The productivity of tone sandhi patterns in Wuxi Chinese

By

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Abstract

The complex tone sandhi patterns of Chinese dialects present analytical challenges to theoretical phonology, and productivity tests can help us address the issue from another perspective. Previous studies have shown that sandhi productivity is negatively affected by phonological opacity, positively affected by clear phonetic motivations, and positively correlated with lexical frequency of the sandhi patterns. It is further argued that the phonological grammar of tone sandhi patterns includes both grammatical constraints and lexical listing.

We complement this research endeavor with a sandhi pattern whose productivity has not been previously studied: pattern substitution in Wuxi Chinese. Pattern substitution in Wuxi is left-dominant, whereby the base tone of the first syllable is first replaced by another tone before being spread to the sandhi domain. As a first step towards understanding the productivity of the pattern, we focus on disyllabic combinations between the three Yin tones on non-checked syllables T1, T3, and T5.

Twenty native Wuxi Chinese speakers produced four sets of stimuli, including one set of Actual-Occurring real words (AO-AO), two sets of novel words made up of Actual-Occurring morphemes (*AO-AO1, *AO-AO2), and one set of novel words composed of an Accidental-Gap syllable and an Actual-Occurring morpheme (AG-AO). The difference between *AO-AO1 and *AO-AO2 was that the first AO morpheme of *AO-AO1 occurs in the initial position of real disyllable words, while that of *AO-AO2 does not. Both acoustic and statistical analyses were conducted.

The results show that speakers had no difficulty producing real words with the expected sandhi, but pattern substitution is not fully productive in novel words. AG-AO showed the lowest productivity, while there was no significant difference between *AO-AO1 and *AO-AO2. This indicates that speakers may have tonal allomorph listings for morphemes as well as for syllables of morphemes (*AO-AO2). When they could not find the syllables in real syllable listing (AG-AO), they tend to spread the base tone of the first syllable or do nothing. Moreover, T3 showed the highest substitution productivity, and the similarity between T3, a low rising tone, and its substitution, a high rising tone, is the highest. It suggests that speakers may rely more on phonetic similarity rather than lexical frequency in applying tone sandhi to novel words.

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1. Introduction

1.1 Tone sandhi types of Chinese dialects

The phonetic pitch on a syllable distinguishes lexical meaning in tone languages. Mandarin Chinese is a well-known and widely spoken tone language. Other tone languages include most Chinese dialects, Thai, Vietnamese, Cherokee, Bantu languages, etc. The widely cited example *ma55/ma35/ma213/ma51*[1] *(mother/hemp/horse/scold)* illustrates that pitch change on a syllable produces meaning differences. When two tones are in contact with each other in continuous speech, the phonetic shape of the tones may change. Chen (2000) claimed that tone can be changed by neighboring tones or morphological contexts, and the affected tone may become either a new tone that only occurs in such environments or a different existing tone. This type of tone change is called tone sandhi.

There are two main types of tone sandhi in the Chinese dialects: last-syllable dominant (right-dominant) and first-syllable dominant (left-dominant) (Yue-Hashimoto, 1987; Zhang, 2007). In right-dominant sandhi, the final syllable in the sandhi domain keeps the citation tone, while the preceding syllables undergo sandhi. Most of Min, Southern Wu, and Mandarin dialects show this type of tone sandhi, such as Xiamen (Chen, 1987), Taiwanese, and Mandarin. Zhang (2007) claimed that the right-dominant sandhi tends to involve local or paradigmatic tone change. Examples in (1) illustrate right-dominant sandhi. The Mandarin tone sandhi in (1a) is tonally induced in that the tone change is induced by its adjacent tone; the Taiwanese tone sandhi in (1b) is positionally induced in that the tone change is

[1] Chao's (1930) system of tone numbers uses '1' to '5' to indicate pitch levels, with '1' as the lowest pitch and '5' the highest.

determined by the position of the tone, in this case, nonfinal position, regardless of what its neighboring tones are. In left-dominant sandhi, the first syllable in the sandhi domain keeps its citation tone, while the following syllables undergo sandhi. It is generally found in Northern Wu dialects such as Shanghai (Zee & Maddieson, 1979) and Changzhou (Wang, 1988). According to Yue-Hashimoto (1980), there are typically two strategies for left-dominant tone sandhi, pattern extension and pattern substitution. Pattern extension is simply spreading the tone of the first syllable to the entire sandhi domain, as found in Shanghai, while pattern substitution involves replacing the tone of the first syllable with another tone before spreading, as found in Tangxi (Kennedy, 1953) and Wuxi (Chan & Ren, 1989). Examples of both pattern extension in Shanghai and pattern substitution in Wuxi are given in (2a) and (2b), respectively. In Shanghai, when tone 24 is combined with any tones, the tones of the disyllable become 22 + 44, a result of spreading the initial base tone 24. In Wuxi, when tone 34 is combined with any tones, the tones of the disyllable become 55 + 31, a result of first substituting the base tone 34 with a falling tone 51 and then spreading the 51 to the disyllable. In (2), "X" refers to any tone in the tonal inventory in Shanghai (2a) and Wuxi (2b).

(1) *Right-dominant sandhi:*

a. Tonally induced tone sandhi: Mandarin third tone sandhi

   213 → 35 / ___213

b. Positionally induced tone sandhi: Taiwanese tone circle

51 → 55 → 33 ← 24 in nonfinal positions

21

(2) *Left-dominant sandhi:*

a. Pattern extension: Shanghai tone sandhi

24 + X → 22 + 44

b. Pattern substitution: Wuxi tone sandhi

34 + X → 55 + 31

These complex tone sandhi patterns of Chinese dialects present challenges to theoretical analysis. There are a number of reasons for the theoretical difficulties. First, the sandhi patterns in Chinese dialects can be extremely complex, and any tone in the inventory may alternate, as we will see in the Wuxi example later on. Second, the articulatory and perceptual motivation of tone sandhi may be lost during diachronic change and cannot be found in the current synchronic systems. For example, the Mandarin 213 → 35 / __ 213 sandhi pattern corresponds to a historical pattern in Chinese, *shang* → *yang ping* / __ *shang*, where *shang* and *yang ping* refer to the historical tonal categories for 213 and 35. The same historical sandhi shows different realizations in other related Mandarin dialects (Court, 1985), as in Tianjin it is 13 → 45 / __ 13 (Yang et al., 1999), and in Jinan 55 → 42 / __ 55 (Qian & Zhu, 1998). This indicates that the synchronic pattern in Mandarin does not reflect any articulatory or perceptual motivations that may have existed historically. Third, some tone sandhi patterns are phonologically opaque,[2] such as Taiwanese in (1b). Due to the lack of markedness motivation of the current tone sandhi as a result of diachronic change and the common presence of opacity, which poses problems for surface oriented phonological theories, many studies found it difficult to account for complex tone sandhi patterns (e.g., Chen, 2000; Lin, 2008; Zhang, 1999; Wang, 2002; Yip, 1999, 2004), particularly using constraint-based Optimality Theory (Prince and Smolensky, 1993/2004).

However, we can address the issue from another perspective, i.e., whether native speakers' tacit knowledge of the tone sandhi patterns is accurately reflected in the synchronic sandhi patterns, in other words, whether the observed sandhi patterns are truly productive as evidenced by nonce-word tests. If the sandhi patterns are truly productive, then the theoretic issues mentioned above indeed need to be addressed head-on. If not, however, then it is likely that the sandhi patterns are more due to lexical listing rather than input-output derivation.

Recent productivity studies have shown that the Chinese sandhi patterns are not entirely productive in novel words. Most of them have been conducted in the right-dominant sandhi system, such as Taiwanese (Hsieh, 1970; Wang, 1993; Zhang et. al. 2009, 2011), Mandarin (Zhang & Lai, 2010), and Tianjin (Zhang & Liu, 2011). The only dialect with left-dominant sandhi that has been tested is Shanghai (Zhang & Meng, 2012). These studies tested different hypotheses in the productivity patterns of tone sandhi. Taiwanese has a tone sandhi circle in nonfinal position causing opacity, as in (1b), and the effect of opacity on productivity has been investigated by a number of studies. Phonetic properties may have an impact on tone

[2] A phonological rule P, A → B / C__D, is opaque if the surface structures are any of the following: (a) instance of A in the C__D environment, or (b) instance of B derived by P in environments other than C__D (Kiparsky, 1973).

sandhi production, as in Mandarin and Tianjin. Lexical frequency has an inconsistent effect on tone sandhi patterns, as collectively shown in Taiwanese, Mandarin, Tianjin, and Shanghai. Generally speaking, opacity, phonetic properties, and lexical frequency may all influence the production of tone sandhi patterns. In the next section, a brief review of the relevant productivity studies is provided.

1.2 Experimental studies addressing the productivity of tone sandhi

Hsieh (1970) investigated speakers' phonological knowledge in Taiwanese tone sandhi which has a tonal circle, using a wug test (Berko, 1958). This tone sandhi pattern of chain shift has been shown to be incomputable by only using IO-faithfulness and markedness constraints in OT (Moreton, 2004). The productivity test showed that speakers had no difficulty pronouncing actual noun compounds. But they had difficulty particularly with the circular chain shift in the wug test. When they were asked to produce novel noun compounds, if they could identify the novel morphemes as two real morphemes, they applied the expected sandhi; if not, they repeated the syllables without sandhi.

Wang (1993) reduplicated Hsieh (1970), but discovered higher sandhi productivity in a four-month longitudinal study. They observed more sandhi produced by the subjects in the later period of the experiment, which may be a result of the practice effect. Wang also pointed out that there was large variation between the sandhi productivity of different tones. They assumed that both the citation tone and the sandhi tone existed in the speakers' lexicon. The words and phrases are connected by phonemes, lexicon and semantics in substructure, which all together form an analogical chain. In other words, language is not rule-governed, but a connection of analogical chains and speakers use this knowledge in production.

Zhang, Lai & Sailor (2009, 2011) investigated the productivity of the sandhi pattern in reduplication in Taiwanese. They discovered that when the syllables did not exist, speakers produced significantly less sandhi. Moreover, both duration of sandhi tones and the lexical frequency of the base tones may influence the productivity among opaque mapping, but they are reflected in different tones. To be specific, the two falling tones 51 and 21 have considerably shorter durations than 55, 33, and 24 according to acoustic studies (Lin, 1988; Peng, 1997). Given that nonfinal syllables have intrinsically shorter duration than final syllable due to the lack of final lengthening, the low productivity of 51 → 55 may be caused by the duration-increasing nature of the sandhi (the sandhi occurs in nonfinal positions); the lexical frequencies of the tones involved cannot explain the productivity pattern, as 51, 55, and the tonal melody 55-51 all occur relatively frequently. On the other hand, the low productivity of 33 → 21 cannot be resulted from duration, as the sandhi is duration-reducing, but may be caused by low lexical frequency of the base tone 33 and the reduplicative melody 21-33. Finally, the lack of rising tone on non-final syllable is generally productive across real and novel words. They suggested that opacity, phonetic basis, and lexical frequency all have an effect on the productivity of tone sandhi.

Zhang & Lai (2010) investigated how native Mandarin speakers apply two types of tone sandhi to novel words. One is T3 (213) → 21 / ___ T (T ≠ 213), which is contour reduction with a clear phonetic motivation, and the other is T3 (213) → T2 (35) / ___ T3 (213), which is perceptually neutralizing with a less clear phonetic motivation. They found that speakers applied the 213 → 21 more accurately than the 213 → 35 sandhi in novel words, which suggested that phonetically more motivated pattern leads to higher productivity in tone sandhi. Moreover, lexical frequency is also related to the sandhis in novel words, but the effect is not as obvious as compared to Taiwanese. The half-third tone (21) in T3 + T2 has the lowest type frequency and also the lowest accuracy in novel words among all half-third sandhi environments. That is to say, phonetic properties and lexical frequency both influence Mandarin tone sandhi.

Zhang & Liu (2011) examined the productivity of the tone sandhis in Tianjin Chinese, also using a wug test. Similar to the results of Zhang and Lai (2010), their results also showed that the phonetic property and lexical frequency of the tone sandhi both have an influence on sandhi productivity: without strong phonetic bases, some fully productive sandhis in the lexicon have lower productivity in wug words than real words, e.g., L + L → LH + L; for sandhis that share similar phonetic motivation, e.g., LH + H → L + H and LH + HL → L + HL, the more frequent one (the latter) is more productive.

Zhang & Meng (2012) investigated the productivity of left-dominant sandhis of Shanghai in both real and novel words. For example, when tone 51 is combined with any tones in the Shanghai tone inventory, 51 + X, the surface tones become 55 + 31, a spreading pattern of tone 51. They found that overall left-dominant sandhi is relatively productive, although certain tonal combinations are not productive, such as 12 + 51 → 11 + 13.[3] They pointed out

[3] Underlined tone number indicates that the tone occurs on checked syllables, which are syllables closed with a glottal stop.

that for this tonal combination, the mismatch between phonological stress (left) and surface phonetic prominence (right), the contour dissimilarity between the base tones and sandhi tones, and the rising sandhi tone on the second syllable may all contribute to its unproductivity. In addition, the lexical frequency of real words has an inconsistent effect on the application of tone sandhi. For left-dominant sandhi, 30 out of 50 pitch contour comparison between high and low frequency words showed significant differences in either mean F0 or F0 shape, or both. These differences may be caused by the different segmental contents of the different words that the speakers read, not lexical frequency. They were unable to deduce a clear pattern from the few significant contour shape comparisons between high and low frequency words.

1.3 Present Study

Previous productivity results of tone sandhi showed that in right-dominant sandhi systems, the sandhis with stronger phonetic motivations also result in high productivity, e.g., in Mandarin and Tianjin, and sandhis that involve opacity, e.g. in Taiwanese, are not very productive. On the other hand, in the left-dominant sandhi system of Shanghai, pattern extension is relatively productive in novel words. Lexical frequency has inconsistent effects on sandhi productivity: it influences the productivity of tone sandhi in Taiwanese, Mandarin, and Tianjin. What we currently do not know is whether pattern substitution in left-dominant sandhi system is productive, or what exists in speakers' phonological knowledge for this pattern. The current study complements the tone sandhi study by testing the productivity of pattern substitution in Wuxi tone sandhi.

Wuxi Chinese is a Northern Wu dialect of Chinese spoken by people living in Wuxi (a medium-sized city near Shanghai). According to traditional practice, there are four categories of tones in Wuxi, Ping, Shang, Qu, Ru. Two registers based on the voicing of the initial consonant separate each category into Yin (voiceless) and Yang (voiced), resulting in eight tones. All Yin-register tones are odd-numbered (T1, T3, T5 and T7), and all Yang-register tones are even-numbered (T2, T4, T6 and T8), listed in (3). T1 to T6 occur on open or sonorant-closed syllables. T7 and T8 occur on checked syllables, which are syllables closed by a glottal stop. According to the acoustic study by Xu (2007), T1, T3 and T5 are different in monosyllabic citation forms, while T2, T4 and T6 have emerged as the same contour tone in monosyllabic citation forms due to historical reasons:

(3) *Wuxi tones*

Tone 1	53	Tone 2	113
Tone 3	323	Tone 4	13
Tone 5	34	Tone 6	113
Tone 7	5	Tone 8	13

Chan & Ren (1989) provided the first instrumental study of tones and tone sandhi in Wuxi Chinese, which have both pattern extension and pattern substitution. Pattern extension applies to reduplicated verbs, reduplicated nouns in baby talk, verbs with resultative or directional complement, and expressions of ‘number + classifier’. Pattern substitution applies to regular compounds, phrases and reduplicated nouns, listed in (4). The first column represents the tone on σ1; and the first row represents the tone on σ2. Tone sandhi of the disyllable examples appear in the body of the table. For example, when T1 (53) is combined with the six tones from T1 to T6, for substitution, it undergoes 53 + X → 43 + 34 (“X” refers to any tone among T1 to T6), such as 新鲜(sin53 siɪ53) →sin43-siɪ34. When T1 is combined with the two tones that only occur on checked syllables, T7 and T8, for substitution, it undergoes 53 + X → 43 + 34 (“X” refers to T7 or T8).

(4) *Wuxi disyllabic tone sandhi substitution patterns*

<table>
<tr><th>2nd Syll. / 1st Syll.</th><th>T1 [53]</th><th>T2 [113]</th><th>T3 [323]</th><th>T4 [13]</th><th>T5 [34]</th><th>T6 [113]</th><th>T7 [5]</th><th>T8 [13]</th><th>Examples</th></tr>
<tr><td>T1 [53]</td><td colspan="6">43+34</td><td colspan="2">43+34</td><td>新鲜(sin53 siɪ53)
fresh</td></tr>
<tr><td>T2 [113]</td><td colspan="6">35+31</td><td colspan="2">35+31</td><td>年轻(ȵɪ113 tɕin53)
young</td></tr>
<tr><td>T3 [323]</td><td colspan="6">44+55</td><td colspan="2">44+5</td><td>胆小(tɛ323 siɔ323)
coward</td></tr>
</table>

<table>
<tr><td>T4
[13]</td><td>33+55</td><td>43+34
(+T3/T4/T5/T6)</td><td colspan="2">33+<u>5</u></td><td>老师(lɔ13 sɿ53) - 33+55
teacher
冷水(læ̃13sɥ323) - 43+34
cold water</td></tr>
<tr><td>T5
[34]</td><td colspan="2">55+31</td><td colspan="2">55+<u>31</u></td><td>奋斗(fən34 tɛi34)
to fight for</td></tr>
<tr><td>T6
[113]</td><td colspan="2">33+55</td><td colspan="2">33+<u>5</u></td><td>号码(ɦɔ113 m̩13)
number</td></tr>
<tr><td>T7
[<u>5</u>]</td><td colspan="2"><u>3</u>+55</td><td rowspan="2"><u>5</u>+<u>5</u></td><td rowspan="2"><u>3</u>+<u>5</u></td><td>发明(faʔ5 min113)
to invent</td></tr>
<tr><td>T8
[<u>13</u>]</td><td colspan="2"><u>3</u>+55</td><td>物理(vəʔ<u>13</u> li13)
physics</td></tr>
</table>

Our study focuses on the pattern substitution of disyllabic combinations between T1 (53), T3 (323) and T5 (34), the three Yin-register tones occurring on open or sonorant-closed syllables, as listed in (5a). They have different tones in monosyllables and the sandhi pattern has fewer exceptions than the other tones. The three tones also display opacity between citation tones and sandhi tones, which is shown in (5b).

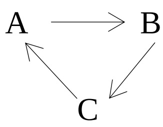
(5) a. *Tonal combinations under investigation*

2nd Syll. / 1st Syll.	T1 [53]	T3 [323]	T5 [34]	Examples

T1 [53]	43+34	新鲜(sin44 siɪ44) *fresh*
T3[323]	44+55	胆小(tε323 siɔ323) *coward*
T5[34]	55+31	奋斗(fən34 tεi34) *to fight for*

b. *Circular chain shift between citation tones and sandhi tones in T1, T3, and T5*

σ1	Citation tone on σ1	Sandhi tone on σ1σ2
T1	53 (A)	43+34 (B)
T3	323[4] (B)	44+55 (C)
T5	34 (C)	55+31 (A)



It appears that the sandhi shape for the disyllables with T1 as the first syllable is phonetically similar to the citation tone shape of T3; the sandhi shape for disyllables with T3 as the first syllable is phonetically similar to the citation tone shape of T5; and the sandhi shape for disyllables with T5 as the first syllable is phonetically similar to the citation tone shape of T1.

Two questions are addressed using the wug test (Berko, 1958) and the hypotheses are proposed based on previous research and the features of pattern substitution. First, is pattern

[4] In the acoustic study by Xu (2007), T3 (323) has a very small falling at the beginning and can be considered as 223.

substitution productive? In other words, does pattern substitution apply in both real and novel words? Although pattern extension is relatively productive in Shanghai, since the spreading needs to be done with a substituted tone and there is opacity between the citation tone and the sandhi tone, the productivity of pattern substitution in Wuxi may be lower. Second, are there any productivity differences among different tonal combinations? We assume that the phonetic similarity between the citation tone of the first syllable and the sandhi tone, as well as the type frequency of the three tones and their token frequency, would all have effects on the productivity.

On the one hand, when we consider phonetic properties between the citation tone shape of the first syllable and the sandhi shape in the whole disyllabic domain, T1+X changes the initial citation tone 53 to 43+34, a falling tone to a dipping shape; T3+X changes the initial citation tone 323 to 44+55, a dipping tone with a small initial falling to two level tones with the second one on slightly higher pitch; and T5+X changes the initial citation tone 34 to 55+31, a mid rising tone to a falling shape. The citation tone of T3 is phonetically more similar with the sandhi shape of T3+X, comparing with the other two. This phonetic similarity of T3 and T3+X may lead to relatively more expected substitution (correct sandhi)[5] among the three tonal combinations. Disyllables with T3 on the first syllable, therefore, may be more likely to undergo the correct sandhi in novel words.

On the other hand, according to the Monosyllabic Morpheme List of Wuxi by Cao (2003) and Wang (2008), there are 886 single morphemes for T1, 449 morphemes for T3, and 579

[5] By "correct", we do not mean to impose a judgment on whether the speakers' sandhi behavior is "correct" or not. "Correct sandhi" only refers to the expected sandhi for convenience here.

morphemes for T5. This frequency will be referred to as type frequency for tones, which means T1 has the highest type frequency. We also calculated the character frequency of these morphemes in Jun Da (2004)'s written Mandarin character frequency corpus including 12,041 characters used in classical and modern Chinese. The reasons that we used Jun Da (2004)'s corpus here and below (in §2.2) is because there is no corpus in Wuxi. Moreover, Wuxi and Mandarin share the same writing system, the frequency of written Mandarin could be used as an estimate for the frequency of Wuxi. The corpus has a total of 258,852,642 character tokens. T1 has a raw token frequency of 42,952,704; T3 25,775,177, and T5 34,360,503. Again, the tokens of T1 have the highest frequency among the tokens of the three tones. In other words, T1 has the highest type and token frequency among the three tones and T3 has the lowest. If frequency has an effect on the productivity of sandhi patterns, disyllabic words with T1 on σ1 would be expected to undergo more correct tone sandhi than those with T3 on σ1. Hence, the question is "which factor has more influence on the productivity of pattern substitution in Wuxi, phonetic similarity or frequency?"

2. Methods

2.1 Subjects

Twenty native speakers of Wuxi Chinese participated in this study, including 12 males and 8 females. They were all born in Wuxi, ranged from 21 to 35 years old, with an average of 27. None of them left Wuxi until 18 years of age, and are all living in Wuxi currently.

2.2 Materials

The experiment is a production task with four sets of stimuli. Following Hsieh (1970) and Zhang (2009, 2010, 2011), the stimuli were designed to investigate the productivity of the sandhis by using pseudo-words with adult speakers. Real words were also tested to serve as the baseline to see whether the speaker applies the correct sandhi. The experiment was implemented in Paradigm (Tagliaferri, 2011).

Four sets of disyllabic words were used in the experiment. The first set is real words, referred to as AO-AO, where AO indicates an actual occurring morpheme. For AO-AO, we controlled the frequency for the disyllabic words, based on Jun Da (2004)'s general fiction bigram[6] frequency list. It is a written Chinese corpus, including 973,338 bigrams, with a frequency of occurrence from 0 to 60,000. The average disyllable frequency of the stimuli is 254.56 in this study.

The other sets are all wug words. The second set (*AO-AO1) is nonsense words formed by combining two real morphemes. Moreover, the first morpheme occurs in initial position in real disyllabic words, which allows the speaker to access the substituted tone used in pattern substitution. For example, we used 煎弯 ([tsiɪ53 uɛ53], *to fry* + *curved*), 煎展 ([tsiɪ53 tsʊ323], *to fry* + *exhibition*), and 煎伞 ([tsiɪ53 sɛ34], *to fry* + *umbrella*) as one set of T1(53)+X stimuli. 煎 ([tsiɪ53], *to fry*) is a morpheme that occurs in initial position. The third set (*AO-AO2) is similar to the second set, but the first morpheme never appears as the first morpheme in real disyllabic words, in which case speakers may have little knowledge of the substituted tone. For instance, 齿军 ([tshɿ323 tɕyən53], *the second character of tooth* +

[6] Bigram refers to every sequence of two adjacent characters in a string of tokens, which may be a nonsense combination of characters in the corpus.

army), 齿掌 ([tshʅ323 tsæ̃323], *the second character of tooth + palm*), and 齿顿 ([tshʅ323 tən34], *the second character of tooth + to pause*) are one set of T3(323)+X stimuli. The morpheme 齿 ([tshʅ323], *the second character of tooth*) would not appear in initial position in Wuxi. The frequency of the first morphemes of these two sets could not be controlled, as morphemes that never appear in initial position have overall lower frequencies than morphemes do occur in initial position. The fourth set is AG-AO, in which the first syllable is an accidental gap (AG) and the second syllable is an actual-occurring morpheme (AO). In the AG syllables, both the segments and the tone of the syllable are legal, but the whole combination does not exist in Wuxi Chinese. For instance, [tsia] is a legal syllable and can take T3 323 'elder sister' and T5 34 'to borrow', yet it is never combined with T1 53. Hence [tsia53] is a possible AG. [tsia53 tɕin53] (tsia53 *gold*), [tsia53 tʰin323] (tsia53 *yacht*), and [tsia53 pʰiɔ34] (tsia53 *ticket*) are one set of stimuli in AG-AO. The AGs were selected by the author, a native speaker of Wuxi Chinese. Only T1, T3, and T5 were tested here, so there were nine tonal combinations (3*3=9). Four words were used for each tonal combination, including two verb + noun disyllabic words and two modifier + noun disyllabic words, which resulted in 36 stimuli (9*4=36) in each set. There were 144 stimuli in total (36*4=144). The entire stimuli list is given in the Appendix.

2.3 Procedure

During the experiment, the participants wore a pair of headphones, and a computer screen and a microphone were also placed in front of them. For AO-AO, *AO-AO1 and *AO-AO2, they listened to two monosyllabic words separated by an 800 ms interval in sequence and saw the Chinese characters on the computer screen, and then they were asked to pronounce them as a disyllabic word in Wuxi. For AG-AO, subjects first listened to cue sentences that provided meanings for the AGs, and then they were asked to put the AGs and AOs together and produce disyllabic words as if they were real. The AGs were represented with a box "口". For example, the subjects would simultaneously hear and see "假设上网买东西叫做 tsia44; 如果黄金还没有tsia44, 那么也可以讲还没___." (*"If to shop online is called tsia44; if gold has not been tsia44-ed, then we can say that we have not* ___*."*) Then he or she was asked to produce "tsia44 金" as if it were a real word. Each AG combines with three monosyllabic words in one block, which are in T1, T3, and T5 respectively, 12 AG blocks appeared randomly for every speaker. Their response was recorded by the microphone.

The experiment was conducted in Wuxi, China. The recording was made with a Marantz PMD-671 solid state recorder through an Electrovoice 767 microphone.

2.4 Analysis/Coding

All stimuli were analyzed in VoiceSauce (Shue, Keating & Vicenik 2009), an application implemented in Matlab, providing automated voice measurements on audio recordings. It gets the F0 measurement at every millisecond through STRAIGHT (Speech Transformation and Representation by Adaptive Interpolation of weiGHTed spectrogram). STRAIGHT is a set of procedures designed for eliminating any traces of interference caused by signal periodicity for synthesis purposes (Kawahara et al., 1999). To assure the quality of resynthesized speech, it extracts F0 based on pitch-adaptive spectral smoothing instantaneously without any traces of F0 jump (Banno et al., 2007). The data were then processed by an R script to get an average 11 points in the duration of the targeted syllables, with the first and last 12 ms of each targeted segment trimmed off. To get more reliable data, the F0 measurement was also checked manually in Praat (Boersma & Weenink 2003) as well. All F0 measurements were then converted to semi-tone, (6a). And the semi-tone values were further transformed into Z-score of ST in (6b). ST_i is the value of every point of all the stimuli produced by the speaker. The information allows a better reflection of pitch perception and normalizes gender variations (Rietveld & Chen, 2006; Rose, 1987; Zhu, 2004).

(6) a. $ST = 39.87 \times \log {}^{Hz}/_{50}$

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

A statistical analysis was conducted afterwards, analyzing F0 by using a three-way Repeated Measures ANOVA in SPSS. Since we expected the major difference in productivity to appear on the second syllable due to the left-dominant nature of the sandhi, we compared the F0 of the second syllable, with Word-type (4 levels), Second-syllable tones (3 levels), Data-point-in-Syllable (11 levels) as independent variables. Huynh-Feldt adjusted values were adopted to correct for sphericity violations.

Meanwhile, the stimuli were transcribed to the 5-level tonal system according to both the normalized F0 measurements and the author's listening judgment. And then we categorized all the sandhis produced by speakers into six sets: correct substitution (expected tone sandhi), wrong substitution (syllables undergoing sandhi but incorrectly using sandhi of other tones), extension (1st syllable spreading), unchanged (both of the syllables keep the base tones), partially unchanged (one of the two syllables keeps the base tone), and others (syllables undergoing unknown sandhi). To examine the productivity patterns, the speakers' production was coded in "1" if it falls into the tested category of sandhi and "0" if it does not. We used Logit Mixed-Effects models with Speaker and Item as random effects and Word-type (AO-AO, *AO-AO1, *AO-AO2, AG-AO), Tonal-combination (T1+X, T3+X, T5+X) as fixed effects. The reasons why we used Logit Mixed-Effects model is: first, binomially distributed outcomes need to be analyzed by this model; second, this model would incorporate factors with repeated levels (fixed-effects) and factors with levels randomly sampled from a much larger population (random-effects), in which case, the resulting model describes the data optimally (Jaeger, 2008).

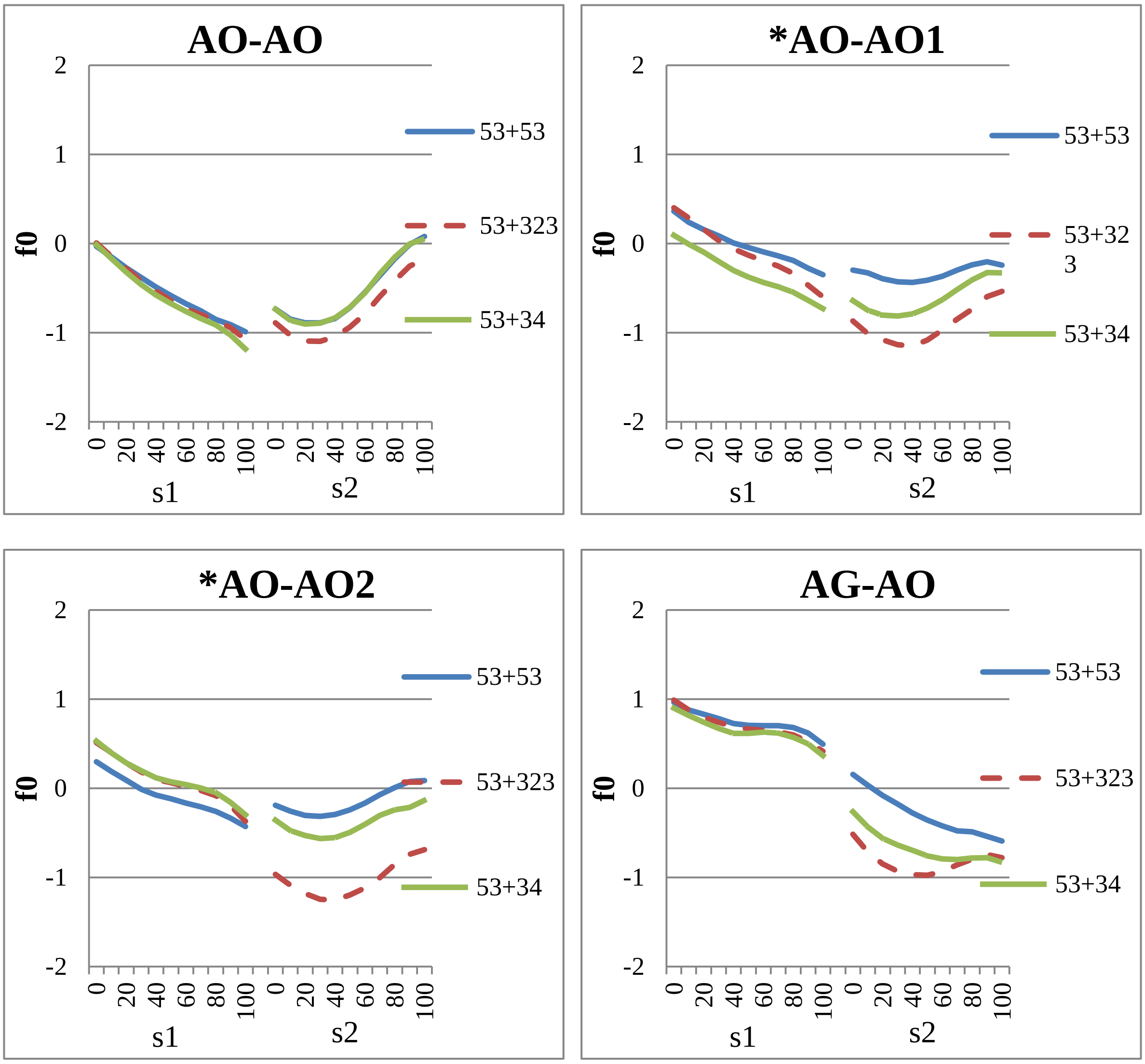
3. Results

The F0 results are illustrated in three ways to answer the research questions: (a) How do T1, T3, and T5 pattern substitution behave in real and novel words? (b) What categories do the speakers' tone sandhi patterns fall into? (c) Are there productivity differences among the four different stimuli sets?

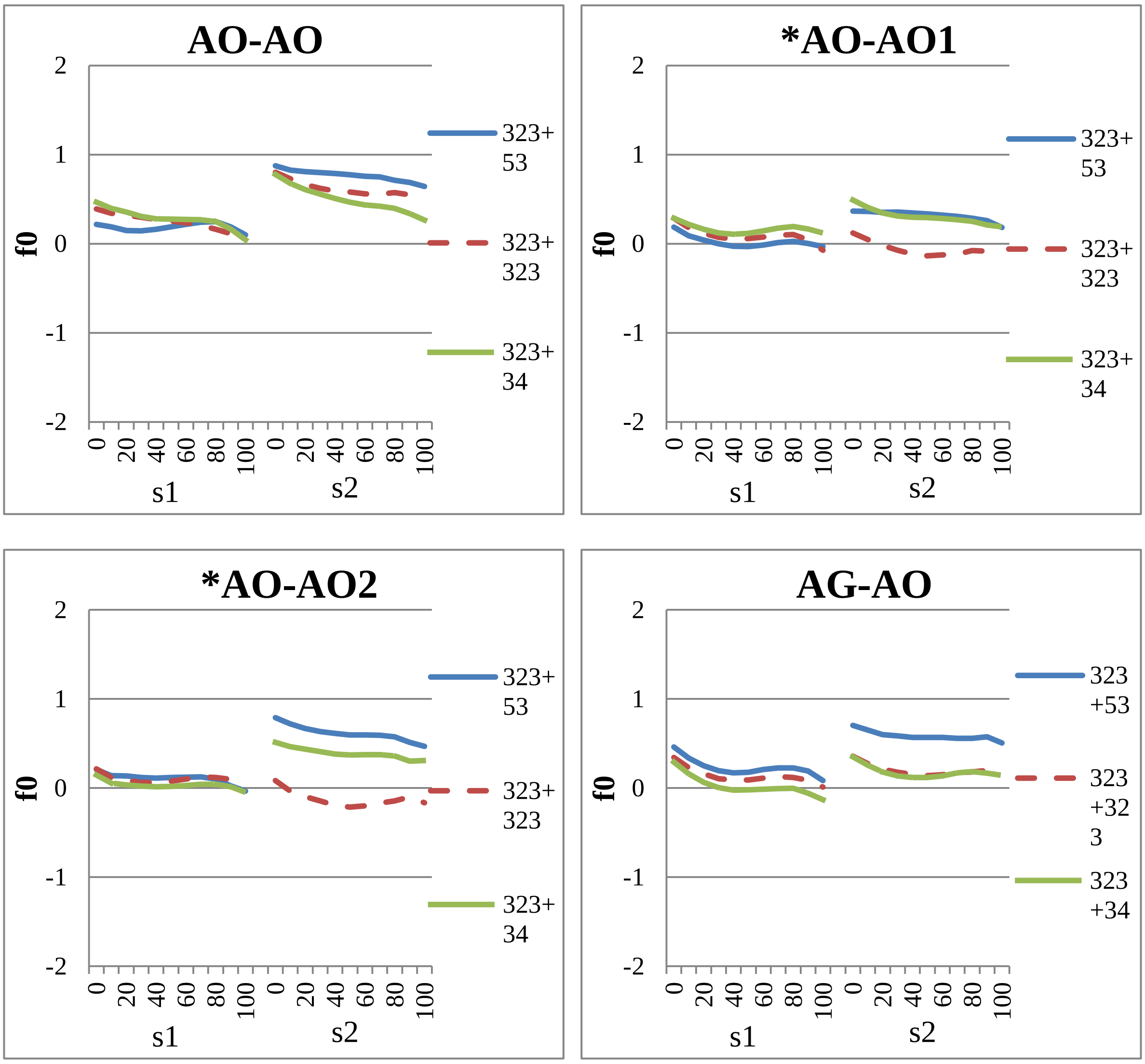
3.1 Tone sandhi patterns

To examine the tone sandhis of T1, T3, and T5 in AO-AO, *AO-AO1, *AO-AO2, and AG-AO, the average pitch tracks of different disyllabic tonal combinations are compared in the four sets of stimuli. Figure 1 shows the average pitch track for T1 (53) + T1, T3, T5; T3 (323) + T1, T3, T5, and T5 (34) + T1, T3, T5 in the four types of words.

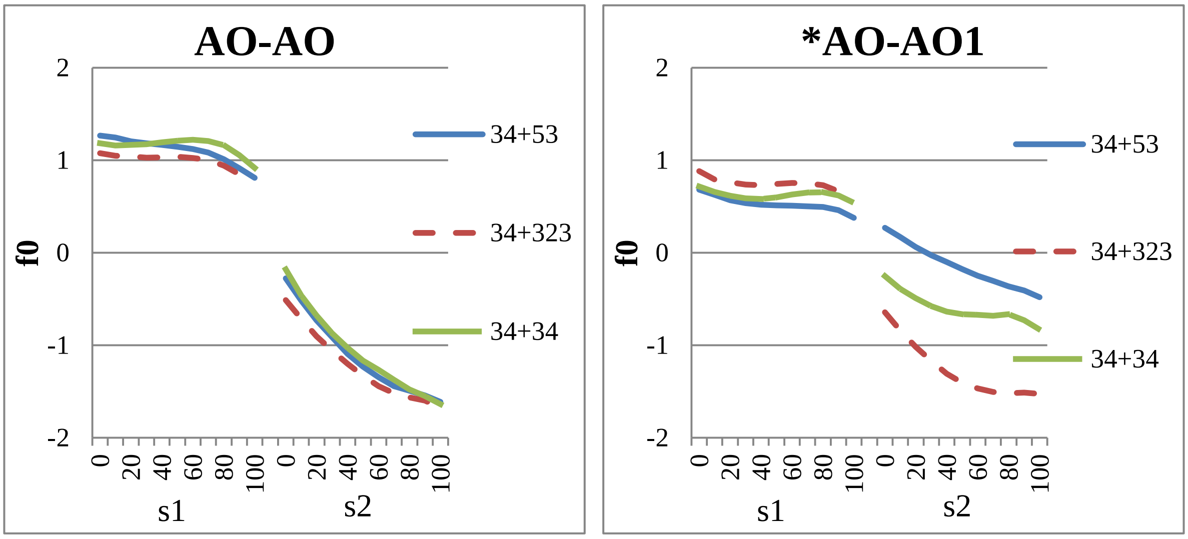
(a) T1 (53) - X → 43-34



(b) T3 (323) - X → 44-55


AO-AO
323+53
323+323
323+34
f0
s1
s2
*AO-AO1
323+53
323+323
323+34
f0
s1
s2
*AO-AO2
323+53
323+323
323+34
f0
s1
s2
AG-AO
323+53
323+323
323+34
f0
s1
s2

(c) T5 (34) - X → 55-31


AO-AO
34+53
34+323
34+34
f0
s1
s2
*AO-AO1
34+53
34+323
34+34
f0
s1
s2

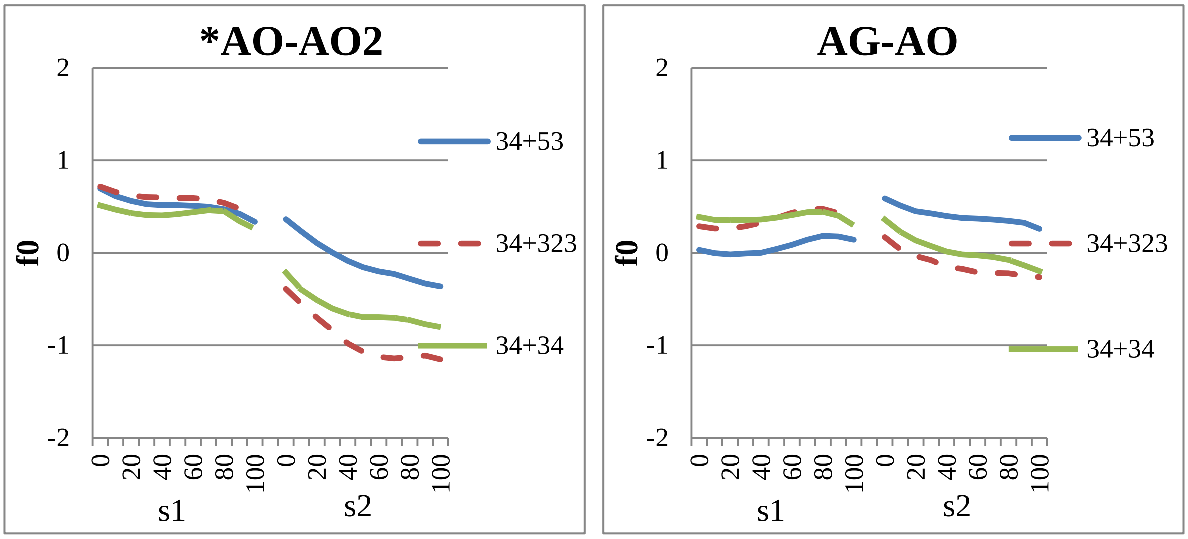


Figure 1. Pitch tracks for disyllabic words undergoing tone sandhi, organized by tone on the first syllable according to the stimulus sets. “X” refers to one of the three tones in this study.

Statistical results for the second-syllable comparisons are listed in Table 1. In the effect of Word-type, T3+X and T5+X are significant, and T1+X is not. In this case, word type alone does not have an effect on the F0 of σ2 in T1+X. A significant effect of Tone for all the three tonal combinations indicates that σ2 of the three tonal combinations have different F0 means. They also have significant effects of Data-point, confirming that the tones on σ2 are all contour tones, as shown in Figure 1. Significant interactions between Word-Type and Tone suggest that AO-AO, *AO-AO1, *AO-AO2, and AG-AO are significantly different in mean F0. T1+X and T5+X also have significantly different contour tones among the four word types, but T3+X does not have such significance. Tone*Data-point suggests that the pitch track of the second syllables have different shapes, however, only T1+X is significant. The three-way interactions only show significance in T5+X. It shows that different word types lead to the different shapes of the second syllables in T5+X, while the tone shapes of σ2 in T1+X and T3+X are not significantly different from each other.

Word-Type	Tone (F0 mean)	Data Point	Word-Type * Tone	Word-Type * Point	Tone*Point (F0 shape)	Word-Type *Tone*Point
T1+X						
F(1.761, 33.461)= .403, p=.646	F(1.939, 36.836)= 25.490, p<.001	F(1.622, 30.811)= 13.067, p<.001	F(5.254, 99.827)= 3.909, p=.002	F(3.561, 67.659)= 29.798, p<.001	F(2.998, 56.959)= 3.638, p=.018	F(7.756, 147.361)= 1.421, p=.194
T3+X						
F(2.358, 44.797)= 6.513, p=.002	F(1.869, 35.517)= 20.288, p<.001	F(1.356, 25.759)= 6.800, p=.009	F(5.451, 103.567)= 3.997, p=.002	F(6.753, 128.316)= 1.783, p=.099	F(2.751, 52.261)= 1.707, p=.181	F(13.468, 255.894)= 1.052, p=.402
T5+X						
F(2.167, 41.172)= 29.648, p<.001	F(1.830, 34.771)= 30.546, p<.001	F(1.665, 31.637)=7 7.716, p<.001	F(5.787, 109.958)= 5.918, p<.001	F(4.426, 84.089)= 16.041, p<.001	F(3.338, 63.414)= 1.902, p=.132	F(8.911, 169.304)= 2.888, p=.003

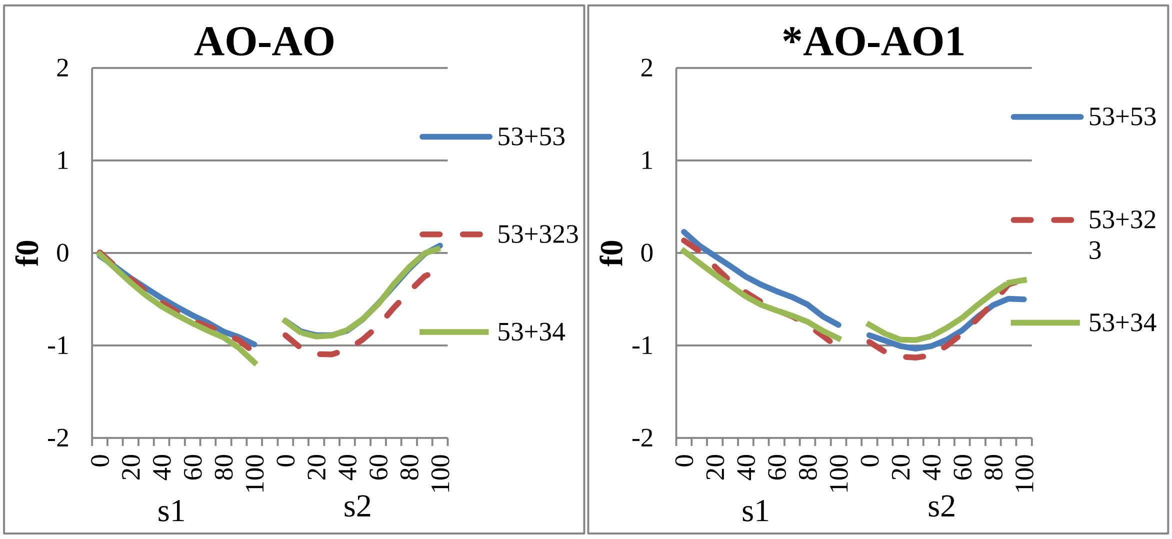
Table 1. ANOVA results for the F0 comparisons among F0 of the second syllables in the combinations with different first syllables.

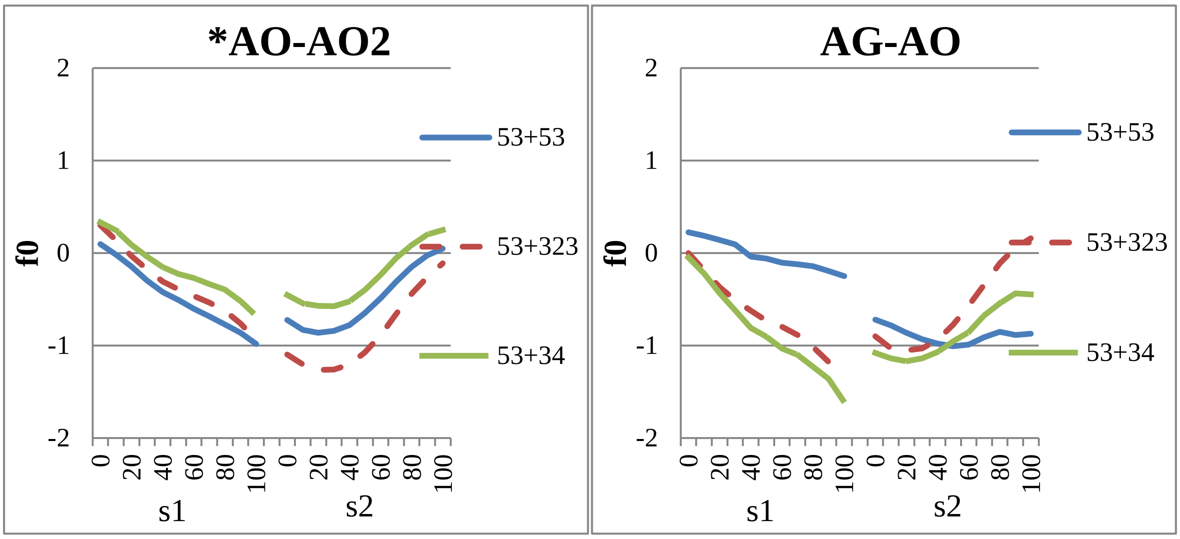
As we can see here, for T1 (53) + X, T3 (323) + X, and T5 (34) + X in real words (AO-AO), the sandhis are consistent with patterns in Xu (2007)'s acoustic study, 43+34, 44+55, and 55+31. In *AO-AO1 and *AO-AO2, it seems that speakers try to maintain the correct tone sandhi patterns, but the F0 of the second syllable is different among the three tones, see *AO-AO1 and *AO-AO2 in Figure 1 (a), (b), and (c). For AG-AO, instead of spreading the substituted tone, speakers simply spread the citation tone of T1 to the sandhi domain T1+X, see AG-AO in Figure 1 (a); the second syllables' F0 of T3+X is lower than that of real words, but T3+X keeps the correct sandhi shape, see AG-AO in Figure 1 (b); T5+X shows a falling tone on the second syllable, like the correct tone sandhi, while two syllables together reveal an extension pattern (44+55), see AG-AO in Figure 1 (c).

It is interesting that in novel words (*AO-AO1, *AO-AO2, AG-AO), except for T3+X in *AO-AO1 and AG-AO, all the other patterns show a pitch height hierarchy on the second syllable, T1 the highest, then T5, and T3 the lowest, which is in accordance with the pitch height of the base tones of the three tones. It seems that there are extensions from the first syllable to the whole disyllabic words in AG-AO, and the second syllable keeps its base tone information across the three novel word types.

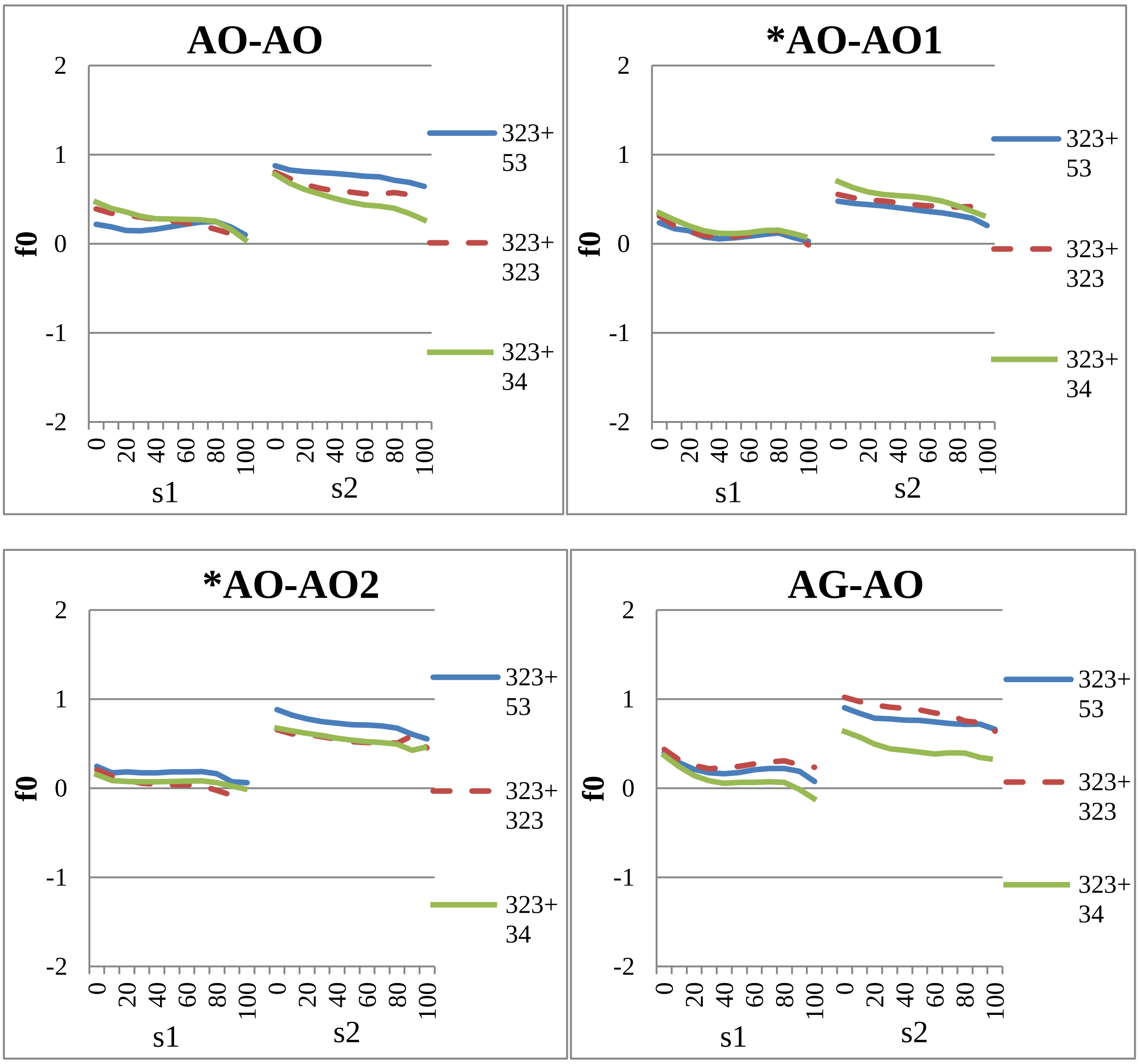
Meanwhile, the average pitch tracks of disyllables undergoing the correct sandhi were also examined, to see whether the transcribed correct sandhi has the same shape across different word types acoustically. Figure 2 shows the average pitch tracks for the correct tone sandhi T1 (53) + T1, T3, T5; T3 (323) + T1, T3, T5, and T5 (34) + T1, T3, T5 in the four types of words.

(a) T1 (53) - X → 43-34





(b) T3 (323) - X → 44-55



(c) T5 (34) - X → 55-31

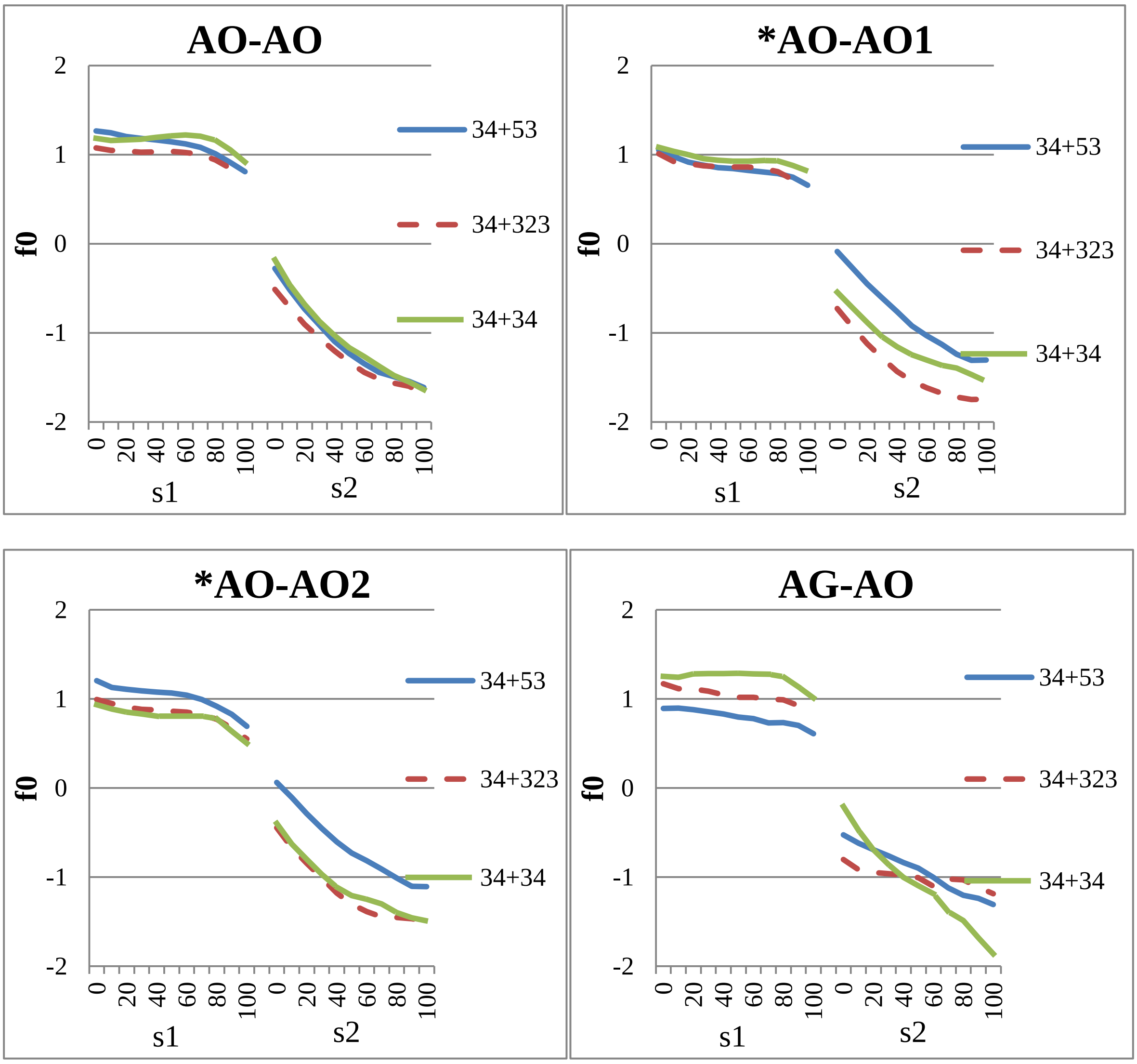


Figure 2. Pitch tracks for the disyllabic words undergoing the correct tone sandhi, organized by tone on the first syllable according to the stimulus sets. “X” refers to one of the three tones in this study.

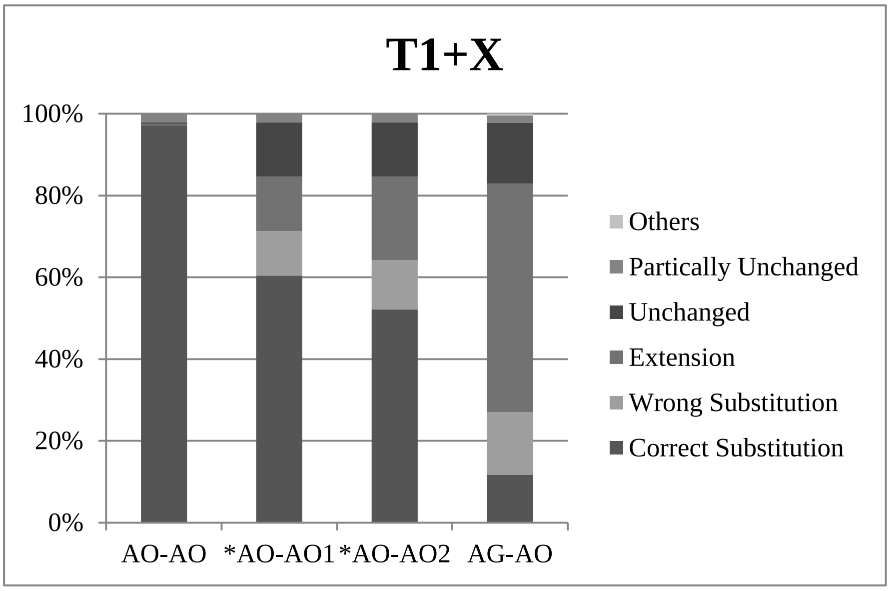
As shown in Figure 2, for words undergoing the correct sandhi in T1 (53) + X, T3 (323) + X, and T5 (34) + X, there are variations among different types of words. *AO-AO1 is the most consistent with AO-AO, while *AO-AO2 and AG-AO show more variations even though they share the same transcription as correct sandhi substitution. For T1+X (Figure 2a), the sandhi pattern in *AO-AO1 keeps the correct sandhi shape, but starts from a little higher pitch and ends in a lower pitch level than AO-AO. The variation becomes more obvious in

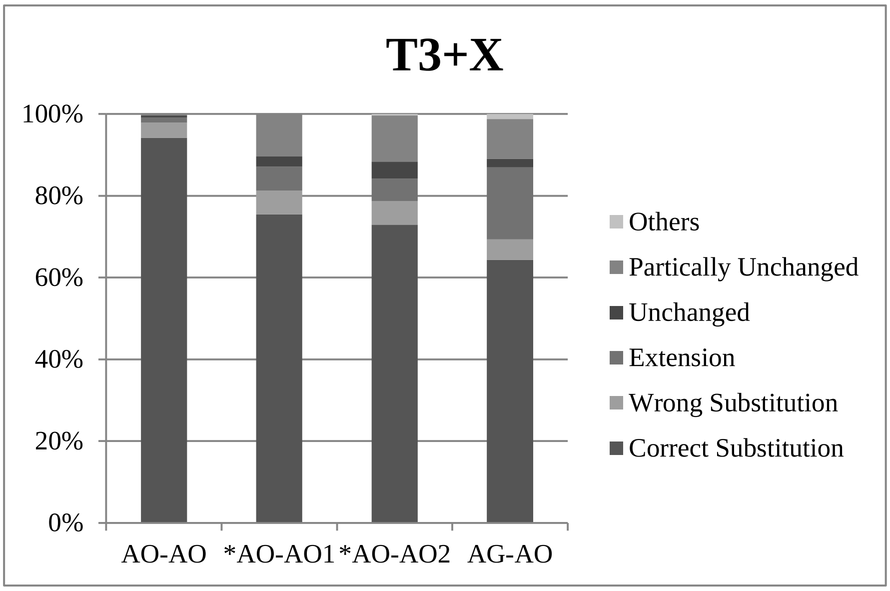
*AO-AO2 on σ2, and in AG-AO on both σ1 and σ2, especially on σ2 in AG-AO. For T3+X (Figure 2b), the pitch tracks in AO-AO, *AO-AO1 and *AO-AO2 are similar, although σ2 has a lower pitch in *AO-AO1 and *AO-AO2. Also, σ2 in AG-AO shows variation compared with that in AO-AO. For T5+X (Figure 2c), compared with the pitch tracks in AO-AO, the correct sandhi shows a lower pitch on σ1 in *AO-AO1 and *AO-AO2 and some variations on σ2. In AG-AO, larger variations appear on both syllables, especially when σ2 is T3.

In all, although the sandhi tones are transcribed as having the correct substitution, there are acoustic differences among the correctly substituted tones in different types of words. AG-AO, in particular, shows greater pitch variation in the correct sandhi cases. But it is not clear how the variation corresponds to the base tone on the second syllable.

3.2 Tone sandhi categories

As mentioned in §2.4, to investigate what types these sandhi patterns are, we categorized them in the following six categories as shown in Figure 3, including correct substitution (expected tone sandhi), wrong substitution (syllables undergoing sandhi but incorrectly using sandhi of other tones), extension (1st syllable spreading), unchanged (both of the syllables keep the base tones), partially unchanged (one of the two syllables keeps the base tone), and others (syllables undergoing unknown sandhi). Twenty-six tokens from AG-AO are excluded because of incorrect production of the combination, either the vowels or the consonants.


T1+X
100%
80%
60%
40%
20%
0%
AO-AO
*AO-AO1
*AO-AO2
AG-AO
Others
Partically Unchanged
Unchanged
Extension
Wrong Substitution
Correct Substitution


T3+X
100%
80%
60%
40%
20%
0%
AO-AO
*AO-AO1
*AO-AO2
AG-AO
Others
Partically Unchanged
Unchanged
Extension
Wrong Substitution
Correct Substitution

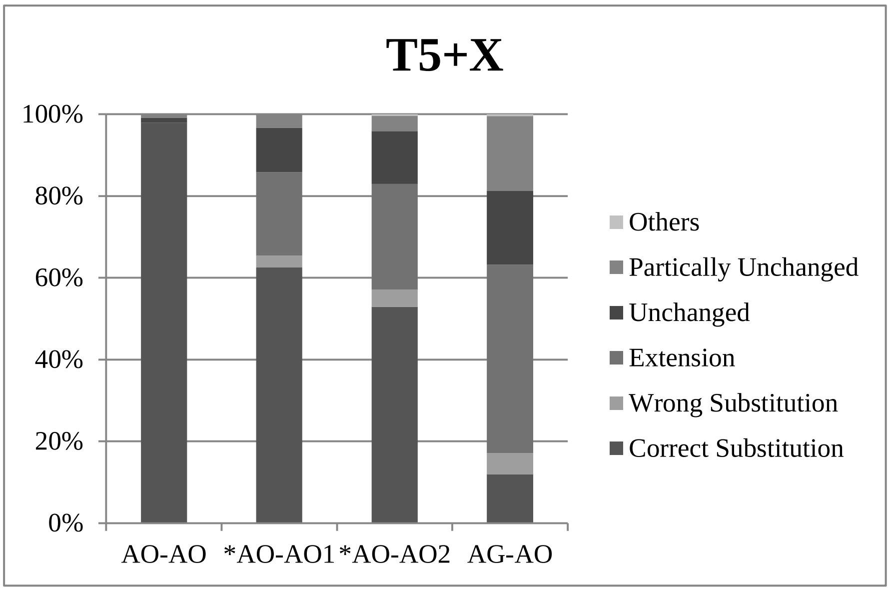

T5+X
100%
80%
60%
40%
20%
0%
AO-AO
*AO-AO1
*AO-AO2
AG-AO
Others
Partically Unchanged
Unchanged
Extension
Wrong Substitution
Correct Substitution

Figure 3. Categories for tone sandhi in four sets of stimuli, “X” refers to one of the three tones in this study.

Overall, the correct substitution occurs most frequently. Most of the correct substitution happens in real words (AO-AO). Among the three novel word types, AG-AO has the least productive application of tone sandhi, while the rates of correct sandhi for *AO-AO1 and *AO-AO2 are similar. In other words, if it is a real morpheme, regardless the appearances in initial position of real disyllabic words, the rates of correct sandhi are similar; but if it is not a real morpheme, the production of correct sandhi is relatively low. This indicates that speakers can still find the correct substituted tone to spread to the sandhi domain if it is a real morpheme, but if they cannot detect a real morpheme, instead of spreading the correct substituted tone, they spread the citation tone of the first syllable. Hence, the second most common pattern is Extension, which primarily occurs in AG-AO, but is also well represented in *AO-AO1 and *AO-AO2, especially for T1+X and T5+X.

The category of Unchanged is the third most common pattern, followed by partially unchanged. The proportion of “unchanged” is the highest in T1+X, followed by T5+X, T3+X. This indicates that T1+X tends to preserve the citation tones of the disyllables more often. On the other hand, T3+X has a relatively higher proportion for “partially unchanged”, especially in T3+T3 in novel words. In these examples, T3 (323) would turn to 32 or 23 as a result of contour reduction, either on σ1 or σ2, or both.

3.3 Productivity and other categories

To further investigate the productivity of the three tonal combinations, correct substitutions of the three tonal combinations with the four types of words are compared in Figure 4. T3+X is the most productive among the three, within 77% of the stimuli undergoing the correct tone sandhi in average. The average correct substitution pattern ratio of T5+X is slightly higher than that of T1+X (56% *vs.* 55%).

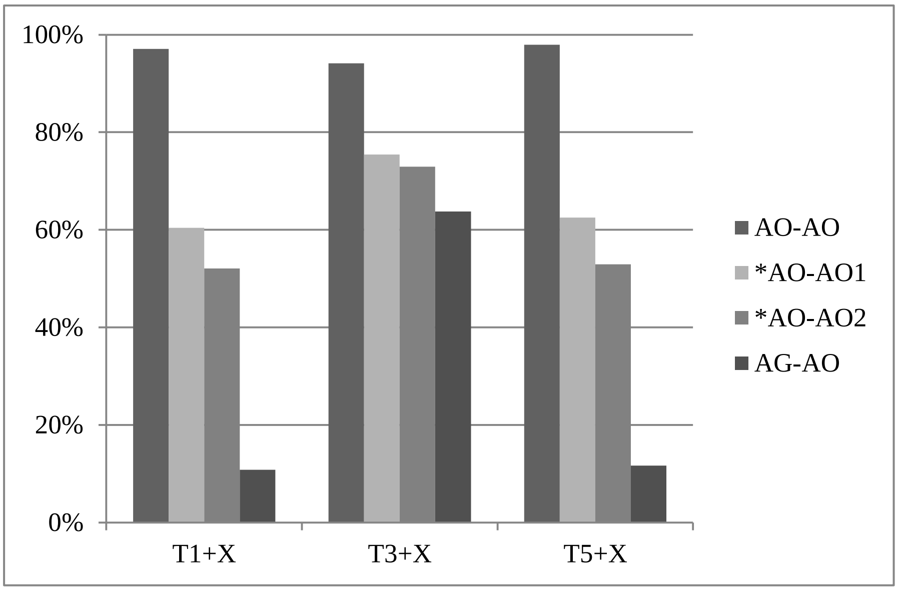


Figure4. Correct substitution (expected sandhi) in the four sets of stimuli for the three tonal combinations, “X” refers to one of the three tones in this study.

These data were analyzed using a Logit Mixed-Effects Model, where word-type and tonal combination are included as fixed effects; and subject and item as random effects. Here the model with interaction is significantly better than the other simpler models without interaction, based on the results of log-likelihood test. The parameter estimates for the model with the interaction between the two fixed effects are listed in Table 2.

Fixed effect	Coefficient	SE of estimate	*z*	p (> |z|)
Intercept	3.9816	0.5037	7.905	2.69e-15 ***
*AO-AO1	-3.4499	0.5504	-6.268	3.66e-10 ***
*AO-AO2	-3.8451	0.5482	-7.014	2.31e-12 ***
AG-AO	-6.4416	0.5783	-11.139	< 2e-16 ***
Syll1ToneT3	-0.6577	0.6167	-1.066	0.2862
Syll1ToneT5	0.3586	0.7294	0.492	0.6230
*AO-AO1×Syll1ToneT3	1.5047	0.7296	2.062	0.0392 *
*AO-AO2×Syll1ToneT3	1.7410	0.7264	2.397	0.0165 *
AG-AO×Syll1ToneT3	3.7865	0.7454	5.080	3.77e-07 ***
*AO-AO1×Syll1ToneT5	-0.2646	0.8228	-0.322	0.7478
*AO-AO2×Syll1ToneT5	-0.3545	0.8205	-0.432	0.6657
AG-AO×Syll1ToneT5	-0.3569	0.8591	-0.415	0.6778
Radom effect	s^2			
Item	0.78451			
Subject	0.68300			

Table 2. Fixed effect estimates (top) and variance estimates (bottom) for multi-level model results of correct sandhi (*N*=2880, log-likelihood: -1261).

There is an effect of word type. Our results showed that *AO-AO1, *AO-AO2, and AG-AO have significantly lower rate of correct sandhi than AO-AO does, and the ranking from high accuracy to low is AO-AO, *AO-AO1, *AO-AO2, AG-AO, which is in accordance with our prediction. But the difference between *AO-AO1 and AO-AO *versus* *AO-AO2 and AO-AO (Coefficient value: -3.4499 *versus* -3.8451) is small, while the coefficient value between AG-AO and AO-AO is -6.4416. It indicates that the stimuli difference between *AO-AO1 and *AO-AO2 did not cause much difference in the production of correct sandhi.

For different tonal combinations (T1+X, T3+X, T5+X), the productivity does not show a significant difference in this model since they are compared with T1+X in AO-AO. However, the interaction between Word-Type × Syll1Tone3 is significant, while the interaction between Word-Type × Syll1Tone5 is not. The significant interaction between *AO-AO1 × Syll1ToneT3 indicates that the difference between T1+X and T3+X in *AO-AO1 is significantly different from the difference between T1+X and T3+X in AO-AO. Considering that the coefficient value 0.847 is positive, in *AO-AO1, T3+X has a significantly higher rate of correct sandhi than T1+X. The coefficient values are 1.0833 for *AO-AO2 and 3.1288 for AG-AO. It suggests that the speakers produced significantly more correct sandhi for T3+X than T1+X in the three types of novel words, and the difference gets bigger from *AO-AO1 to AG-AO. To evaluate the correct sandhi rate of T3+X alone, the coefficient for the difference of T3+X between AO-AO and *AO-AO1 is -1.9452, which indicates that T3+X in *AO-AO1 is less productive than in AO-AO. T3+X in *AO-AO2 is less productive than in AO-AO by a coefficient value of –2.1041. And T3+X in AG-AO is less productive than in AO-AO by a coefficient value of -2.6551. The rate of correct sandhi for T3+X is influenced by word type effect. On the other hand, T5+X shows no significant difference from T1+X.

According to the log-likelihood tests, for the categories of Extension and Unchanged, the same model with Word-Type×Syll1Tone is also significantly better than other simpler models with only one effect, but not significantly different from model with Word-Type + Syll1Tone. For the categories of Wrong Substitution and Partially Unchanged, the interaction model is significantly better than both the simpler models with one effect and the model with Word-Type + Syll1Tone; however, neither word type nor tonal combination has an effect on the two categories. The effect of Word-type, tonal combination, and the interaction among word-type and tonal combination in the Logit Mixed-Effect model without interaction for the categories of Extension (first syllable tonal spreading) and Unchanged (when the base tones of both the two syllables remained unchanged) are listed in Table 3 and 4.

Fixed effect	Coefficient	SE of estimate	*z*	p (> |z|)
Intercept	-5.70758	0.71525	-7.980	1.47e-15 ***
*AO-AO1	3.82487	0.71939	5.317	1.06e-07 ***
*AO-AO2	4.10766	0.71773	5.723	1.05e-08 ***
AG-AO	5.48864	0.71399	7.687	1.50e-14 ***
Syll1ToneT3	-1.49607	0.27693	-5.402	6.57e-08 ***
Syll1ToneT5	0.08905	0.25079	0.355	0.723
Radom effect	s^2			
Item	0.90772			
Subject	0.59730			

Table 3. Fixed effect estimates (top) and variance estimates (bottom) for multi-level model results of extension sandhi (*N*=2880, log-likelihood: -984).

Fixed effect	Coefficient	SE of estimate	*z*	p (> |z|)
Intercept	-5.58574	0.59242	-9.429	< 2e-16 ***
*AO-AO1	2.96021	0.55304	5.353	8.67e-08 ***
*AO-AO2	3.21965	0.55043	5.849	4.94e-09 ***
AG-AO	3.24536	0.55027	5.898	3.68e-09 ***
Syll1ToneT3	-1.87209	0.31790	-5.889	3.89e-09 ***
Syll1ToneT5	0.06022	0.23985	0.251	0.802
Radom effect	s^2			
Item	0.74462			
Subject	1.12452			

Table 4. Fixed effect estimates (top) and variance estimates (bottom) for multi-level model results of unchanged sandhi (*N*=2880, log-likelihood: -608.8).

Word-Type has a significant effect in both of the categories. In the category of Extension, *AO-AO1, *AO-AO2, and AG-AO are significantly different from AO-AO, but in a different direction from that of the category of correct substitution. With positive coefficient values, it indicates that the spreading pattern is significantly more common in *AO-AO1 than AO-AO, and the ranking of the rate of spreading the base tone of σ1 from high to low is AG-AO, *AO-AO2, *AO-AO1, AO-AO. Again, the difference between the comparison of *AO-AO1/AO-AO and *AO-AO2/AO-AO is small (Coefficient value: 3.82487 *versus*

4.10766). That is to say, speakers tend to apply more spreading in novel words, but whether the first morpheme occur in initial position in real disyllabic words or not does not have an effect on what pattern the speakers apply. The extension pattern for Syll1ToneT3 (T3+X) is significantly different from T1+X in AO-AO. Since the coefficient value is negative (-1.49607), the extension cases in T3+X are significantly fewer than in T1+X. In other words, word type and the tones on σ1 both have an effect for the spreading pattern.

In the category of Unchanged, *AO-AO1, *AO-AO2, and AG-AO are significantly different from AO-AO, and the ranking of the rate of remaining unchanged base tones from high to low is AG-AO, *AO-AO2, *AO-AO1, AO-AO. The differences among the three novel word types are small despite the fact that they are all significantly different from AO-AO. The base tone of σ1 also has an effect here. T3+X has significantly fewer unchanged cases than T1+X in AO-AO, as the coefficient value is -1.87209.

In Figures 5 and 6, individual speakers' category responses for correct substitution, extension, unchanged, and partially unchanged are plotted against each other for the three types of novels words to see how these categories are related to each other.

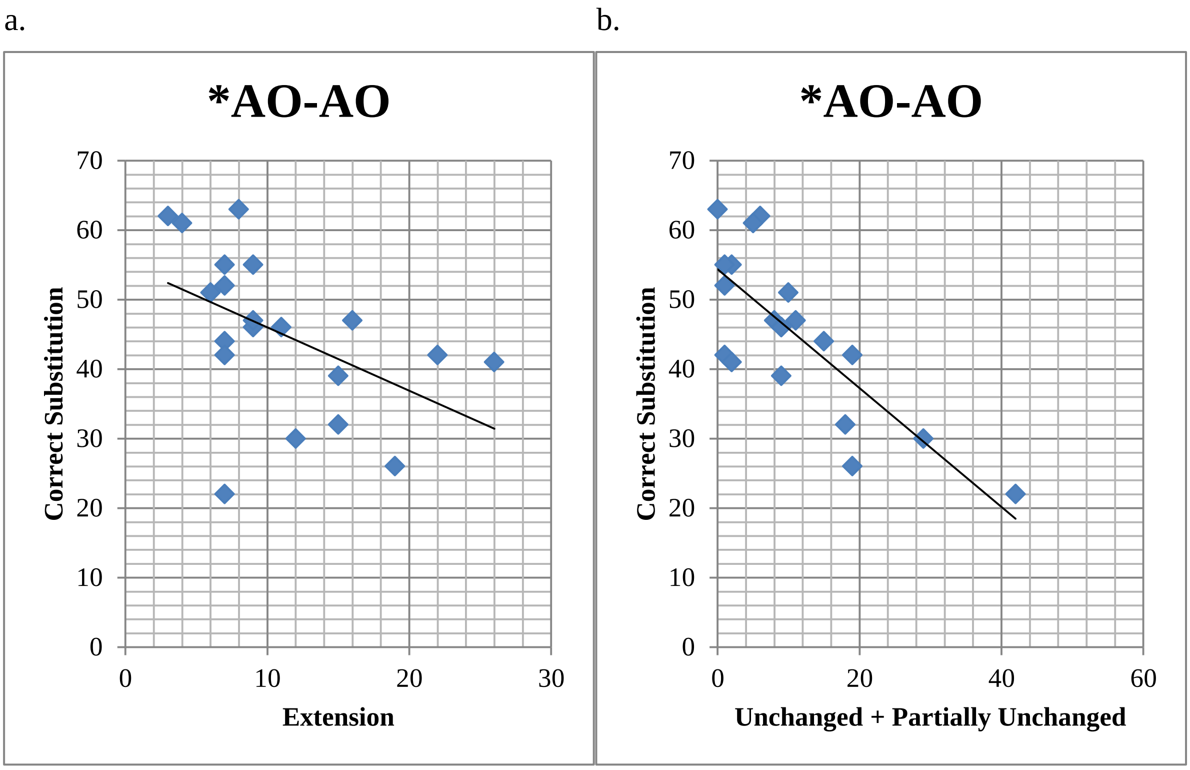


Figure 5. Sandhi behaviors comparison among the 20 speakers in *AO-AO1 and *AO-AO2.

Since there is no significant difference between *AO-AO1 and *AO-AO2 in the tone sandhi categories, the two types are combined together as *AO-AO in Figure 5. There is a negative correlation between the categories of correct substitution and extension, as shown in Figure 5a (B = -.256, SE = .109, β = -.483, $t(18)$ = -2.337, R^2 = .233, p < .05). The more extension patterns a speaker used, the fewer correct substitution sandhis he or she produced in *AO-AO. The same negative correlation is also manifested between the categories of correct substitution and unchanged (including partially unchanged) in Figure 5b (B = -.727, SE = .134, β = -.788, $t(18)$ = -5.427, R^2 = .621, p < .001). It indicates that if a speaker has a higher rate of correct substitution, he or she will have fewer unchanged cases and vice versa.

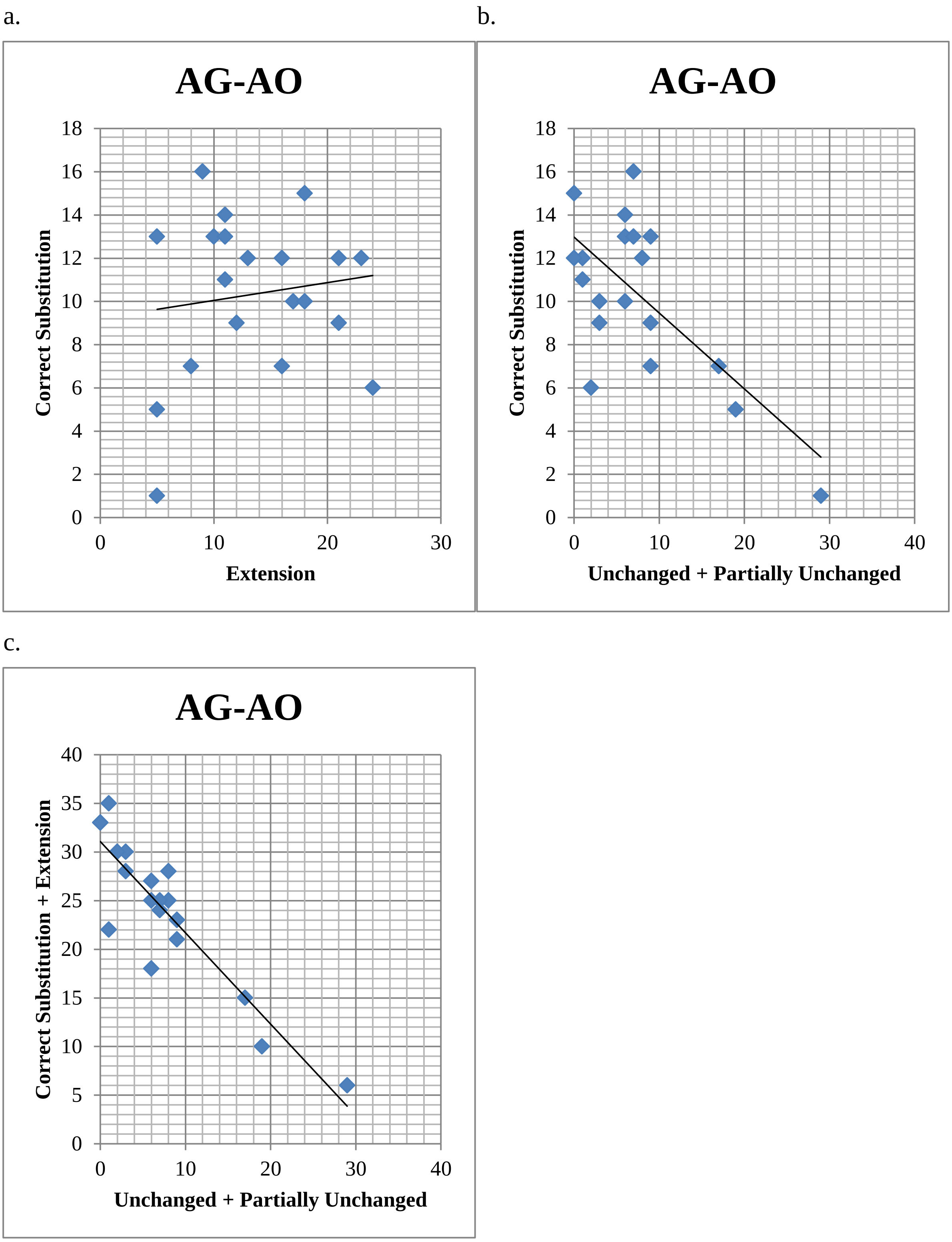


Figure 6. Sandhi behaviors comparison among the 20 speakers in AG-AO.

In AG-AO, the categories of correct substitution and extension fail to reveal a negative correlation, as shown in Figure 6a (B = .215, SE = .377, β = .133, $t(18)$ = .571, R^2 = .018, p

= .575). The relation between the two categories of individual speakers is unclear in AG-AO. It suggests that speakers may not have a clear preference for either category as they did in *AO-AO. However, in Figure 6b (B = -1.303, SE = .334, β = -.676, $t(18)$ = -3.896, R^2 = .457, p < .01), the categories of correct substitution and unchanged (including partially unchanged) still show a negative correlation. If the speaker tended to preserve the base tones of the syllables in more cases, then fewer correct substitution cases were produced. Finally, if we treat correct substitution and extension as one category of undergoing tone sandhis in AG-AO, they display a negative correlation with the categories of unchanged (including partially unchanged), as shown in Figure 6c (B = -.864, SE = .098, β = -.900, $t(18)$ = -8.771, R^2 = .810, p < .001). That is to say, there are speakers who prefer to apply extensional tone sandhis in AG-AO, and there are speakers who tend to keep the base tones unchanged.

4. Discussion

First of all, pattern substitution is not fully productive in Wuxi. It is fully productive in real words but not in novel words. Speakers failed to apply the correct substitution productively in novel words; instead, they often applied the spreading pattern. In addition to correct substitution and extension, speakers also often kept the base tones in novel words, referred as "unchanged" and "partially unchanged". T1+X and T5+X mainly keep the citation tones for both of the syllables, and T3+X undergoes contour reduction, e.g., 323 → 23 or 32. It appears that the speakers had difficult in spreading the correct substituted tone to the sandhi domain when they encountered novel words. Additionally, our pitch results showed that there is a pitch hierarchy of the second syllables in novel words, T1 the highest, then T5, and then T3 the lowest, suggesting that the information of the second syllable shows up, and speakers are aware of the underlying tones of the second syllables.

This pattern may be caused by the following reasons. First, it is more difficult for the speakers to spread the substituted tone than only to spread the citation tone of the first syllable. When they cannot find it as a real morpheme, they do not have the substituted tone listed in the lexicon. Second, the substitution pattern among T1, T3, and T5 in Wuxi has a circular chain shift between their citation tones and sandhi tones. This circle causes phonological opacity. In this case, speakers have difficulty in producing the correct pattern in wug words. This agrees with the Taiwanese results from previous studies (Zhang et. al., 2009, 2011).

Second, T3+X is the most productive tonal combination. Considering that T1 has the highest type and token frequencies among the three tones, this suggests that type and toke frequencies do not have an effect here. Phonetic similarity, on the other hand, facilitates correct substitution, as the similar shapes between the citation tone and the sandhi tone allow the speakers to find the substituted tone more easily.

Another interesting finding is that *AO-AO1 and *AO-AO2 are more productive than AG-AO, but there is little difference between *AO-AO1 and *AO-AO2. *AO-AO1 has a rate of 66% in correct substitution, and *AO-AO2 has 59%, while AG-AO has 29%. This means that speakers may not rely on single morpheme to apply the sandhi, and it may be the pronunciation of the morpheme that actually matters. Based on this, we checked the frequencies of all homophones of the first morphemes in *AO-AO1 and *AO-AO2 in Cao (2003) and Wang (2008)'s Monosyllabic Morpheme List of Wuxi, as well as Jun Da (2004)'s combined character frequency corpus. Because each tonal combination (T1+X, T3+X, and T5+X) has four tokens, the number of their homophones is averaged by four, as well as the frequencies. The average frequencies of the homophones of stimuli in *AO-AO2 turns out to be higher than that of those in *AO-AO1, as shown in Table 5.

Tones	Number of Homophones	Number of Homophones that appear in initial position	Frequency of all homophones	Frequency of Homophones that appear in initial position
*AO-AO1				
T1	6	5.75	103,883	102,821.75
T3	2	2	43,933.5	43,933.5
T5	3.75	2.5	68,306.75	63,079.5
*AO-AO2				
T1	7.25	5.5	344,505.5	340,923.25
T3	5.25	3.5	246,819.5	241,045.25
T5	5.75	4.25	214,060.25	209,528

Table 5. The average number and frequencies of homophones for all the first morphemes in *AO-AO1 and *AO-AO2 and the average number and frequencies of homophones that occur in initial position, based on Cao (2003) and Wang (2008)'s Monosyllabic Morpheme Listing of Wuxi, as well as Jun Da (2004)'s combined character frequency corpus.

When the citation tone and substituted tone of the first morpheme are both listed, but the disyllabic word is not familiar, as in *AO-AO1, speakers know the substituted tone to some extent, but are not as familiar with it as they are with real words. In this case, the rate of correct sandhi of *AO-AO1 is higher than that of AG-AO, but still not fully productive. When only the base tone of the first morpheme is listed in the lexicon, and the substituted tone is not listed, for example, in *AO-AO2, where the first morpheme never occur in initial position, speakers are still able to detect the substituted tone and produce the correct sandhi. Provided that homophones of the morpheme appear in initial position, it suggests that they rely on the pronunciation of the morpheme instead of the morpheme itself. If neither the citation tone nor the substituted tone of the first morpheme is listed in speakers' lexicon, for instance, in AG-AO, where the syllable is non-existent, they can only rely on the citation tone of the first morpheme to apply tone sandhi. This results in tonal spreading or unchanged base tones. The little difference between the rates of correct sandhi in *AO-AO1 and *AO-AO2 indicates that speakers are aware of the substituted tone as long as the whole syllable of the first morpheme exists in the lexicon and there are homophones that occur in initial position, while the occurrence in the initial position of the specific morpheme does not matter. Therefore the speakers seem to rely more on the sandhi tone listing of the syllable than that of the specific morpheme.

Finally, different speakers likely have different tone sandhi preferences when they encounter novel words. There are speakers who tend to apply spreading-like tone sandhi, and there are speakers who tend to keep the base tones unchanged. But this effect is only observable in AG-AO. In *AO-AO1 and *AO-AO2, however, correct sandhi application is simply negatively correlated with incorrect sandhi including extension and unchanged patterns.

5. Conclusion

Based on the results of the production experiment on disyllabic tone sandhi in both real and novel words in Wuxi, we found that pattern substitution is not fully productive. The speakers can substitute the base tone of the first syllable and spread the substituted tone to the whole disyllable if they could find the syllable of the morpheme in real syllables (*AO-AO1 and *AO-AO2), although not at a high ratio. If they could not find the syllable in real syllable listing (AG-AO), they tend to spread the base tone directly or do nothing. The tonal combination of T3+X is the most productive in correct sandhi although T3 has the lowest type and token frequencies, suggesting that phonetic similarity has more effect on pattern substitution in Wuxi.

This study complements our knowledge on the productivity of tone sandhi patterns by providing the instance of pattern substitution. It also echoes the findings of previous research. Tones in a circular chain shift cause difficulty for the speakers of Wuxi, just like for the speakers of Taiwanese. Phonetic properties influence tone sandhi productivity in Wuxi, which is similar to the findings in Mandarin (Zhang & Lai, 2010) and Tianjin (Zhang & Liu, 2011). For example, in Mandarin sandhi with a clear phonetic motivation is more productive. In addition, the effect of lexical frequency on sandhi application is inconsistent with previous studies. Specifically speaking, in Mandarin (Zhang & Lai, 2010), the tonal combination with the lowest type frequency has the lowest accuracy of sandhi application in novel words. In

Taiwanese (Zhang, Lai & Sailor, 2009; 2011), low lexical frequency of the base tone 33 and the reduplicative melody 21-33 cause low productivity of 33 → 21. But in Tianjin, sandhis with high frequency are not necessarily more productive in novel words (Zhang & Liu, 2011). Frequency also fails to show a clear pattern of the contour comparison in Shanghai (Zhang & Meng, 2012). These indicate that opacity, phonetic properties, and lexical frequency all have an effect on the productivity of sandhi patterns.

The productivity test in Wuxi is the first step to understand pattern substitution. Diachronically, how this pattern works in speakers' phonological knowledge, which tone they choose to substitute the base tone with and why have been wiped out. These are still questions that remained unsolved. A theoretical model of how speakers apply pattern substitution also needs to be built.

Appendix

AO-AO

Base tones	Chinese	Transcription	Gloss	compounds freq.
T1+T1 43+34	开窗	kʰɛ tsʰɒ̃	to open the window	140
	翻身	fɛ sən	to turn over the body	270
	西瓜	si ku	watermelon	192
	花椒	hu tsiɔ	Chinese pepper	22
T1+T3	浇水	tɕiɔ sɥ	to water	108
	招手	tsɔ ɕiəɯ	to wave hands	229
	山顶	sɛ tin	mountain top	200
	东海	toŋ xɛ	east sea	181
T1+T5	收费	ɕiəɯ fi	to charge a fee	126
	通信	tʰoŋ sin	to communicate	211
	青菜	tsʰin tsʰɛ	green leaf vegetable	96
	抽屉	tɕʰiəɯ tʰi	drawer	420
T3+T1 44+55	写书	sia sɥ	to write a book	75
	打呼	tæ̃ xu	to snore	36
	饼干	pin kʊ	cookie	102
	宝刀	pɔ tɔ	precious knife	48
T3+T3	炒股	tsʰɔ ku	to invest in stocks	56
	改口	kɛ kʰɛi	to correct oneself	77
	喜酒	ɕi tsɛi	wedding feast	81
	警犬	tɕin tɕʰyʊ	police dog	20
T3+T5	讲课	kɒ̃ kʰəɯ	to give a lecture	98
	喘气	tsʰʊ tɕʰi	to take a breath	154
	苦笑	kʰu siɔ	bitter smile	460
	彩票	tsʰɛ pʰiɔ	lottery	12
T5+T1 55+31	化妆	xu tsɒ̃	to put on make-up	302
	唱歌	tsʰæ̃ kəɯ	to sing a song	488

	汽车	tɕʰi tsʰeɯ	car	2475
	线衫	siɪ sɛ	sweater	35
T5+T3	散伙	sɛ xəɯ	to separate	35
	泡澡	pʰɔ tsɔ	to take a bath	12
	报纸	pɔ tsɥ	newspaper	1146
	记者	tɕi tsa	reporter	869
T5+T5	放假	fɒ̃ tɕia	to have a vacation	124
	进货	tsin xəɯ	to stock with goods	47
	志向	tsɥ ɕiæ̃	aspiration	48
	抗战	khɒ̃ tsʊ	wars against aggression	169

***AO-AO1**

Base tones	Chinese	Transcription
T1+T1 43+34	煎弯	tsiɪ uɛ
	消涛	siɔ tʰɔ
	秋街	tsʰɛi ka
	灯蛙	tən ua
T1+T3	煎展	tsiɪ tsʊ
	消体	siɔ tʰiɪ
	秋彩	tsʰɛi tsʰɛ
	灯狗	tən kɛi
T1+T5	煎伞	tsiɪ sɛ
	消戏	siɔ ɕi
	秋炮	tsʰɛi pʰɔ
	灯素	tən səɯ
T3+T1 44+55	垮弯	kʰua uɛ
	卷涛	tɕyʊ tʰɔ
	毯街	tʰɛ ka
	巧蛙	tɕʰiɔ ua
T3+T3	垮展	kʰua tsʊ
	卷体	tɕyʊ tʰiɪ
	毯彩	tʰɛ tsʰɛ

***AO-AO2**

Base tones	Chinese	Transcription
T1+T1 43+34	疚军	tɕiəɯ tɕyən
	叨松	tɔ soŋ
	蒿冰	xɔ pin
	筝坡	tsən pʰəɯ
T1+T3	疚掌	tɕiəɯ tsæ̃
	叨土	tɔ tʰəɯ
	蒿主	xɔ tsʮ
	筝底	tsən ti
T1+T5	疚顿	tɕiəɯ tən
	叨贩	tɔ fɛ
	蒿蒜	xɔ sʊ
	筝剑	tsən tsiɪ
T3+T1 44+55	齿军	tsʰɿ tɕyən
	帚松	tɕiəɯ soŋ
	柬冰	tɕiɪ pin
	袄坡	ɔ pʰəɯ
T3+T3	齿掌	tsʰɿ tsæ̃
	帚土	tɕiəɯ tʰəɯ
	柬主	tɕiɪ tsʮ

	巧狗	tɕ^{h}iɔ kɛi
T3+T5	垮伞	k^{h}ua sɛ
	卷戏	tɕyʊ ɕi
	毯炮	t^{h}ɛ p^{h}ɔ
	巧素	tɕ^{h}iɔ səɯ
T5+T1 55+31	替弯	t^{h}i uɛ
	照涛	tsɔ t^{h}ɔ
	帅街	sua ka
	脆蛙	ts^{h}ɛ ua
T5+T3	替展	t^{h}i tsʊ
	照体	tsɔ t^{h}iɪ
	帅彩	sua ts^{h}ɛ
	脆狗	ts^{h}ɛ kɛi
T5+T5	替伞	t^{h}i sɛ
	照戏	tsɔ ɕi
	帅炮	sua p^{h}ɔ
	脆素	ts^{h}ɛ səɯ

	袄底	ɔ ti
T3+T5	齿顿	ts^{h}ɿ tən
	帚贩	tɕiəɯ fɛ
	柬蒜	tɕiɪ sʊ
	袄剑	ɔ tsiɪ
T5+T1 55+31	锢军	ku tɕyən
	涕松	t^{h}i soŋ
	沛冰	p^{h}ɛ pin
	尬坡	ka p^{h}əɯ
T5+T3	锢掌	ku tsæ̃
	涕土	t^{h}i t^{h}əɯ
	沛主	p^{h}ɛ tsʮ
	尬底	ka ti
T5+T5	锢顿	ku tən
	涕贩	t^{h}i fɛ
	沛蒜	p^{h}ɛ sʊ
	尬剑	ka tsiɪ

AG-AO

Base tones	Cue sentences
T1(53)+X	要是上网买东西叫做 tsia… “If to shop online is called tsia44…”
T1+T1	如果黄金还没有口，那么也还可以讲还没（口金）。 “If the gold has not been tsia44-ed, then we can say that we have not (口 gold).”
T1+T3	如果游艇还没有口，那么也还可以讲还没（口艇）。 “If the yacht has not been tsia44-ed, then we can say that we have not (口 yacht).”
T1+T5	如果门票还没有口，那么也还可以讲还没（口票）。 “If the ticket has not been tsia44-ed, then we can say that we have not (口 ticket).”
T1(53)+X	要是用飞船运输叫做 kuən… “If to transport via a spaceship is called kuən44…”
T1+T1	如果猪还没有口，那么也还可以讲还没（口猪）。 “If pigs have not been kuən44-ed, then we can say that we have not (口 pigs).”
T1+T3	如果鼓还没有口，那么也还可以讲还没（口鼓）。 “If drums have not been kuən44-ed, then we can say that we have not (口 drums).”
T1+T5	如果菜还没有口，那么也还可以讲还没（口菜）。 “If dishes have not been kuən44-ed, then we can say that we have not (口 dishes).”
T1(53)+X	要是有一种形状叫做 ts^hia… “If there is a shape called ts^hia44…”
T1+T1	如果客厅是这个形状口，那么也还可以讲这个是一个（口厅）。 “If a living room has this shape ts^hia44, then we can call it a (口 room).”
T1+T3	如果手表是这个形状口，那么也还可以讲这个是一个（口表）。 “If a watch has this shape ts^hia44, then we can call it a (口 watch).”
T1+T5	如果书架是这个形状口，那么也还可以讲这个是一个（口架）。 “If a bookshelf has this shape ts^hia44, then we can call it a (口 shelf).”
T1(53)+X	要是有一种气味叫做 p^hõ44… “If there is a smell called p^hõ44…”
T1+T1	如果一朵花是这个味道口，那么也还可以讲这个是一朵（口花）。 “If a flower has this smell p^hõ44, then we can call it a (口 flower).”
T1+T3	如果一棵草是这个味道口，那么也还可以讲这个是一棵（口草）。 “If a piece of grass has this smell p^hõ44, then we can call it a (口 grass).”
T1+T5	如果一种酱是这个味道口，那么也还可以讲这个是一种（口酱）。 “If a type of jam has this smell p^hõ44, then we can call it a (口 jam).”
T3(323)+X	要是有一种卖东西的方式叫做 p^hɛ323… “If a form of sales is called p^hɛ323…”
T3+T1	如果黄金还没有口，那么也可以讲还没（口金）。 “If the gold has not been p^hɛ323-ed, then we can say that we have not (口 gold).”
T3+T3	如果游艇还没有口，那么也还可以讲还没（口艇）。 “If the yacht has not been p^hɛ323-ed, then we can say that we have not (口 yacht).”

T3+T5	如果门票还没有口，那么也还可以讲还没（口票）。 “If the ticket has not been p^hε323-ed, then we can say that we have not (口 ticket).”
T3(323)+X	要是有一种走私的方式叫做 k^huε323… If a form of smuggling is called k^huε323…
T3+T1	如果猪还没有口，那么也还可以讲还没（口猪）。 “If pigs have not been k^huε323-ed, then we can say that we have not (口 pigs).”
T3+T3	如果鼓还没有口，那么也还可以讲还没（口鼓）。 “If drums have not been k^huε323-ed, then we can say that we have not (口 drums).”
T3+T5	如果菜还没有口，那么也还可以讲还没（口菜）。 “If dishes have not been k^huε323-ed, then we can say that we have not (口 dishes).”
T3(323)+X	要是有一种人造材料叫做 tɕyn323… “If a man-made material is called tɕyn323…”
T3+T1	如果客厅是这种材料口，那么也还可以讲这个是一个（口厅）。 “If a living room is made of this material tɕyn323, then we can call it a (口 room).”
T3+T3	如果手表是这种材料口，那么也还可以讲这个是一个（口表）。 “If a watch is made of this material tɕyn323, then we can call it a (口 watch).”
T3+T5	如果书架是这种材料口，那么也还可以讲这个是一个（口架）。 “If a bookshelf is made of this material tɕyn323, then we can call it a (口 shelf).”
T3(323)+X	要是有一个国家叫做 ts^hei323… “If a country is called ts^hei323…”
T3+T1	如果一种花产在这个国家口，那么也还可以讲这个是一种（口花）。 “If a type of flower comes from this country ts^hei323, then we can call it a (口 flower).”
T3+T3	如果一种草产在这个国家口，那么也还可以讲这个是一种（口草）。 “If a type of grass comes from this country ts^hei323, then we can call it a (口 grass).”
T3+T5	如果一种酱产在这个国家口，那么也还可以讲这个是一种（口酱）。 “If a type of jam comes from this country ts^hei323, then we can call it a (口 jam).”
T5(34)+X	要是有一种送东西的方式叫做 la34… “If there is a form of gift-giving called la34…”
T5+T1	如果黄金还没有口，那么也可以讲还没（口金）。 “If the gold has not been la34-ed, then we can say that we have not (口 gold).”
T5+T3	如果游艇还没有口，那么也还可以讲还没（口艇）。 “If the yacht has not been la34-ed, then we can say that we have not (口 yacht).”
T5+T5	如果门票还没有口，那么也还可以讲还没（口票）。 “If the ticket has not been la34-ed, then we can say that we have not (口 ticket).”
T5(34)+X	要是有一种研究方式叫做 tsɿ34… “If there a research method called tsɿ34…”
T5+T1	如果猪还没有口，那么也还可以讲还没（口猪）。 “If pigs have not been tsɿ34-ed, then we can say that we have not (口 pigs).”
T5+T3	如果鼓还没有口，那么也还可以讲还没（口鼓）。 “If drums have not been tsɿ34-ed, then we can say that we have not (口 drums).”

T5+T5	如果菜还没有口，那么也还可以讲还没（口菜）。 “If dishes have not been tsʅ34-ed, then we can say that we have not (口 dishes).”
T5(34)+X	要是有一种颜色叫做 piɔ34… “If there is a color called piɔ34…”
T5+T1	如果客厅是这种颜色口，那么也还可以讲这个是一个（口厅）。 “If a living room has this color piɔ34, then we can call it a (口 room).”
T5+T3	如果手表是这种颜色口，那么也还可以讲这个是一个（口表）。 “If a watch has this color piɔ34, then we can call it a (口 watch).”
T5+T5	如果书架是这种颜色口，那么也还可以讲这个是一个（口架）。 “If a bookshelf has this color piɔ34, then we can call it a (口 shelf).”
T5(34)+X	要是有一种果实叫做 ɕyʊ34… “If there is a fruit called ɕyʊ34…”
T5+T1	如果有一种花的果实是口，那么也还可以讲这个是一种（口花）。 “If a type of flower has this fruit ɕyʊ34, then we can call it a (口 flower).”
T5+T3	如果有一种草的果实是口，那么也还可以讲这个是一种（口草）。 “If a type of grass has this fruit ɕyʊ34, then we can call it a (口 grass).”
T5+T5	如果有一种酱出自这种果实口，那么也还可以讲这个是一种（口酱）。 “If a type of jam is made from this fruit ɕyʊ34, then we can call it a (口 jam).”

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