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Tonal Neutralization of Taiwanese Checked and Smooth Syllables: An Acoustic Study

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Abstract

Taiwanese tonal alternation is realized in a circular chain shift fashion for both smooth and checked syllables. Debate regarding the processes of less productive Taiwanese tonal alternation has centered on whether a surface tone is derived from an underlying tone, or whether a surface tone is selected without undergoing any derivation. The current study investigates this controversial issue by examining Taiwanese checked tone and smooth tone sandhi neutralization in production. In particular, we analyzed whether checked citation and sandhi tone 53 (C21→C53), checked citation and sandhi tone 21 (C53→C21), smooth citation and sandhi tone 55 (S51→S55), and smooth citation and sandhi tone 21 (S33→S21) are acoustically completely neutralized in fundamental frequency (F0) height, contour, and duration. A non-sandhi exception was also included to evaluate the effect of position-in-word on F0 height and duration given that citation tones always appear in phrase-final position. Any trace of influence from the underlying representation would indicate a computational mechanism, whereas the absence of any trace would suggest a lexical mechanism for the production of Taiwanese tonal alternation. Results did not show any influence of F0 height, F0 contour, or tone duration from the underlying representation for both checked and smooth tones, supporting a lexical mechanism in speech production for less productive tonal alternations.

Keywords

Taiwanese, phonological alternation, tone sandhi, neutralization, speech production

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1 Introduction

Most theoretical phonologists assume that abstract representations at the phonological level involve categorical representations that consist of distinct features and phonemes (Kenstowicz, 1994; Kenstowicz & Kisseberth, 1979). It has long been recognized that speakers in certain conditions treat phonologically different sounds as phonetically identical, a phenomenon called complete neutralization. A large body of literature has already investigated the phonetics of neutralization at the segmental level, focusing on phenomena such as final devoicing in German (e.g., Port & Crawford, 1989), Dutch (e.g., Warner, Jongman, Sereno, & Kemper, 2004), and Russian (Dmitrieva, Jongman, & Sereno, 2010), as well as flapping in US English (Charles-Luce, 1997; Herd, Jongman, & Sereno, 2010). Warner et al. (2004), for example, investigated neutralization between final alveolar stops /t/ and /d/ (i.e., /d/ undergoes final devoicing) preceded by long and short vowels in Dutch. Minimal pairs were compared where the two members of each pair only differed in terms of the underlying representation of their final alveolar stops (e.g., /bɛt/ "dab sg." vs. /bɛd/ "bed"). They found that vowels preceding underlying /d/ were significantly longer than those preceding underlying /t/ by 3.5 milliseconds (ms). Moreover, underlying /t/ following long vowels displayed significantly longer burst durations than did underlying /d/ by 9 ms. Warner et al. (2004) concluded that the underlying distinction between final alveolar stops /t/ and /d/ is not completely neutralized. They further suggested that orthography can also influence the degree of incomplete neutralization in Dutch.

A few studies have also investigated neutralization at the suprasegmental level, mainly for the tonal alternation phenomena found in many Chinese languages. Similar to many studies on segmental neutralization, these studies usually show that sandhi tones and citation tones are not completely neutralized acoustically, demonstrating a trace of influence from the underlying representation. Mandarin tone 3 sandhi is perhaps the best-known example of tone assimilation. It is a highly productive process in that Mandarin speakers apply the tone 3 sandhi rule without exception to both real words and novel words consisting of accidental gap syllables (Zhang & Lai, 2010). Sandhi high-rising tone 2, derived from underlying low-dipping tone 3, and citation high-rising tone 2 are involved in a case of incomplete neutralization, whereby sandhi tone 2 is lower than citation tone 2 in average fundamental frequency (F0) height, exhibiting an influence from the sandhi tone 2's underlying low tone register (Myers & Tsay, 2003; Peng, 2000). Although several tone sandhi neutralization studies have been conducted in Mandarin, little is known about less productive tone sandhi neutralization processes (Zhang & Lai, 2008; Zhang, Lai, & Sailor, 2011). The details of tone sandhi neutralization in production have important theoretical implications since they address whether speakers access sandhi forms (surface representations) directly or derive them from their corresponding underlying representations during production (Zhang & Lai, 2010; Zhang et al., 2011; Zhang C., Xia, & Peng, 2015), and whether words in highly productive and less productive tone sandhi systems undergo similar or different processes. The present study focuses on the less productive Taiwanese tone sandhi (i.e., Zhang et al. (2011) showed that Taiwanese tone sandhi rules were not always applied to novel words with accidental gap syllables) and aims to investigate whether or not the distinction between Taiwanese citation tones and sandhi tones in both smooth syllables (i.e., open syllables or syllables ending with a nasal coda) and checked syllables (i.e., syllables ending with a stop coda) is completely neutralized. Results will contribute to a better understanding of the contribution of both underlying and surface representations for less productive phonological alternations during speech production.

Table 1. Taiwanese citation tones (the numbers refer to F0 height, with 1 representing the lowest F0 and 5 the highest F0 within a speaker's pitch range in normal speech.)

Tone type	Long tone (smooth syllables)					Short tone (checked syllables)	
Notation	55	24	33	21	51	53	21

1.1 Taiwanese and Taiwanese tone sandhi

Taiwanese is one of the major Chinese dialects in Taiwan besides Taiwan Mandarin. Taiwanese is historically derived from Southern Min, which is spoken in Zhangzhou, Quanzhou as well as Xiamen in Fujian province, China (Ting, 1970). Taiwanese has a rich tonal system, including five long tones and two short tones. The five long tones occur in smooth syllables, while the two short tones occur in checked syllables. Among the five long tones, tones 55 and 33 are the longest; tone 24 is the second longest, and tones 21 and 51 are the shortest (Peng, 1997). The two short tones are similar in duration and F0 contour (Kuo, 2013; Peng, 1997). The seven Taiwanese citation tones and their notations on a five-point scale are listed in Table 1 (Peng, 1997).

Like many Chinese languages, Taiwanese has phonological alternations called tone sandhi. Taiwanese tone sandhi is right-dominant: tones that appear in the non-phrase-final position undergo tone sandhi, while those that occur in the phrase-final position are exempted from it (Chen, 1987; Lin, 1994; Soh, 2001). Taiwanese tone sandhi is complex in that each of the seven contrastive tones changes to its sandhi tone in a circular chain-shift fashion, as illustrated in (1) for smooth syllables, and in (2) for checked syllables ending with [p, t, k]. According to (1) and (2), which show that every Taiwanese citation tone converts to a different lexical tone after undergoing tone sandhi, Taiwanese tone sandhi is structure-preserving and phonologically opaque (Kiparsky, 1973).

[55] → [33] ← [24]
↑ ↓
[51] ← [21]

(1). Taiwanese tone sandhi circle: smooth syllables

[21] ⇄ [53]

(2). Taiwanese tone sandhi circle: checked syllables

Phonologically, Taiwanese tone sandhi has been assumed to be an instance of complete neutralization in the sense that the distinction between citation tones, such as citation tone 55, and their corresponding sandhi tones, such as sandhi tone 55 derived from 51, is acoustically completely neutralized (Chen, 1987; Hsiao, 1991; Lin, 1994; Peng, 1997). However, studies concerning Taiwanese tone sandhi in the past two decades that have investigated this issue by examining the acoustic realizations of citation tones and their corresponding sandhi tones, have not reached any consensus yet (Kuo, 2013; Lin, 1988; Tsay, Charles-Luce, & Guo, 1999). Thus, whether Taiwanese citation tones and their corresponding sandhi tones show complete neutralization is still unclear.

Lin (1988) investigated Taiwanese tone sandhi neutralization using smooth-syllable nonwords. Production results showed that sandhi tone 33, derived from underlying tone 55, and sandhi tone 33, derived from underlying tone 24, were not completely neutralized; the sandhi tone 33 derived from underlying tone 55 was approximately 8 Hz higher than the sandhi tone 33 derived from underlying tone 24. This finding indicates that the difference in F0 height between the two sandhi tones 33 was due to their corresponding underlying tones, with the higher underlying tone leading to the higher sandhi tone, and vice versa. However, the fact that segmental environments were not controlled in this study might have affected the results in the sense that a tone in a syllable starting with a voiceless consonant would be higher in F0 than that in a syllable beginning with a voiced consonant. Moreover, high error rates resulting from low productivity of sandhi for nonwords might also be problematic.

Myers and Tsay (2008) investigated Taiwanese tone sandhi neutralization of smooth-syllable words in sentences, comparing citation 33 to sandhi 33 (derived from underlying 55), and sandhi 33 derived from underlying 24 to sandhi 33 derived from underlying 55. Results showed complete F0 neutralization between citation 33 and sandhi 33 (derived from underlying 55), as well as between sandhi 33 (derived from underlying 24) and sandhi 33 (derived from underlying 55). No F0 height or contour difference was observed for the two pairs of stimuli. With respect to duration, Myers and Tsay (2008) found that citation 33 was significantly longer than sandhi 33 (derived from underlying 55), which was expected because citation 33 occurred in the phrase-final position. However, the sandhi 33 derived from underlying 24 was 8 ms longer than the sandhi 33 derived from underlying 55. Based on the results in this study, Taiwanese sandhi neutralization can be deemed complete at least in terms of F0 realization.

With regard to Taiwanese tone sandhi in checked syllables, Kuo (2013) investigated the neutralization issue in both smooth and checked syllable words using a corpus in which one native Taiwanese speaker read a written story out loud. Disyllabic phrases with 42 tonal combinations were recorded and analyzed. In general, the results of this study showed that citation tones had longer durations, wider F0 range, and creakier voice than their sandhi tone counterparts in both smooth and checked syllables. As a result, Kuo (2013) concluded that citation tones and their sandhi counterparts were not completely neutralized acoustically. However, the fact that only one speaker was recruited makes it impossible to draw any firm conclusions.

Another Taiwanese checked tone neutralization study is Tsay (1996) in which disyllabic words were analyzed. Tsay (1996) showed that checked tone 53 and checked tone 21 differed from each other in F0 in the non-phrase-final position but were acoustically completely neutralized in F0 in the phrase-final position. Therefore, Tsay (1996) proposed that Taiwanese checked tone sandhi is "left dominant," which contradicts the traditional right-dominant claim concerning the directionality of Taiwanese tone sandhi. The fact that Tsay (1996) lumped together checked tone syllables with a [p, t, k] coda and those ending with a glottal stop may have complicated the results since Southern Min checked tone sandhi is realized differently depending on the final coda of a syllable (Chen, 1987). Moreover, Tsay's (1996) results are based on *t*-tests on F0 values obtained at a single point along the F0 contour (vowel midpoint). More time points and, accordingly, a more sophisticated statistical analysis is needed, so that a more detailed picture of Taiwanese checked tone sandhi neutralization can emerge. Given the limitations of the studies mentioned above, it is warranted to examine Taiwanese tone sandhi neutralization in both smooth and checked syllables using a more controlled experimental design, more robust temporal analyses, as well as a representative sample of speakers. In particular, we tried to better understand the contribution of both underlying and surface representations during production for less productive phonological alternations.

1.2 Neutralization and the representation of tone sandhi

Incomplete neutralization is often associated with influence from the underlying representation, in which case a sandhi tone would exhibit some acoustic characteristics of its underlying representation. Preservation of the information from the underlying representation suggests a computational mechanism during tone sandhi word production (Chien, Sereno, & Zhang, 2016; Myers & Tsay, 2003; Peng, 2000; Zhang & Lai, 2010). In contrast, complete neutralization could be taken as evidence for direct access to the surface form of a sandhi tone (Chien, Sereno, & Zhang, 2017; Myers & Tsay, 2008). Since the surface form is not influenced by the underlying representation, this indicates a lexical mechanism during sandhi word production. One way to examine the mechanism employed when producing Taiwanese tone sandhi words is to analyze whether a sandhi tone and its citation counterpart are acoustically completely neutralized. However, it should be noted that sandhi tones occur in the non-phrase final position, while citation tones occur in the phrase-final position in Taiwanese. Positional effects such as final F0 lowering and final lengthening would affect F0 and duration results. Therefore, factoring out positional effects by using non-sandhi exceptions is of paramount importance to help understand the nature of neutralization.

Zhang and Lai (2008) as well as Zhang et al. (2011) conducted a nonce-probe test to investigate Taiwanese tone sandhi production in which participants heard two monosyllables presented as their citation tones individually and were asked to produce them as a disyllabic unit. Their results demonstrated that different Taiwanese tone sandhi rules have different degrees of productivity, with around 80% of expected tone sandhi application for novel words for the most productive sandhi 24→33, and around 30% of expected tone sandhi application for novel words for the least productive sandhi 51→55 and 33→21. In contrast to these low-productivity Taiwanese sandhi rules, Mandarin tone 3 sandhi is extremely productive. Using a similar methodology, Zhang and Lai (2010) showed that Mandarin tone 3 sandhi applied without exception to both real and novel words. These results indicate that speakers are more sensitive to phonetically motivated and phonologically transparent tone sandhi rules such as Mandarin tone 3 sandhi, and less sensitive to phonetically unmotivated and phonologically opaque (i.e., due to the tone sandhi circle) tone sandhi rules such as Taiwanese tone sandhi. Specifically, Mandarin tone 3 sandhi is phonetically motivated since the rising tone 2 is shorter than the low-dipping tone 3, which makes tone 2 preferred in the non-phrase-final position. Likewise, for Taiwanese sandhi 51→55, since tone 55 is longer than tone 51, tone 55 is not preferred in the non-phrase-final position over tone 51. In addition, Zhang et al. (2011) also showed that the lexical frequency of tones might be responsible for sandhi rule productivity, with lower frequency tones exhibiting lower sandhi productivity, such that the lower lexical frequency of checked tones in Taiwanese might be comparable with the less productive Taiwanese smooth tone sandhi rules. These results further suggest that words undergoing different sandhi rules of various productivity are accessed in different ways during production.

From the point of view of perception, Chien et al. (2017) conducted an auditory priming lexical decision task to investigate the representation of Taiwanese tone sandhi words. Their results show that for highly productive tone sandhi 24→33, priming effects emerged most strongly when primes and targets overlapped in the underlying representation, while for less productive sandhi 51→55, priming effects occurred when primes and targets overlapped in the surface form. Together, these production and perception data show that speakers are sensitive to the underlying representations and sandhi rules with high productivity but they have to access the surface form directly for a less productive tone sandhi. Therefore, highly productive tone sandhi rules would predict incomplete neutralization due to the influence from the underlying representation, while less productive tone sandhi rules would predict complete neutralization due to direct access to the surface form. Resolving debates regarding computational and lexical mechanisms during sandhi word production is critical to better understand how these words are represented and accessed in the mental lexicon.

The present research takes the less studied Taiwanese smooth tone sandhi 51→55 and 33→21, as well as checked tone sandhi 53→21 and 21→53 as test cases to tackle the representational issue by examining neutralization in the production of these sandhi words. Given that there are acoustic interactions between vowel F0 and the voicing of final consonants in a syllable (see Gruenenfelder & Pisoni, 1980 for discussion), both smooth and checked tones are chosen, so that we are able to evaluate whether the neutralization pattern for smooth tones is similar to that for checked tones. Based on Zhang and Lai (2008), Zhang et al. (2011), and Chien et al. (2017), we predict that the sandhi tones generated by the four target sandhi rules will not show any influence from their corresponding underlying tones since speakers have to access the surface form of words undergoing less productive sandhi rules. Additionally, we predict a final F0 lowering and lengthening effect when comparing a non-sandhi syllable in the initial and final positions. Such a comparison can help evaluate positional effects when sandhi is not involved.

2 Methods

Two production experiments were conducted. Experiment 1 examined checked tone sandhi 53→21 and 21→53. Experiment 2 investigated smooth tone sandhi 51→55 and 33→21.

2.1 Experiment 1

2.1.1 Subjects. Eleven native Taiwanese speakers were recruited and tested in Taiwan (7 males and 4 females). Eight of them grew up in the Kaohsiung City metropolitan area (the largest city in southern Taiwan), and the other three grew up in the Taipei City metropolitan area (the largest city in northern Taiwan). None of them reported any speech or hearing impairments before participating in the experiment. Their ages ranged from 30 to 45 years old (mean = 39 years).

2.1.2 Stimuli. Eight checked monosyllables, ending either in /t/ or /k/, were selected as target syllables. They all began with a voiceless obstruent in order to avoid any F0 differences due to the voicing status of the preceding obstruent. The eight checked monosyllables were /sik53/ "seat," /sik21/ "color," /tsok53/ "race," /tsok21/ "to rise," /tok53/ "poison," /tok21/ "to supervise," /sit53 / "real," and /sit21/ "to lose." They occurred as either the first or second syllable of a disyllabic word, resulting in 16 Taiwanese disyllabic words. In order to minimize an effect of tonal assimilation (Peng, 1997), all checked tone 53 syllables on the surface were followed and preceded by a smooth tone 55; all checked tone 21 syllables on the surface were followed by a smooth tone 21 and preceded by a smooth tone 33. Notice that the tones of the eight target monosyllables all changed to their corresponding sandhi tones when serving as the first syllable of a disyllabic word, while the second syllable of a disyllabic word kept its citation tone. The eight target stimuli and the 16 disyllabic words they formed are listed in Table 2.

Since citation checked tones and their corresponding sandhi checked tones differ in terms of their position in a phrase, it would be difficult to segregate an effect of sandhi from an effect of position if any F0 or durational differences were observed. F0 lowering and syllable lengthening which typically occur in the phrase-final position, might contribute to the differences. Hence, a non-sandhi disyllabic word, which is an exception to Taiwanese tone sandhi (Cheng, 1997), was included to examine potential final lengthening and final F0 lowering effects in the absence of sandhi. This non-sandhi word was [te33 taŋ33] "earthquake" in which the first syllable keeps the citation tone rather than undergoing tone sandhi. Another disyllabic word was chosen in which the second syllable came from the first syllable of the non-sandhi disyllabic word, as shown in Table 3. Notice that the F0 offset of the first syllable (33) and the F0 onset of the second syllable (33) are the same.

Since the first syllable of the non-sandhi word does not undergo tone sandhi, its F0 height, slope, and duration can be compared to those when it is in the second syllable of a disyllabic word.

Table 2. Checked tone target stimuli.

Target morpheme	As first syllable (sandhi tone)	As second syllable (citation tone)
/sik53/ "seat"	[sik21 tsʰu21] "seating arrangement"	[tsu55 sik53] "chairperson"
/sik21/ "color"	[sik53 ku55] "pervert"	[kim33 sik21] "golden"
/tsok53/ "race"	[tsok21 siŋ21] "family name"	[tsiŋ55 tsok53] "ethnicity"
/tsok21/ "to rise"	[tsok53 ka55] "writer"	[kaŋ33 tsok21] "job"
/tok53/ "poison"	[tok21 ke21] "evil scheme"	[kai55 tok53] "detoxify"
/tok21/ "to supervise"	[tok53 kun55] "military governor"	[ki33 tok21] "Christ"
/sit53/ "real"	[sit21 tse21] "reality"	[sja55 sit53] "realistic"
/sit21/ "to lose"	[sit53 tsin55] "lack fidelity"	[sjao33 sit21] "disappear"

Table 3. Non-sandhi words and their counterparts.

Target monosyllable	As first syllable (citation tone)	As second syllable (citation tone)
/te33/ "ground"	[te33 taŋ33] "earthquake"	[toŋ33 te33] "local"

Any difference between the first syllable of the non-sandhi word and the second syllable of its counterpart can only be due to the positional effect, not to tone sandhi, so that potential effects of final F0 lowering and final lengthening can be accounted for.

Twenty-six additional Taiwanese disyllabic words served as fillers. Four of them contained an initial checked syllable and four of them contained a final checked syllable. The remaining 18 disyllabic fillers included two types of smooth syllables, which were either open syllables or syllables with a nasal coda (/m/, /n/, or /ŋ/), as both of their first and second syllables. Tone was balanced across the first and second syllables.

2.1.3 Procedure. Participants were first asked to provide informed consent and filled out a language background questionnaire adapted from Chang (2012). They were then recorded in sound-attenuated rooms in Taipei and Kaohsiung, Taiwan, with a cardioid microphone (Shure, model SM57) and a digital solid-state recorder (Zoom H4N), using a sampling rate of 22,050 Hz.

Four identical blocks were created. In each block, 44 disyllabic words, including 16 disyllabic checked tone target words, one pair consisting of a non-sandhi word and its counterpart, as well as 26 fillers, were randomly presented at the center of the screen of a VAIO laptop using Paradigm software (Tagliaferri, 2005). Because Taiwanese does not have a writing system, stimuli were presented via Chinese characters, as is customary. On each trial, a Taiwanese disyllabic word written in Chinese characters was presented on the screen for 2000 ms, during which participants were asked to put the two Chinese characters together and pronounce them as a Taiwanese word. The intertrial interval was 3000 ms. Eight practice trials were provided before the main production experiment and instructions were given before the practice section. A total of 176 tokens (44 disyllabic words × 4 repetitions) were produced by each participant in approximately 20 minutes. The disyllabic words produced by participants were recorded and subjected to further analysis.

2.1.4 Data analysis. The F0 of the vowels of the eight checked target syllables in two positions (citation position and sandhi position) was measured using Praat software (Boersma & Weenink, 2017), as was F0 of the vowel of the non-sandhi syllable [te33] in the phrase-final and non-phrase-final positions. The vowel portion was defined as the stretch of signal between the onset of vocal fold vibration (the onset of periodicity in the waveform) and the point at which formant 2 disappeared from the spectrogram. F0 height and F0 slope were measured using Yi Xu's TimeNormalizedF0 Praat script (Xu, 2005) where F0 measurements were taken at every 11.11% of the tone duration, resulting in 10 F0 measurements for each target syllable. Extracted F0 tracks were then hand-checked and corrected for octave-jumps. For such cases, the vowel portion was equally divided into ten points and the F0 of the ten points was manually calculated by using F0 = 1/T(s) (i.e., T refers to the duration of one period of the waveform). In total, 792 syllables (11 participants × 18 target syllables × 4 repetitions) were analyzed. However, 117 out of 792 (14.8%) were excluded due to the fact that they were either not produced as checked syllables (no closure of the stop coda was visible in the waveform), were produced as Mandarin syllables (misled by the presented Mandarin characters) or unintelligible words or skipped. Of the 117 excluded trials, 39 were not pronounced as checked syllables (final citation: 2, final sandhi: 12, non-final citation: 15, non-final sandhi: 10); 3 were produced as Mandarin syllables; 41 were pronounced as unintelligible syllables, and 34 were skipped. All trials were judged by the authors and two trained native Taiwanese speakers.

The F0 measurements generated by Yi Xu's Praat script (Xu, 2005) were then transformed into semi-tones using the formula in (3) below to better reflect pitch perception (Rietveld & Chen, 2006). The semi-tone values were further converted to *z*-scores using the formula in (4) below on all measurements of a speaker in order to minimize gender differences and speaker variation (Rose, 1987; Zhu, 2004). For a given speaker, all the F0 measurement values of the eight checked syllables (i.e., [sik53], [sik21], [tsok53], [tsok21], [tok53], [tok21], [sit53], and [sit21]) were averaged across the four production tokens of the same word and across all syllables with the same tone, while all the F0 measurement values of the target smooth syllable [te33] in [te33 taŋ33] and [toŋ33 te33] were averaged within each individual stimulus across four repetitions. The averaged values of each speaker were subjected to statistical analyses.

$$ST = 39.87 \times \log\left(Hz/_{50}\right) \quad (3)$$

$$z_{\mathrm{STx}} = \frac{STx - \frac{1}{n}\sum_{i=1}^{n} STi}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(STi - \frac{1}{n}\sum_{i=1}^{n} STi)^2}} \quad (4)$$

Tone durations of the eight target checked syllables in the sandhi (non-phrase-final) and citation (phrase-final) positions, as well as that of the non-sandhi target syllable in the non-final and final positions were also measured. For a given speaker, all the tone duration values were averaged across the four target checked syllables within a tone type (i.e., 4 tone types: sandhi tone 53, citation tone 53, sandhi tone 21, and citation tone 21), and averaged across the target smooth syllable within a syllable position (i.e., final and non-final positions) across four repetitions. Statistical

Table 4. Smooth tone target stimuli.

Smooth sandhi tone	Smooth citation tone
[sju55 sjan55] "first of all"	[be55 sju55] "bribe"
[tsau55 su55] "smuggle"	[tsju55 tsau55] "wine lees"
[tswi55 kau55] "drain"	[ko55 tswi55] "cute"
[kʰɤ55 kwã55] "examiner"	[kʰi55 kʰɤ55] "dentistry"
[sja21 kau21] "socialist education"	[hau21 sja21] "school building"
[tso21 se21] "create publicity"	[tjã21 tso21] "customized"
[po21 so21] "method"	[bin21 po21] "face napkin"
[pwe21 so21] "multiple"	[hjo21 pwe21] "younger generation"

analyses were conducted on the ratio of the non-phrase final tone duration to phrase final tone duration across all speakers.

2.2 Experiment 2

2.2.1 Subjects. Eighteen native Taiwanese speakers participated in Experiment 2 (9 males and 9 females). Sixteen grew up in Kaohsiung City metropolitan area and two in the Taipei City metropolitan area. They were tested in a sound attenuated room in either Kaohsiung or Taipei. None of them reported any speech or hearing impairments before participating in the experiment. Their ages ranged from 35 to 50 years old (mean = 43 years).

2.2.2 Stimuli. Eight smooth monosyllables were selected as target syllables. They occurred either in the non-phrase-final (sandhi) position, or phrase-final (citation) position, resulting in 16 disyllabic target words, as shown in Table 4. Eight of them had a tonal melody of 55–55, and eight of them had a tonal melody of 21–21. Note that the initial and final syllables of target words carried the same tone, so that tonal coarticulation, which might impact the onset or offset F0 of targets, was minimized. Moreover, both syllables of the target words started with an obstruent, which marked a clear boundary between initial and final syllables and prevented the vocal folds from vibrating across the two syllables.

A different set of disyllabic words was chosen as fillers. Among them, the following tonal melodies were represented: 51–24 (9 words); 33–51 (5 words); 33–33 (4 words); 21–51 (1 word); and 55–51 (1 word). While most syllables of the fillers started with an obstruent, some began with a nasal or a vowel. Some filler syllables ended with a nasal coda; the others were open syllables.

2.2.3 Procedure. Recording equipment and procedures were identical to those described for Experiment 1. Three identical blocks were created. In each block, 16 disyllabic target words and 20 filler words were randomly presented in the middle of the screen of an ASUS laptop using Paradigm software (Tagliaferri, 2005). Before recording, participants were given five minutes to familiarize themselves with the stimuli. In total, 108 tokens (three repetitions of 36 disyllabic words) were produced by each participant. The whole experiment took approximately 20 minutes.

2.2.4 Data analysis. The F0 tracks and tone duration of the eight smooth target syllables in both the non-phrase-final (sandhi) position and phrase-final (citation) position were analyzed using the same methods as in Experiment 1. 123 tokens out of 864 (14.24%) were excluded from analysis since they were either produced as Mandarin syllables (n = 36), as unintelligible syllables (n = 73), or skipped (n = 14).

3 Results

Based on the previous studies mentioned in section 1, we hypothesize that speakers access the surface sandhi form of words undergoing checked tone sandhi 53→21, 21→53, and smooth tone sandhi 33→21, 51→55, such that participants' production data should not exhibit any influence from the underlying representation. For F0 height and F0 contour, we predict that checked citation and sandhi tone 21, checked citation and sandhi tone 53, smooth citation and sandhi tone 21, as well as smooth citation and sandhi tone 55 should be completely acoustically neutralized in F0 height and F0 contour. However, given that the final lowering effect might be in play, all citation tones may be lower in F0 than their sandhi counterparts. That is to say, the non-sandhi tone in [te33] would also show lower F0 in the phrase-final position than in the non-phrase final position.

For tone duration, under the surface access hypothesis, we predict that the duration ratio of sandhi tone to citation tone should be close to 1 for checked citation to sandhi tone 21, checked citation to sandhi tone 53, smooth citation to sandhi tone 21, smooth citation to sandhi tone 55, and the phrase-final to non-phrase-final tone 33 in [te33]. However, if the positional effect of final lengthening plays a role, their ratios would be much smaller than 1 and constant across groups.

For Experiment 1, we will first compare citation checked tones 21 and 53 in terms of F0 height and F0 contour to examine whether they are completely neutralized as Tsay (1996) suggested. We will then present analyses to determine the shape of the checked tones, and whether checked citation and sandhi tone 21, as well as checked citation and sandhi tone 53 are completely neutralized in F0 height and F0 contour. Thirdly, we will compare the non-sandhi syllable in the phrase-final and non-phrase-final positions with regard to F0 height and F0 contour to evaluate positional effects. For Experiment 2, we will report the shape of the smooth tones first, and then whether smooth citation and sandhi tone 21, as well as smooth citation and sandhi tone 55 are completely neutralized in F0 height and F0 contour. Results of tone duration ratios will be presented at the end.

3.1 F0 analyses for checked syllables and the non-sandhi pair in Experiment 1

To ensure that the two citation checked tones 21 and 53 were contrastive in Taiwanese, rather than completely neutralized in the phrase-final position as reported by Tsay (1996), growth curve analyses (Mirman, 2014) were first conducted in R using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) to analyze their F0 tracks. This statistical method was also used for subsequent analyses. A series of likelihood ratio tests were conducted to determine the shape of the F0 track (i.e., linear, quadratic, or cubic). Results showed that the F0 track of each tone as represented by the 10 data points was best captured with a first-order (linear) orthogonal polynomial on all the 10 data points and a random effect of participant on all the 10 data points, linear versus linear + quadratic: $\chi^2 = 0.662$, $p = 0.956$; linear + quadratic versus linear + quadratic + cubic: $\chi^2 = 1.443$, $p = 0.920$. Based on the linear term, a second series of likelihood ratio tests were conducted to examine the effect of tone and the effect of tone on the linear term. For tone, citation checked tone 53 was treated as the baseline and relative parameters were estimated for the citation checked tone 21. Statistical significance (*p*-values) for individual parameter estimates was evaluated using the normal approximation (i.e., treating the *t*-value as a *z*-value, Mirman, 2014).

Results of the second series of likelihood ratio tests showed that the model including the linear term and tone was a better model than that containing only the linear term, $\chi^2 = 163.047$, $p < 0.001$. Furthermore, the model containing the linear term, tone, and tone on the linear term was not a better model than that including the linear term and tone, $\chi^2 = 1.767$, $p = 0.184$. Within the best model including the linear term and tone as fixed factors, there was a significant effect of the linear term, estimate = -0.955, standard error (*SE*) = 0.111, $p < 0.001$, illustrating that F0 declined over time in a linear fashion. Tone was also significant, estimate = -0.728, *SE* = 0.046, $p < 0.001$, indicating a higher F0 track for citation checked tone 53 than for citation checked tone 21. Contrary to Tsay (1996), the present results demonstrate that citation checked tone 21 and 53 are contrastive acoustically, rather than completely neutralized.

Statistical analyses were also conducted to examine the F0 tracks of citation checked tone 21 and sandhi checked tone 21, and those of citation checked tone 53 and sandhi checked tone 53. A series of likelihood ratio tests were conducted to evaluate the shape of the F0 tracks. Results showed that the F0 tracks as represented by the 10 data points were best captured with a first-order (linear) orthogonal polynomial on all the 10 data points and a random effect of participant on all 10 data points, for checked tones 21, linear versus linear + quadratic: $\chi^2 = 2.208$, $p = 0.698$; linear + quadratic versus linear + quadratic + cubic: $\chi^2 = 3.444$, $p = 0.632$; for checked tones 53, linear versus linear + quadratic: $\chi^2 = 0.632$, $p = 0.960$; and linear + quadratic versus linear + quadratic + cubic: $\chi^2 = 0.259$, $p = 0.998$.

Based on the linear term, a second series of likelihood ratio tests were conducted to investigate the effect of position (citation checked tone 21 vs. sandhi checked tone 21, citation checked tone 53 vs. sandhi checked tone 53) and the effect of position on the linear term. For citation checked tone 21 and sandhi checked tone 21, the model containing the linear term and position was not significantly better than that including only the linear term, $\chi^2 = 3.315$, $p = 0.069$. Moreover, the model containing the linear term, position, and position on the linear term was not significantly better than that including the linear term and position either, $\chi^2 = 0.450$, $p = 0.502$. The results illustrated that citation checked tone 21 and sandhi checked tone 21 were not different in F0 height or F0 contour. Therefore, their distinction was completely neutralized acoustically, as shown in Figure 1.

In terms of citation checked tone 53 and sandhi checked tone 53, likelihood ratio tests showed that the model containing the linear term and position was significantly better than that including only the linear term, $\chi^2 = 243.270$, $p < 0.001$. Additionally, the model including the linear term, position, and position on the linear term was not a better model than the model containing the linear term and position, $\chi^2 = 0.327$, $p = 0.567$, suggesting that these two tones did not differ in F0 contour. Within the best model containing linear term and position as fixed factors, linear term was significant, indicating that the F0 tracks of the two tones decreased linearly as a function of time, estimate = -0.911, *SE* = 0.111, $p < 0.001$. Position was also significant, demonstrating that citation checked tone 53 was lower in F0 than sandhi checked tone 53, estimate = 1.226, *SE* = 0.057, $p < 0.001$, as shown in Figure 2.

In order to assess the effect of position on final F0 lowering, a series of likelihood ratio tests were conducted to investigate the shape of the F0 tracks of final tone 33 and non-sandhi non-final tone 33. Results showed that the F0 tracks as represented by the 10 data points were best captured with a second-order orthogonal polynomial on all 10 data points and a random effect of participant on all 10 data points, linear versus linear + quadratic: $\chi^2 = 17.615$, $p = 0.001$; and linear + quadratic

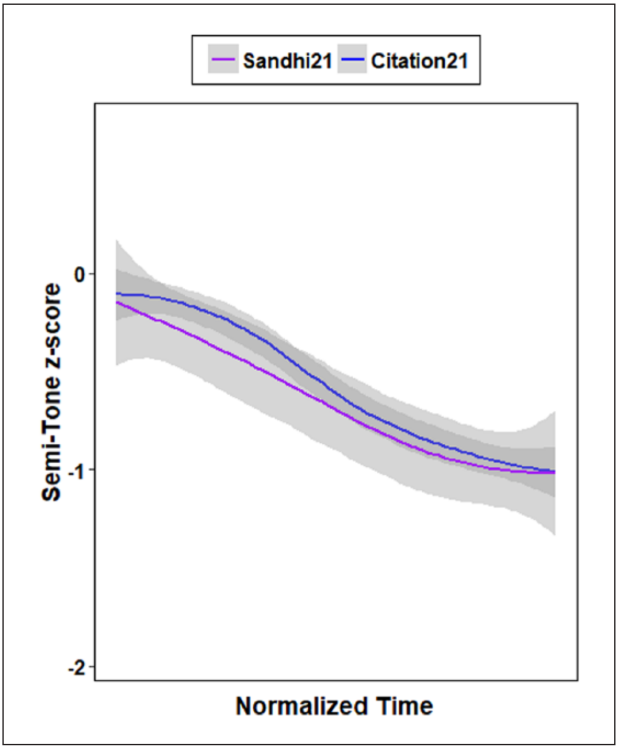

Figure 1. Fundamental frequency (F0) tracks of citation checked tone 21 and sandhi checked tone 21 (the F0 tracks are smoothened. The confidence limit is in the gray area, with a confidence level of 0.95).

versus linear + quadratic + cubic: $\chi^2 = 0.567$, $p = 0.989$, indicating that the F0 tracks of final tone 33 and non-phrase-final tone 33 declined more steeply at the beginning than at the end.

Based on the best model containing linear and quadratic terms, a second series of likelihood ratio tests were conducted to examine the effect of position, the effect of two terms (linear and quadratic terms), and their interaction. Results showed that the model containing the two terms and position was a better model than the model containing only the two terms, $\chi^2 = 45.690$, $p < 0.001$. Moreover, the model including the two terms, position, and their interaction was not a better model than the model including the two terms and position, $\chi^2 = 4.401$, $p = 0.111$, demonstrating that the F0 tracks of these two tones did not differ in contour. Within the best model, both linear and quadratic terms were significant, linear: estimate = -0.766, $SE = 0.106$, $p < 0.001$; and quadratic: estimate = 0.308, $SE = 0.069$, $p < 0.001$, indicating that tone 33 was shaped as a U tilted to the right. Position also showed a significant effect, estimate = 0.295, $SE = 0.041$, $p < 0.001$, demonstrating that the phrase-final tone 33 was lower in F0 than the non-phrase-final tone 33 (see Figure 3). Since sandhi did not apply to the non-phrase-final tone 33, the result here could only be due to the final lowering effect.

3.2 F0 analyses for smooth syllables in Experiment 2

Growth curve analyses were performed to compare the F0 tracks of citation and sandhi smooth tone 21, as well as those of citation and sandhi smooth tone 55. Likelihood ratio tests were conducted to evaluate the shapes of smooth tone 21 and smooth tone 55. Results showed that their F0 tracks as

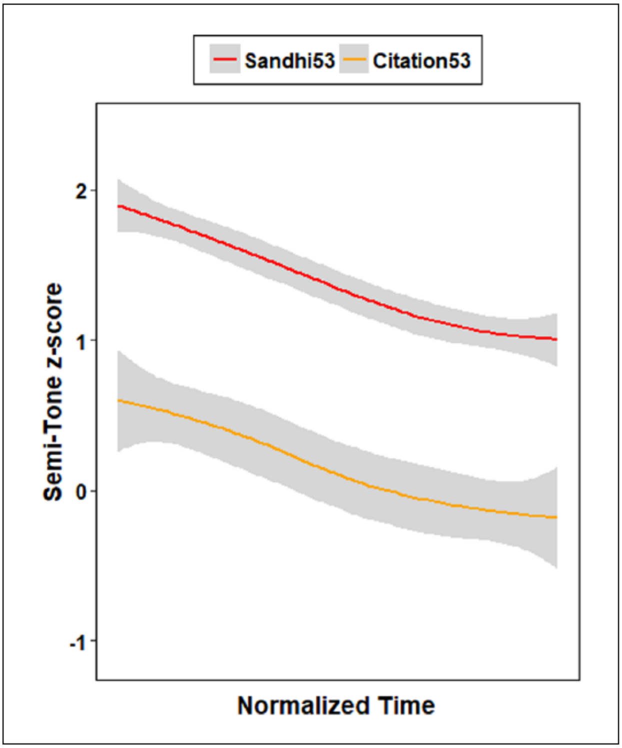

Figure 2. Fundamental frequency (F0) tracks of citation checked tone 53 and sandhi checked tone 53 (the F0 tracks are smoothened. The confidence limit is in the gray area, with a confidence level of 0.95).

represented by the 10 data points were best modeled by a third-order orthogonal polynomial on all the 10 data points and a random effect of participant on all 10 data points, for smooth tones 21, linear versus linear + quadratic: $\chi^2 = 71.304$, $p < 0.001$; linear + quadratic versus linear + quadratic + cubic: $\chi^2 = 12.597$, $p = 0.027$; for smooth tones 55, linear versus linear + quadratic: $\chi^2 = 9.122$, $p = 0.058$; and linear + quadratic versus linear + quadratic + cubic: $\chi^2 = 24.609$, $p < 0.001$, indicating that smooth tone 21 and 55 were shaped as an S.

A second series of likelihood ratio tests was performed to compare citation to sandhi smooth tone 21, and citation to sandhi smooth tone 55, by examining the effect of position, the effect of three terms (i.e., linear, quadratic, and cubic) and their interaction. For smooth tone 21, the model including the three terms and position was the best model, linear + quadratic + cubic versus linear + quadratic + cubic + position: $\chi^2 = 284.223$, $p < 0.001$; and linear + quadratic + cubic + position versus linear + quadratic + cubic + position + interaction: $\chi^2 = 4.488$, $p = 0.213$. The lack of interaction in the best model indicated that citation and sandhi smooth tone 21 showed identical F0 contours. For smooth tone 55, the model containing the three terms, position, and interaction was the best model, linear + quadratic + cubic versus linear + quadratic + cubic + position: $\chi^2 = 16.226$, $p < 0.001$; and linear + quadratic + cubic + position versus linear + quadratic + cubic + position + interaction: $\chi^2 = 25.660$, $p < 0.001$.

Within the optimal model for smooth tone 21, linear term, quadratic term, and cubic term were all significant, indicating that the shape of these two tones resembled both an S-shape and a U-shape at an angle, linear: estimate = -1.252, *SE* = 0.096, $p < 0.001$; quadratic: estimate = 0.544, *SE* =

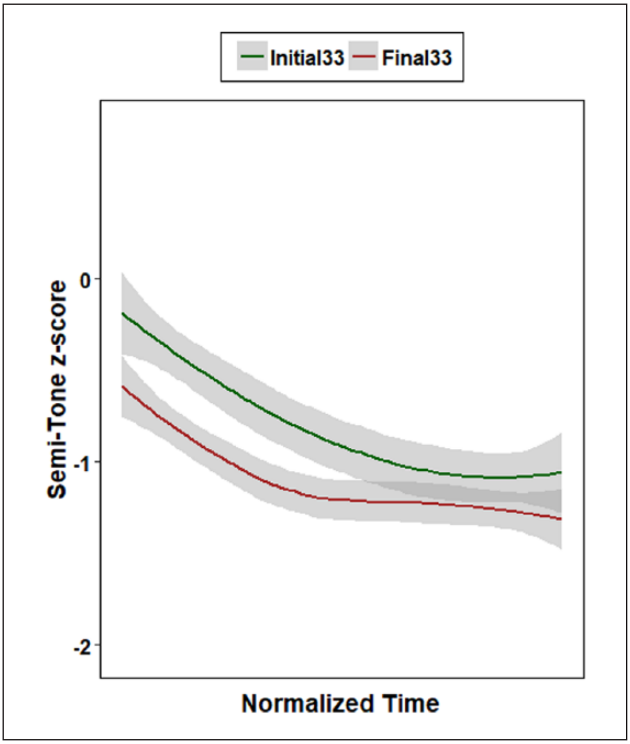

Figure 3. Fundamental frequency (F0) tracks of final tone 33 and initial tone 33 (the F0 tracks are smoothened. The confidence limit is in the gray area, with a confidence level of 0.95).

0.067, $p < 0.001$; and cubic: estimate = 0.210, *SE* = 0.040, $p < 0.001$. Position was also a significant fixed factor, indicating that citation smooth tone 21 was lower in F0 than sandhi smooth tone 21, as shown in Figure 4, estimate = 0.517, *SE* = 0.024, $p < 0.001$. Within the best model for smooth tone 55, linear term and cubic term were significant, demonstrating that the shape of citation and sandhi smooth tone 55 resembled an S-shape at an angle, linear: estimate = 0.252, *SE* = 0.061, $p <$ 0.001; and cubic: estimate = 0.180, *SE* = 0.039, $p < 0.001$. Position also showed a significant effect, suggesting that citation smooth tone 55 is lower in F0 than its counterpart, estimate = 0.072, *SE* = 0.017, $p < 0.001$. Finally, interaction effects between linear term and position, estimate = -0.174, *SE* = 0.053, $p = 0.001$, as well as between quadratic term and position, estimate = -0.199, *SE* = 0.053, $p < 0.001$, were all significant. These interaction effects indicated that the F0 contour of citation smooth tone 55 and that of sandhi smooth tone 55 were different as a function of time, as shown in Figure 5.

3.3 Tone duration analyses

In order to assess the extent to which position contributed to duration differences between initial and final tones, two one-way analyses of variance (ANOVAs) were conducted in R using the lme4 package on duration ratios (non-final tone duration divided by final tone duration). Duration ratios were compared among checked tone 21 (checked sandhi tone 21 divided by checked citation tone 21), checked tone 53 (checked sandhi tone 53 divided by checked citation tone 53), and the

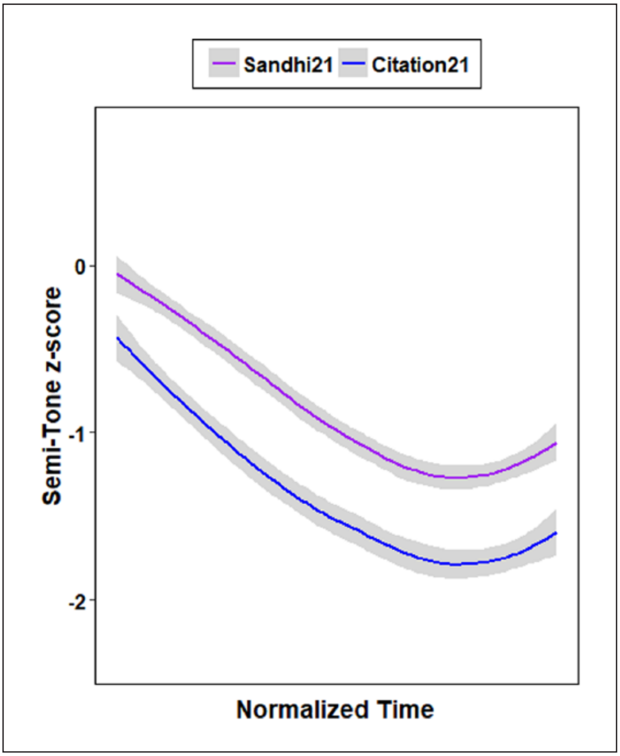

Figure 4. Fundamental frequency (F0) tracks of citation smooth tone 21 and sandhi smooth tone 21 (the F0 tracks are smoothened. The confidence limit is in the gray area, with a confidence level of 0.95).

non-sandhi pair (non-phrase-final tone 33 divided by phrase-final tone 33), and among smooth tone 21 (smooth sandhi tone 21 divided by smooth citation tone 21), smooth tone 55 (smooth sandhi tone 55 divided by smooth citation tone 55), and the non-sandhi pair. Tone (3 levels for each ANOVA) was treated as an independent variable and a within-subjects factor. Participant was regarded as a random factor. Results did not show a significant effect of tone for the checked tone group, $F(2, 20) = 0.284$, $p = 0.756$, as shown in Figure 6. Tone was not significant either for the smooth tone group, $F(2, 27) = 1.385$, $p = 0.268$, as shown in Figure 7. These results indicated that the ratios were comparable across tone types within each group. Tones in the first syllable are approximately 33% shorter than tones in the second syllable, regardless of tone type.

4 Discussion

The current study examined Taiwanese as a test case to investigate how words undergoing less productive phonological alternations are accessed during production. Lexical and computational mechanisms were tested by examining neutralization between citation and sandhi tones. We first tested Tsay's (1996) finding that Taiwanese checked tone sandhi is left-dominant and checked citation tones 21 and 53 are completely neutralized in the phrase-final position. We then compared citation to sandhi checked tone 21, citation to sandhi checked tone 53, citation to sandhi smooth tone 21, as well as citation to sandhi smooth tone 55 in terms of F0 height, F0 contour, and tone duration. Given that citation tones always occur in the phrase-final position and sandhi tones

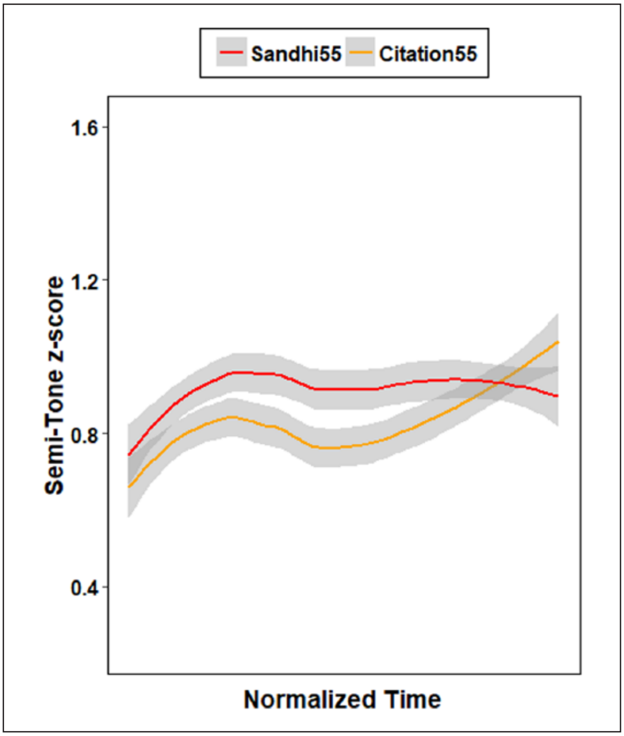

Figure 5. Fundamental frequency (F0) tracks of citation smooth tone 55 and sandhi smooth tone 55 (the F0 tracks are smoothened. The confidence limit is in the gray area, with a confidence level of 0.95).

always show up in the non-phrase-final position, differences between citation tones and sandhi tones due to positional effects might confound the results. Therefore, an additional exceptional syllable to which tone sandhi in the non-phrase-final position does not apply was included to directly evaluate final lengthening and F0 lowering effects. This syllable was compared to the same syllable in the phrase-final position. In the following section, we discuss F0 contour and F0 height first, then tone duration. Secondly, we compare the neutralization results in the present study with those in previous studies. Finally, we discuss the lexical and computational mechanisms regarding words with phonological alternations.

4.1 Could our F0 contour and F0 height results be due to a confound of position?

We found incomplete neutralization in both F0 contour and F0 height for citation smooth tone 55 compared to sandhi smooth tone 55. We also found incomplete neutralization in F0 height for citation compared to sandhi checked tone 53, citation compared to sandhi smooth tone 21, as well as the final compared to initial tone 33 in the non-sandhi exception. These data together suggest a positionally-induced rather than a sandhi-induced final lowering effect. Notice that sandhi smooth tone 55 is assumed to be derived from the underlying smooth tone 51. If the incomplete neutralization between citation and sandhi smooth tone 55 had been due to sandhi, sandhi smooth tone 55 should have shown a lower F0 than citation smooth tone 55. Moreover, sandhi smooth tone 55 was shaped as an ascending S instead of a descending linear slope, indicating that sandhi smooth tone 55 did not exhibit any trace of influence from its underlying smooth tone 51. The result of checked

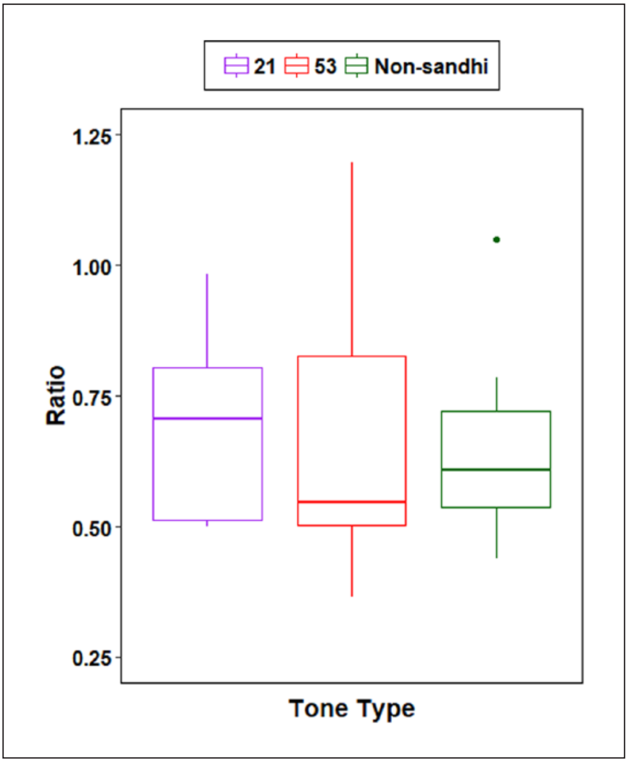

Figure 6. Duration ratio comparison among checked tone 21, 53 and smooth tone 33 (error bars are plotted with a confidence level of 0.95.).

tone 53 could be explained in the same way as that of smooth tone 55 in that sandhi checked tone 53, which is assumed to be derived from underlying checked tone 21, was higher in F0 than citation checked tone 53. If the incomplete neutralization between citation and sandhi checked tone 53 had been due to the influence from the underlying checked tone 21, a lower F0 for sandhi checked tone 53 should have emerged. Given these data, we propose that Taiwanese speakers may access the surface form of Taiwanese disyllabic words directly (i.e., [53, 55] for checked stimuli and [55, 55] for smooth stimuli in the current study).

The result of the comparison between the initial syllable in [te33 toŋ33] "earthquake," which is exempted from the sandhi process, and the final syllable in [toŋ33 te33] further justifies our interpretation. Without sandhi being involved, the initial [te33] showed a higher F0 than did the final [te33], indicating a final lowering effect. After considering the [te33] result, we solidify our claim that the decrease in F0 for the citation checked tone 53 and smooth tone 55 compared to their sandhi counterparts should also be due to this robust final lowering effect.

In contrast, sandhi checked tone 21 did not reveal a higher F0 than citation checked tone 21. Instead, both tones were completely neutralized not only in F0 height, but also in F0 contour. We suspect that the lack of F0 lowering for citation compared to sandhi checked tone 21 can be attributed to the fact that the tonal melody of the disyllabic stimuli used to elicit citation checked tone 21 already contained an intrinsic declination in F0 (i.e., [33, 21]). Hence, no genuine final lowering occurred to further decrease the F0 of citation checked tone 21, and this yielded complete neutralization. This complete neutralization in both F0 height and F0 contour can be

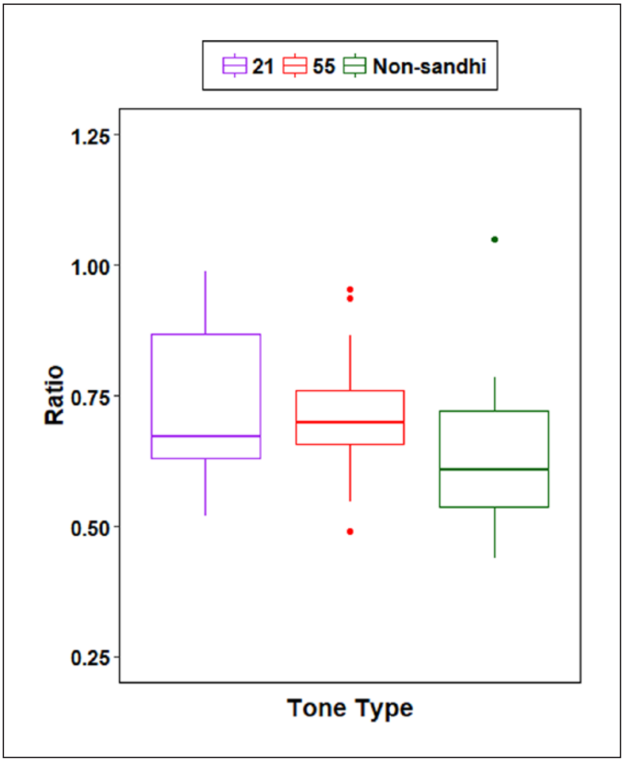

Figure 7. Duration ratio comparison among smooth tone 21, 55 and smooth tone 33 (error bars are plotted with a confidence level of 0.95).

considered as support for a lexical mechanism in that sandhi checked tone 21, which is assumed to be derived from underlying checked tone 53, should have shown a higher F0 than citation checked tone 21 if there had been any trace of influence from its underlying high tone. This result suggests that Taiwanese speakers access the surface form of these sandhi stimuli during production.

Regarding citation and sandhi smooth tone 21, we also found incomplete neutralization, with sandhi smooth tone 21 being significantly higher in F0 than its citation counterpart. This incomplete neutralization could be attributed to either F0 final lowering pertaining to citation smooth tone 21, or the influence from the underlying smooth tone 55. We acknowledge that it is difficult to separate one factor from the other entirely given the evidence we obtained in this study. However, the evidence from the pattern of results obtained in the above-mentioned comparisons, from the previous Taiwanese sandhi production studies (Zhang & Lai, 2008; Zhang et al., 2011) as well as from an auditory priming experiment (Chien et al., 2017) in which Taiwanese speakers showed less sensitivity to the less productive tone sandhi rules (smooth tone 51→55; 33→21) and accessed the surface form of these words, suggests that the incomplete neutralization exhibited by citation and sandhi smooth tone 21 may be due to final F0 lowering. Future studies, which include target words occurring in different positions of a sentence, are needed in order to more elegantly evaluate the position-induced final lowering effect given that this effect was shown to vary across different types of syntactic boundaries (Peng, 1997).

4.2 Could our tone duration results be due to a confound of position?

With respect to the tone duration of checked tones, we did not expect any difference between citation tones and their sandhi counterparts due to the influence from the underlying tone since checked tone 21 and 53 have similar durations (Peng, 1997). That is to say, we should not have observed any tone duration difference between citation and sandhi checked tone 21, as well as citation and sandhi checked tone 53 if sandhi had been the cause. Instead, we found that citation checked tones were about 33% longer than sandhi checked tones, suggesting a final F0 lengthening effect. Such an effect was further supported by a similar amount of lengthening generated by the non-sandhi syllable [te33] when we compared its duration in the initial position to that in the final position. This similar amount of F0 lengthening across checked tone 21, checked tone 53, and the non-sandhi exception was confirmed by the lack of statistical significance among the duration ratios of the initial tone to the final tone across different tone types.

Regarding the duration of smooth tones, despite the fact that an underlying effect would predict sandhi smooth tone 55, which is assumed to be derived from a shorter underlying smooth tone 51, to be shorter than citation smooth tone 55, and sandhi smooth tone 21, which is assumed to be derived from a longer underlying smooth tone 33, to show longer tone duration than citation smooth tone 21, we did not observe a significant effect among the ratios of the sandhi or initial tone duration to the citation or final tone duration across various tone types (smooth tone 55 vs. smooth tone 33 vs. the non-sandhi exception), demonstrating a global final lengthening effect. Taken together, the constant ratio of the initial tone duration to the final tone duration across tone types indicates no trace of influence from the underlying tone duration, suggesting a lexical mechanism.

4.3 Neutralization of Taiwanese tone sandhi

Despite varying experimental designs and statistical methods, incomplete neutralization of Taiwanese tone sandhi has been shown repeatedly. However, some methodological issues and interpretations of the data in the previous studies deserve more scrutiny. Recall that Kuo (2013) found incomplete neutralization between citation and sandhi tones in duration, F0 range, and voice quality. Kuo (2013) was a corpus study in which one male native Taiwanese speaker read a story out loud. The number and phonological environment of each target tone were not controlled. Moreover, the positional effect was not taken into consideration either. These methodological differences make it difficult to directly compare the current study with Kuo (2013). Tsay (1996) used six speakers' data and found that Taiwanese tone sandhi occurs in the phrase-final position. In addition, she demonstrated that checked tone 21 and checked tone 53 are acoustically completely neutralized in the phrase-final position, but contrastive in the non-phrase-final position. However, the fact that Tsay (1996) conducted *t*-tests to only compare one measurement point and analyzed two types of checked syllables that may be realized distinctively in terms of their sandhi patterns (i.e., checked syllables with a [p, t, k] or a [ʔ] coda), makes it difficult to interpret the implications of her results for the Taiwanese neutralization issue.

Tsay (1996) further claimed that Taiwanese checked tone sandhi is left-dominant rather than right-dominant. This claim is questionable in several respects. The first reason stems from right- and left-dominant sandhi behaviors. For a right-dominant sandhi system, tones in the final position of a sandhi domain preserve their citation tones, while those in the non-final position undergo tone sandhi. A sandhi tone can either be a lexical tone, or a tone that is not in the tonal inventory of that particular language (Chen, 2000; Yue-Hashimoto, 1987; Zhang, 2007, 2014). For a left-dominant sandhi system, a tone in the left-most position of a sandhi domain usually extends its F0 contour to the entire sandhi domain (Chen, 2000; Yue-Hashimoto, 1987; Zhang, 2007, 2014). If Taiwanese checked tone sandhi were left-dominant, the tonal extension sandhi pattern would predict a 55–33 tonal melody for disyllabic words starting with a checked tone 53, and a 22–11 tonal melody for disyllabic words beginning with a checked tone 21. The tones in the phrase-final position would not be neutralized, contradicting Tsay (1996). Second, research on the typological distribution of tone sandhi across Chinese dialects has shown that left-dominant sandhi exists mainly in Northern Wu dialects, such as Shanghai and Changzhou, while right-dominant sandhi systems have been found in Southern Wu, Northern dialects, and Min (Taiwanese is one of the Min dialects). In addition, Taiwanese smooth tone sandhi has been shown to exhibit a right-dominant pattern (Myers & Tsay, 2008; Zhang & Lai, 2010; Zhang et al., 2011). It is difficult to understand why Taiwanese checked tone sandhi would be left-dominant, that is, different from Taiwanese smooth tone sandhi.

Contrary to the current study, which compared tones in different positions, Lin (1988) as well as Myers and Tsay (2008) investigated two kinds of smooth sandhi tone 33 in the same position (non-phrase-final position), yet they showed different results. Lin (1988) used disyllabic nonwords as stimuli and found that sandhi tone 33 derived from underlying tone 55 was 8 Hz higher in F0 than sandhi tone 33 coming from underlying tone 24, indicating an underlying tone influence on the surface acoustic realization of the sandhi tone. However, Myers and Tsay (2008) used sentences in which target stimuli were embedded and obtained complete neutralization between these two kinds of smooth sandhi tone 33, suggesting a lexical mechanism. The discrepancies between these two studies could be due to the nature of the experimental methods. They also echo previous studies which illustrate that both the underlying and surface representations of words undergoing highly productive sandhi may contribute to lexical access (Chien et al., 2017; Zhang & Lai, 2008; Zhang et al., 2011). In Zhang et al. (2011), when asked to combine two accidental gap syllables and utter them as a disyllabic chunk, Taiwanese speakers produced expected tone sandhi outputs approximately 90% of the time for smooth tone sandhi 24→33 and 55→33, demonstrating that speakers are highly sensitive to the rule of these two sandhis. Moreover, Chien and colleagues' (2017) perception study showed that both monosyllabic surface primes (tone 33) and monosyllabic underlying primes (tone 24) facilitated lexical decision responses to disyllabic tone sandhi targets ([tone 33, tone 51]/[tone 24, tone 51]), with underlying primes eliciting a significantly stronger effect. Given that both underlying and surface sandhi forms of words undergoing highly productive sandhi might be represented in the mental lexicon, different stimuli implemented in various methods might tap into different representations. This could explain why Lin (1988) as well as Myers and Tsay (2008) achieved different neutralization results for F0.

Like the present study, Myers and Tsay (2008) also compared tones in different positions. Their results showed that smooth sandhi tone 33 derived from smooth citation tone 55 and smooth citation tone 33 are completely neutralized in F0 contour and F0 height, suggesting a lexical mechanism. The fact that there was no effect of final lowering may be because their stimuli did not occur in the utterance-final position, which differs from the experimental design of the current study in which each stimulus was presented in isolation. The pattern that the utterance-final position results in more F0 final lowering than does the phrase-final position in Taiwanese has been reported in Peng (1997). Future studies with target stimuli embedded in varying positions should be conducted to further research this issue.

4.4 Lexical mechanism versus computational mechanism of tone sandhi word production

Neutralization between a sandhi tone and its citation counterpart has been used as a means to investigate the mechanism that speakers adopt during sandhi word production. For example, Mandarin tone 3 sandhi neutralization, in which the word-initial citation tone 2 (a high-rising tone) is compared to the word-initial sandhi tone 2, has been shown to be phonetically incomplete. Specifically, sandhi tone 2 displayed a lower F0, a smaller F0 rise, and a later time point for F0 rise, suggesting an influence of the underlying tone 3 from which sandhi tone 2 is derived (Myers & Tsay, 2003; Peng, 2000; Yuan & Chen, 2014). This evidence for incomplete neutralization in Mandarin tone 3 sandhi is further supported by Zhang and Lai (2010) in which speakers heard two tone 3 monosyllables presented individually and were asked to produce them as a disyllabic word. Their results showed that all initial tone 3 syllables were converted to tone 2 without exception in this particular phonological environment even though the resulting disyllabic units were novel words, indicating that Mandarin tone 3 sandhi is an extremely productive phonological rule and speakers apply this rule online during production. Zhang C. et al., (2015) adopted a similar production method as in Zhang and Lai (2010) and compared Mandarin speakers' event-related potentials when producing segmentally matched T3+T3 words (i.e., sandhi T2+T3 on the surface) and T2+T3 words. Their results showed that T3+T3 words yielded stronger P2 amplitude than did T2+T3 words, indicating a more effortful process for Mandarin tone 3 sandhi word production.

The fact that Mandarin speakers may need to access underlying tone 3 is also evident in studies of spoken word recognition. In an auditory priming experiment, Chien et al. (2016) showed that when monosyllabic primes and the first syllable of tone 3 sandhi targets were matched in both segments and tones in the underlying representation, reaction times were facilitated; however, when they overlapped in both segments and tones on the surface, no priming effect was observed. This reflects a crucial role of the underlying tone 3 for Mandarin tone 3 sandhi words and suggests that Mandarin speakers compute the sandhi rule.

Unlike the extremely productive Mandarin tone 3 sandhi, less productive Taiwanese tone sandhi showed variable results across different sandhi rules in a nonce probe test. Zhang et al. (2011) found that Taiwanese smooth tone sandhi 33→21 and 51→55 yielded approximately 20–40% of expected tone sandhi outputs when Taiwanese participants heard two accidental gap syllables presented separately and were asked to produce them as a disyllabic chunk, while tone sandhi 55→33 and 24→33 induced over 80% of expected sandhi outputs (see also Zhang & Lai, 2008). In contrast, for real words, the rate of successful tone sandhi outputs was above 80% regardless of sandhi type, suggesting that Taiwanese speakers may not be sensitive to the less productive tone sandhi linguistic rules, such that they need to store and access those sandhi words via a lexical mechanism. The incomplete neutralization in the current study is consistent with such an account.

The present production results are also consistent with the perception results reported by Chien et al. (2017) in which Taiwanese speakers heard primes and targets matched in segments and tones either in the underlying representation, or in the surface representation. Their results showed that participants' lexical decision times to the targets were much faster in the underlying-match condition for highly productive sandhi 24→33, relative to a control condition. However, for less productive sandhi 51→55, participants were faster in the surface-match condition, indicating that Taiwanese tone sandhi words are processed differently and speakers have to access the surface form of less productive sandhi words. The present study suggests that words undergoing less productive tone sandhi (smooth tone 33→21, smooth tone 51→55, checked tone 21→53, and checked tone 53→21) may be produced via a lexical mechanism as evidenced by the lack of influence from the underlying tone for sandhi tones.

5 Conclusion

The current study investigated neutralization of less productive tone sandhi words. Particularly, we compared sandhi to citation checked tone 21, sandhi to citation checked tone 53, sandhi to citation smooth tone 21, and sandhi to citation smooth tone 55 in terms of F0 height, F0 contour, as well as tone duration. Moreover, a non-sandhi syllable was used to evaluate positional effects between initial and final tones. After accounting for the positional effects, both complete and incomplete neutralization results showed solid evidence that sandhi tones were not influenced by their corresponding underlying tones. The current findings, together with the results from previous productivity and auditory priming studies, provide a picture that speakers employ a lexical mechanism to produce words with less productive phonological alternations.

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References

Bates, D., Maechler, M., Bolker, B. M., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48.

Boersma, P., & Weenink, D. (2017). Praat: doing phonetics by computer [Computer program], Version 6.0.36. Retrieved from http://www.praat.org/

Chang, Y. (2012). *First language attrition: An investigation of Taiwanese tones and tone sandhi*. Ph.D. Dissertation, Indiana University, USA.

Charles-Luce, J. (1997). Cognitive factors involved in preserving a phonemic contrast. *Language and Speech*, *40*(3), 229–248.

Chen, M. Y. (1987). The syntax of Xiamen tone sandhi. *Phonological Yearbook*, 4, 109–149.

Chen, M. Y. (2000). *Tone sandhi: Patterns across Chinese dialects*. Cambridge, UK: Cambridge University Press.

Cheng, R. (1997). *台語的語音與詞法* (Taiwanese Phonology and Morphology). Taipei, Taiwan: Yuanliou. [In Chinese.]

Chien, Y.-C., Sereno, J. A., & Zhang, J. (2016). Priming the representation of Mandarin tone 3 sandhi words. *Language, Cognition, and Neuroscience*, *31*(2), 179–189.

Chien, Y.-C., Sereno, J. A., & Zhang, J. (2017). What's in a word: Observing the contribution of underlying and surface representations. *Language and Speech*, *60*(4), 643–657.

Dmitrieva, O., Jongman, A., & Sereno, J. A. (2010). Phonological neutralization by native and non-native speakers: The case of Russian final devoicing. *Journal of Phonetics, 38*(3), 483–492.

Gruenenfelder, T. M., & Pisoni, D. B. (1980). Fundamental frequency as a cue to postvocalic consonantal voicing: Some data from speech perception and production. *Perception and Psychophysics*, *28*(6), 514–520.

Herd, W., Jongman, A., & Sereno, J. (2010). An acoustic and perceptual analysis of /t/ and /d/ flaps in American English. *Journal of Phonetics*, *38*(4), 504–516.

Hsiao, Y. (1991). *Syntax, rhythm and tone: A triangular relationship*. Ph.D. Dissertation, University of California, San Diego, USA.

Kenstowicz, M. (1994). *Phonology in generative grammar*. Cambridge, MA: Blackwell Publishers.

Kenstowicz, M., & Kisseberth, C. (1979). *Generative phonology*. New York, NY: Academic Press.

Kiparsky, P. (1973). Abstractness, opacity, and global rules. In O. Fujimura (Ed.), *Three dimensions of linguistic theory* (pp. 57–86). Tokyo, Japan: TEC.

Kuo, C.-H. (2013). Perception and acoustic correlates of the Taiwanese tone sandhi group. Ph.D. Dissertation, University of California at Los Angeles, USA. Retrieved from http://linguistics.ucla.edu/general/dissertations/Kuo2013_Dissertation.pdf

Lin, H.-B. (1988). *Contextual stability of Taiwanese tones*. Ph.D. Dissertation, University of Connecticut, USA.

Lin, J. W. (1994). Lexical government and tone group formation in Xiamen Chinese. *Phonology*, *11*(2), 237–275.

Mirman, D. (2014). *Growth curve analysis and visualization using R*. Boca Raton, FL: Chapman & Hall/CRC.

Myers, J., & Tsay, J. (2003). Investigating the phonetics of Mandarin tone sandhi. *Taiwan Journal of Linguistics*, *1*(1), 29–68.

Myers, J., & Tsay, J. (2008). Neutralization in Taiwan Southern Min tone sandhi. *Interfaces in Chinese Phonology*, *49*(1), 47–78.

Peng, S.-H. (1997). Production and perception of Taiwanese tones in different tonal and prosodic contexts. *Journal of Phonetics*, *25*(3), 371–400.

Peng, S.-H. (2000). Lexical versus 'phonological' representations of Mandarin tones. In M. B. Broe, & J. B. Pierrehumbert (Eds.), *Papers in laboratory phonology 5* (pp. 152–167). Cambridge, UK; New York, NY: Cambridge University Press.

Port, R. F., & Crawford, P. (1989). Incomplete neutralization and pragmatics in German. *Journal of Phonetics*, *17*(4), 257–282.

Rietveld, T., & Chen, A. (2006). How to obtain and process perceptual judgments of intonational meaning. In S. Sudhoff, D. Lenortová, R. Meyer, S. Pappert, P. Augurzky, I. Mleinek, … Schieβer (Eds.), *Methods in empirical prosody research* (pp. 283–319). Berlin, Germany: Walter de Gruyter, Berlin.

Rose, P. (1987). Considerations in the normalization of the fundamental frequency in linguistic tone. *Speech Communication*, *6*(4), 343–351.

Soh, H. L. (2001). The syntax and semantics of phonological phrasing in Shanghai and Hokkien. *Journal of East Asian Linguistics*, *10*(1), 37–80.

Tagliaferri, B. (2005). Paradigm. Perception Research Systems. Inc. Retrieved from www.paradigmexperoments.com

Ting, P.-H. (1970). *Taiwan Yuyan Yuanliu: The origins of the languages in Taiwan*. Taichung, Taiwan: Press Secretary's Office, Taiwan Provincial Government.

Tsay, J. (1996). Neutralization of short tones in Taiwanese. In *Proceedings of the First Seoul International Conference on Phonetic Sciences (SICOPS'96)*, *Seoul, Korea*, 24–26 October 1996, pp. 136–141.

Tsay, J., Charles-Luce, J., & Guo, Y.-S. (1999). The syntax–phonology interface in Taiwanese: acoustic evidence. In J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville, & A. C. Bailey (Eds.), *Proceedings of the 14th International Congress of Phonetic Science (ICPhS'99)*, *San Francisco*, 1-7 August 1999, pp. 2407–2410.

Warner, N., Jongman, A., Sereno, J., & Kemper, R. (2004). Incomplete neutralization of sub-phonemic durational differences in production and perception of Dutch. *Journal of Phonetics*, *32*(2), 251–276.

Xu, Y. (2005). TimeNormalizedF0 (Praat script). Retrieved from http://www.phon.ucl.ac.uk/home/yi/tools.html

Yuan, J. H., & Chen, Y. (2014). Third tone sandhi in Standard Chinese: A corpus approach. *Journal of Chinese Linguistics, 42*(1), 218–237.

Yue-Hashimoto, A. O. (1987). Tone sandhi across Chinese dialects. In Chinese Language Society of Hong Kong (ed.), *Wang Li Memorial Volumes, English Volume* (pp. 445–474). Hong Kong, China: Joint Publishing Co.

Zhang, C., Xia, Q., & Peng, G. (2015). Mandarin third tone sandhi requires more effortful phonological encoding in speech production: Evidence from an ERP study. *Journal of Neurolinguistics*, *33*, 149–162.

Zhang, J. (2007). A directional asymmetry in Chinese tone sandhi systems. *Journal of East Asian Linguistics*, *16*(4), 259–302.

Zhang, J. (2014). Tones, tonal phonology, and tone sandhi. In C.-T. J. Huang, Y.-H. A. Li, & A. Simpson (Eds.), *The handbook of Chinese linguistics* (pp.443–464). Hoboken, NJ: John Wiley & Sons Inc.

Zhang, J., & Lai, Y.-W. (2008). Phonological knowledge beyond the lexicon in Taiwanese double reduplication. In Y. E. Hsiao, H.-C. Hsu, L.-H. Wee, & D.-A. Ho (Eds.) *Interfaces in Chinese phonology: Festschrift in honor of Matthew Y. Chen on his 70th birthday* (pp. 443–464). Taipei City, Taiwan: Academia Sinica.

Zhang, J., & Lai, Y.-W. (2010). Testing the role of phonetic knowledge in Mandarin tone sandhi. *Phonology*, *27*(1), 153–201.

Zhang, J., Lai, Y.-W., & Sailor, C. (2011). Modeling Taiwanese speakers' knowledge of tone sandhi in reduplication. *Lingua*, *121*(2), 181–206.

Zhu, X.-N. (2004). Jipin guiyihua – ruhe chuli shengdiao de suiji chayi? (F0 normalization—How to deal with between-speaker tonal variations?), *Yuyan Kexue (Linguistic Science)*, *3*(1), 3–19.