. Similar to the raising effect in carryover coarticulation, following mid onset always raises its target tone, but following high onset tends to lower the mid and low offset of its preceding target tones. The anticipatory dissimilation is possible to be explained by the 'vocal fold adjustment' theory of Gandour et al. (1994). Nevertheless, some subtle problems are involved in this study. Even though that the F_0 region (High, Mid and Low) was divided well through detailed values averaged from ten speakers, that is, there should be no doubts on the division, the trigger onset and offset located in Mid region has High-region-liked performance that it always raises its adjacent targets. If the Mid trigger does have the same influence as High trigger, but it does not cause anticipatory dissimilation just like High trigger did. The nature of the Mid trigger is still left without good explanations. Also, it could be strange that the anticipatory dissimilation found in this study is very different from the results of anther Mandarin study of Xu (1994 & 1997). Each of the study contains only one type of possible anticipatory dissimilation, while both types should be found theoretically. Whether there are other factors influencing the Mandarin anticipatory coarticulation which was not being considered should be involved in the future related studies to solve this inconsistency.

5.2 MOA effects on Mandarin Tonal coarticulation

In this study, the hypothesis about MOA is that different MOAs will affect the tonal coarticulation. To be more specific, it was assumed that obstruent consonants such as stop, fricative and affricate will more likely reduce the coarticulatory effect to some degree, so their adjacent tones should be produced more like its canonical form. On the other hand, sonorant consonants (e.g., liquid and nasal) might prolong the coarticulatory effect from one tone to another one. Therefore, the coarticulatory effect on tones next to sonorants may be greater, i.e., their F_0 will diverse from their canonical forms more. However, according to the data collected in the Exp. II, the results seem not to be that straightforward as the assumption.

To examine the MOA effect in general, it is found that across all time points of four target tones the main effect of MOA is significant in less of half of situations. Even in the significant cases, some of them are dispersed that the MOA effect is not continuous, which is possible due to the random influence rather than the systematic influence on tonal coarticulation. Such phenomenon that MOA does not have a powerful effect is probable because of the effort to maintain the contrast of tones. Since tones in tonal languages are the key elements to distinguish the meaning of spoken words, it is important to preserve the distinctiveness of each tone in speaking. As tones must be influenced by its tonal context (from both of its preceding and following tonal adjacent values), which is exemplified in Exp. I, it is possible that there is no much space left for tones being affected by other factors. Even if there is a factor like MOA does affect tonal coarticulation to some degree, the extent or the magnitude of influence should be quite limited.

In addition, if we explore the detail values of the mean delta F_0 caused by five MOAs in post-hoc analyses, it is found out that only few results correspond to the prediction exactly. For all target tones on both V_1 and V_2, only the results of target Tone 2 is similar to the hypothesis that intervening liquid and sonorant will cause greater tonal coarticulation and thus involve greater delta F_0 than other intervening consonants. For target Tone 1, Tone 3 and Tone 4, the results are contrary that delta F_0 caused by intervening affricate, stop or fricative tend to be greater. Another minor problem is that the five MOAs included in this study do not show any particular order across four target tones, therefore it is difficult to rank a certain MOA with the tendency to trigger or block tonal coarticulation.

However, the interesting part is that the values of delta F_0 of five MOAs seem to be close to each other by group: the value caused by liquid is close to the value by nasal while the values caused by other three MOAs are close to each other. Based on this observation, the data were further analyzed by separating them into two parts: the values caused by sonorants and the values caused by obstruents. These data were also presented in the previous chapter. However, even if the classification of data is simplified to examine the effect of sonorancy, the prediction is not completely supported by the new results. In addition to most time points of target Tone 2, which is mentioned through the data of five

MOAs, only some time points of target Tone 4 show that the delta F_0 caused by intervening sonorants is greater by the one caused by intervening obstruents. For other time points or other target tones (Tone 1 and Tone 2), the results remain opposite. Thus, here comes a question that why some results violate the hypothesis of MOA effect (or sonorancy effect). Though the MOA effect on tonal coarticulation is significant in limited cases, the reason that two kinds of contrary results are involved in this study is still unclear. By introspecting the hypothesis and the experiment design of this study, it was found that the places of articulation (POAs) of intervening consonants are possible to be the factor which interfere the results. The original aim of the Exp. II in this study was to explore the effects merely from different MOAs, so only MOA was under well controlled when designing the stimuli for recording. However, as reviewed in section 2.3 that POA will affect coarticulation between segments, it is possible that those intervening consonants with the same MOA but different POAs lead to those unexpected results. Therefore, to get a better picture of the coarticulatory effects from each MOA, further research should be done with both MOA and POA of intervening consonants are taken into consideration. There's also another possibility that MOA does not have such critical influence on tonal coarticulation. As all obstruents in Mandarin Chinese are voiceless consonants, the difference between obstruents and sonorants found in Exp. II probably results from the voicing of consonants, rather than the MOA itself. Therefore, it should be further considered that whether MOA does affect tonal coarticulation or how does it affect in reality.

5.3. Conclusion

This study re-examined Mandarin tonal coarticulation via rigorous experimental settings. The data of this study is valuable because 10 measurements of F_0 values were included for each measured target, which is more detailed than most of the previous studies. Also, the F_0 variation caused by tonal coarticulation was calculated by comparing the F_0 of target tones with the F_0 of speaker-specific canonical forms. This is a new and precise way to analyze tonal coarticulation thus all possible speaker differences were excluded. What’s more, in this study, tonal coarticulation is examined through both of the temporal extent and also the magnitude, which makes the conclusion more complete. Another important contribution is that triggers of tonal coarticulation are discussed through the specific tonal onsets and offsets rather than the entire tones. In addition, in this study, a new way is conducted to check whether there is another intervening factor beyond tonal context that will affect tonal coarticulation. Though there are some issues remained to be explored in the future, this study provides a good mode to investigate tonal coarticulation in Mandarin.

Reference

Ashby, Michael, and Maidment, John. 2005. *Introducing Phonetics Science*. Cambridge University Press.

Ball, Martin J., and Rahilly, John. 1999. *Phonetics: the science of speech*. Oxford University Press Inc.

Black, J. W. 1949. Natural frequency, duration, and intensity of vowels in readings. *Journal of Speech and Hearing Disorder* 14:216-221.

Bladon, R. A. W., and Al-Bamerni, A. 1976. Coarticulation resistance in English /l/. *Journal of Phonetics* 4:137-150.

Brunelle, Marc. 2009. Northern and Southern Vietnamese Tone Coarticulation: a Comparative Case Study. *Journal of the Southeast Asian Linguistics Society* 1:49-62.

Chang K. 1973. The reconstruction of protp-Miao-Yao tones. *Bulletin of the Institute of History and Philology-Academic Sinica* 44.4:541-628.

Cope, A. T. 1970. Zulu tonal morphology. *Studies in African Linguistics* 7:175-194.

Daniloff, R.G., and Hammarberg, R.E. 1973. On defining coarticulation. *Journal of Phonetics* 1:239-248.

Di Cristo, A., and Chafcouloff, M.1976. An acoustic investigation of microprosodic effects in French vowels. Paper presented at the 14th Conference on Acoustics. High Tatra, Czechoslavakia.

Farnetani, E. 1990. V-C-V Lingual Coarticulation and Its Spatiotemporal Domain. *Speech production and speech modelling* 55:93-130.

Flemming, Edward. 2008. The Grammar of Coarticulation. To appear in La Coarticulation: Indices, Direction et Representation, ed. by M. Embarki & C. Dodane.

Fowler Carol A, and Brancazio, Lawrence. 2000. Coarticulation Resistance of American English Consonants and its Effects on Transconsonantal Vowel-to-Vowel Coarticulaiton. *Language and Speech* 43.1:1-41.

Gandour, Jack., Potisuk, Siripong., Dechongkit, Sumalee.,and Ponglorplait, Suvit. 1992b. Tonal coarticulation in Thai disyllabic utterances: a preliminary study. *Linguistics of the Tibeto-Burman Area* 15.1:93-110.

Gandour, Jack., Potisuk, Siripong., Dechongkit, Sumalee.,and Ponglorplait, Suvit. 1992c. Anticipatory tonal coarticulation in Thai noun compounds. *Linguistics of the Tibeto-Burman Area* 15.1:111-123.

Gandour, Jack., Potisuk, Siripong., and Dechongkit, Sumalee. 1994. Tonal coarticulation in Thai. *Journal of Phonetics* 22:477-492.

George, I. 1970. Nupe tonology. *Studies in African Linguistics* 1:100-122.

Han, Mieko S., and Kim, Kong-On. 1974. Phonetic variation of Vietnamese tones in disyllabic utterances. *Journal of Phonetics* 2:223-232.

Hombert, J. M. 1975. Perception of contour tones: An experimental investigation. *Proceedings of the 1st annual Meeting of the Berkeley Linguistics Society* 221-232.

Hombert, J. M. 1978. Consonant Types, Vowel Quality and Tone. *Tone: A linguistic Survey,* ed. by Victoria A. Fromkin, 77-111. Academic Press Inc.

House, A.S., and Fairbaks, G. 1953. The influence of consonant environment upon the secondary acoustical characteristics of vowels. *Journal of the Acoustical Society of America* 25:105-113.

Hyman, L. M., and Schuh, R. G. 1974. Universals of tone rules: evidence from West Africa, *Linguistic Inquiry* 5:81-115.

Hyman, L. M. 2007. Universals of tone rules: 30 years later, C. Gussenhoven & T. Raid (eds.) *Tones and Tunes, vol. 1: Studies in Word and Sentence Prosody*. Berlin: Mouton de Gruyter.

Kent, Ray D., and Read, Charles. 2002. *Acoustic Analysis of Speech*. Singular.

Kim, C. W. 1968. Review of Liberman 1967. *Language* 44:830-842.

Kühnert, Barbara, and Nolang, Francis. 1999. The origin of coarticulation. *Coarticulation: Theory, Data and Techniques,* ed. by William J. Hardcastle and Nigel Hewlett, 7-30. Cambridge University Press.

Ladefoged, Peter. 1993. *A Course in Phonetics*. Harcourt Brace Jovanovich, Inc.

Ladefoged, Peter. 2001. *A Course in Phonetics*. Heinle & Heinle.

Laver, John. 1994. *Principles of Phonetics*. Cambridge University Press.

Lea, W. A. 1973. Segmental and Suprasegmental influences on fundamental frequency contours. In L. M. Hyman (Ed.), Consonant Types and Tone. *Southern California Occasional Papers in Linguistics* 1: 15-70.

Lehiste, Ilse. 1976. Suprasegmental Features of Speech. *Comtemporary Issues in experimental Phonetics*, ed. by Norman J. Lass, 225-239. Academic Press Inc.

Lehiste, Ilse., and Peterson, G.E. 1961. Some basic considerations in the analysis of intonation. *Journal of the Acoustical Society of America* 33:419-425.

Lin, Maocan., and Yan, Jingzhu. 1992. Tonal coarticulation patterns in quadrisyllabic word and phrase of mandarin. *Acta Acustia* 17.6:456-467.

Löfqvist, A. 1975. Intrinsic and extrinsic F_0 variation in Swedish tonal accents. *Phonetica* 31:18-27.

Lukas, J. 1969. Tonpermeable und tonimpermeable Konsonanten im Bolanci

(Nordnigerien). In *Ethnological and linguistic studies in honor of N. J. van Warmelo*. Department of Bantu Administration and Development, Republic of South Africa, Ethnological Publications No.52 133-138.

MacKay, Ian. 1987. *Phonetics: the science of speech production*. Allyn and Bacon.

Mohr, B. 1968. Intrinsic fundamental frequency variation, II. *Monthly Internal Memorandum, Phonology Laboratory, Univ. of California, Berkeley,* June, 22-32.

Ohala, J. J. 1978. Production of Tone. *Tone: A linguistic Survey,* ed. by Victoria A. Fromkin, 5-39. Academic Press Inc.

Peterson, G. E., and Barney, H. L. 1952. Control methods used in a study of the vowels. *Journal of the Acoustical Society of America* 24:175-184.

Peterson, N. R. 1976. Intrinsic fundamental frequency of Danish vowels. *Annual Report of the Institute of Phonetics,* University of Copenhagen, 1-27.

Potisuk, Siripong., Gandour, Jack., and Harper, Mary P. 1996. Contextual Variations in Trisyllabic Sequences of Thai Tones. *Phonetica* 54:22-42.

Recasens, Daniel. 1984b. Vowel-to-Vowel Coarticulation in Catalan VCV Sequences. *Journal of the Acoustical Society of America* 76:1624-1635.

Recasens, Daniel. 1985. Coarticulatory Patterns and Degrees of Coarticulatory Resistance in Catalan CV Sequences. *Language and Speech* 28.2:97-114.

Recasens, Daniel. 1987. An Acoustic Analysis of V-to-C and V-to-V: Coarticulatory Effects in Catalan and Spanish VCV Sequences. *Journal of Phonetics* 15:299-312.

Recasens, Daniel., Pallarès, Maria Dolors., and Fontdevila, Jordi. 1997. A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America* 102.1:544-560.

Recasens, Daniel., and Espinosa, Aina. 2009. An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan. *Journal of the Acoustical Society of America* 125.4:2288-2298.

Reetz, Henning, and Jongman, Allard. 2009. *Phonetics: Transcription, Production, Acoustics and Perception*. Wiley-Blackwell.

Roach, Peter. 2001. *Phonetics*. Oxford University Press.

Schuh, R. G. 1971. Verb forms and verb aspects in Ngizim. Journal of African Languages 10:47-60.

Schuh, R. G. 1978. Tone Rules. *Tone: A linguistic Survey,* ed. by Victoria A. Fromkin, 221-256. Academic Press Inc.

Shen, Xiaonan Susan. 1990. Tonal coarticulation in Mandarin. *Journal of Phonetics*

18:281-295.

Singh, Sadanand, and Singh, Kala. 2006. *Phonetics: Principles and Practices*. Plural Publishing.

Xu, Yi. 1993. Production and perception of coarticulated tones. *Acoustical Society of America* 95.4:2240-2253.

Xu, Yi. 1994. Asymmetry in Contextual Tonal Variation in Mandarin. *Advances in the Study of Chinese Language Processing* 1:383-395.

Xu, Yi. 1997. Contextual tonal variation in Mandarin. *Journal of Phonetics* 25:61-83.

.

Appendix I

Word list of Exp. II

2nd syllable 1st syllable	Tone 1 (stop C)	Tone 1 (fricative C)	Tone 1 (affricate C)	Tone 1 (nasal C)	Tone 1 (liquid C)
Tone 1	書包	枯梢	粗糙	孤貓	撲撈
Tone 2	屠刀	離騷	毒招	狸貓	提撈
Tone 3	米糕	筆梢	體操	母貓	捕撈
Tone 4	細胞	樹梢	入超	棄貓	細撈
2nd syllable 1st syllable	Tone 2 (stop C)	Tone 2 (fricative C)	Tone 2 (affricate C)	Tone 2 (nasal C)	Tone 2 (liquid C)
Tone 1	出逃	哭號	譏嘲	雞毛	積勞
Tone 2	葡萄	泥勺	築巢	皮毛	疲勞
Tone 3	土陶	里豪	米槽	阻撓	苦勞
Tone 4	蜜桃	富豪	覆巢	兔毛	地牢
2nd syllable 1st syllable	Tone 3 (stop C)	Tone 3 (fricative C)	Tone 3 (affricate C)	Tone 3 (nasal C)	Tone 3 (liquid C)
Tone 1	督導	稀少	出草	豬腦	攜老
Tone 2	離島	極好	提早	毒腦	耆老
Tone 3	乞討	你好	洗澡	洗腦	古老
Tone 4	祝禱	不少	牧草	氣惱	故老
2nd syllable 1st syllable	Tone 4 (stop C)	Tone 4 (fricative C)	Tone 4 (affricate C)	Tone 4 (nasal C)	Tone 4 (liquid C)
Tone 1	書報	批號	枯燥	哭鬧	積澇
Tone 2	獨到	符號	急躁	胡鬧	泥澇
Tone 3	筆套	喜好	鼓譟	禮貌	土澇
Tone 4	密告	癖好	護照	地貌	鑄烙

“Stop C” in the table refers that the intervening C_2 is a stop consonant. Other consonants are shortened in the similar ways.