# Polysyllabic tone sandhi and morphosyntax in Xiangshan Wu Chinese

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## Abstract

In this study, we examined disyllabic and trisyllabic tone sandhi patterns in Xiangshan Wu Chinese, an under-studied Northern Wu variety. With detailed acoustic analyses, we confirmed that Xiangshan, similar to other Northern Wu dialects, shows both left- and right-dominant disyllabic tone sandhi patterns that are correlated with morphosyntax. An asymmetry of tone sandhi patterns is found for two left-branching trisyllabic compounds: (a) [[Lexical Compound] Noun] shows an extension of a left-dominant pattern; (b) [[Verb Noun] Noun] applies both right- and left-dominant patterns in a cyclic fashion. While the disyllabic data fit neatly with previous theoretical accounts, e.g., a syntax-driven edge-based approach, a stress-driven metrical approach, etc., the trisyllabic patterns cannot be fully explained by either approach. To this end, this study provides challenges for the existing theoretical frameworks and calls for re-evaluations of such accounts.

**Index Terms**: tone sandhi, morphosyntax, Northern Wu Chinese

## 1. Introduction

Northern Wu Chinese dialects, which arguably provide the most interesting tone sandhi patterns across all Chinese languages, show two contrasting sandhi processes that frequently correlate with different morphosyntactic structures. The *left-dominant pattern*, which usually applies to lexical compounds, Modifier-Head phrases, etc., preserves the underlying tone of the leftmost tone in a sandhi domain, and typically exhibits a left-to-right tone extension pattern. The *right-dominant pattern*, on the other hand, is found in a smaller range of structures, such as Verb-Object phrases, and it preserves the rightmost tone in a sandhi domain instead [1], [2].

The theoretical proposal that phonological rules are operating in prosodic domains, e.g., mora, syllable, foot, prosodic word, prosodic phrase, etc. [3], [4], has also formed the foundation for many tone sandhi analyses. For example, an end-based approach posits that the prosodic domain for the left-dominant tone sandhi in Shanghai Wu Chinese is a *prosodic word* [5]. According to this analysis, prosodic domains are defined in relation to syntactic structures by setting two parameters: the left or right edge of an $X^0$ (syntactic word) or $X^{max}$ (maximal phrasal projection) [5], [6]. In the case of left-dominant sandhi in Shanghai Wu, the left edge of a prosodic word aligns with the left edge of a syntactic item, including Noun (N), Verb (V), or Adjective (A). Thus, a prosodic word spans from the left edge of one syntactic lexical item to the left edge of the next. Within a prosodic word, only the leftmost tone is preserved and is subsequently re-associated with the remaining syllables in a left-to-right fashion. This approach treats lexical compounds with complex internal structures, such as 手风琴 *hand-wind-organ 'accordion'*, as a singular lexical item, which thus forms only one prosodic word domain. The right-dominant sandhi is not addressed in detail and is merely seen as no application of tone sandhi.

Another thread of studies relate tone sandhi phenomena to *stress* [1], [7], [8], [9], [10]. It has been claimed that a left-dominant sandhi domain is a *left-headed metrical domain* (i.e., trochees), in which the stressed (i.e., the leftmost) syllable retains its tones and the rest get deleted [10], [11]. The distinction of left- vs. right-dominant patterns is attributed to the contrast in stress positions within compounds and phrases, with stress being placed on the left in compounds and on the right in phrases. Such a contrast is originally derived from the positional differences in syntactic non-heads, which act as the anchor for stress [12], [13]. In this way, the Modifier on the left in Modifier-Head phrases, and the Object on the right in Verb-Object phrases, get a stress respectively. Subsequently, left-headed metrical domains are formed from left to right, thus creating one single domain in Modifier-Head phrases, and two separate domains in Verb-Object phrases. The latter adopt a right-dominant sandhi pattern, which is usually characterised by contour simplification on the non-final tones. The incapacity of unstressed syllables—in this case, the non-final syllables—to carry contour tones necessities such tone reduction [1].

Both analyses provide new insights into the mechanisms and motivation of tone sandhi, and have successfully accounted for many tone sandhi processes across different Chinese languages (e.g., a metrical account for Taiwanese [10]). However, the majority of the previous studies were based solely on impressionistic analyses, and an "empirical foundation" is urgently in need for studies of tone sandhi [14]. This paper gives an acoustic analysis of tone sandhi regarding its interaction with morphosyntax in Xiangshan Chinese, an under-studied Northern Wu variety spoken in Xiangshan County, Zhejiang Province in China. Xiangshan has six distinctive citation tones, which encompass four non-checked tones (i.e., HH, HL, LHL, LH) and two checked tones (i.e., Hq, LHq) [15], [16]. By exploring the tone sandhi in disyllables and trisyllables with different syntactic structures, we aim to address the following rquestions: (1) What tone sandhi patterns does Xiangshan have? (2) Does tone sandhi in Xiangshan also correlate with morphosyntax? (2) Can the tone sandhi patterns be explained by the existing theoretical frameworks? This study aims to provide new phonetic evidence and a re-evaluation of the two above-mentioned approaches based on the phonetic data.

## 2. Methodology

### 2.1. Materials

In the current analysis, we investigated the tone sandhi patterns of non-checked tone combinations with an initial LHL underlying tone in disyllabic and trisyllabic contexts. Three syntactic structures were selected for disyllables: Lexical Compounds (LC), Modifier-Head phrases (MH), and Verb-Object phrases (VO). Both LC and MH have an internal [A N]

structure, but LC is semantically opaque whilst MH is not. All four LHL-initial non-checked tone combinations were covered, i.e., LHL-HH, LHL-HL, LHL-LHL, LHL-LH. The trisyllables include two types of left-branching compounds: [[V N] N] and [[LC] N], the brackets indicating the syntactic constituent boundaries. The current study focused only on the trisyllabic citation tone combinations involving HH and LHL tones, which covers four possible sequences: LHL-HH-HH, LHL-HH-LHL, LHL-LHL-HH, LHL-LHL-LHL. We selected 26 frequently used tokens, including 18 disyllables (6 LC, 6 MH, 6 VO) and 8 trisyllables (4 [[V N] N], 4 [[LC] N]). The complete lists of materials are provided in Table 1. A total of 208 (26 tokens × 8 speakers) tokens were analysed in this study.

Table 1: *Selected disyllables (top) and trisyllables (bottom). The first column list citation tone combinations. Syntactic structures are in bold.*

| | **LC** | **MH** | **VO** |
|---|---|---|---|
| LHL-HH | 黄瓜<br>*cucumber*<br>梅花<br>*plum blossom* | 皮袄<br>*leather jacket*<br>黄花<br>*yellow flower* | 造纸<br>*produce paper*<br>卖花<br>*sell flowers* |
| LHL-HL | 油菜<br>*Chinese cabbage* | 黄布<br>*yellow cloth* | 卖布<br>*sell cloth* |
| LHL-LHL | 杨梅<br>*a variety of local berries* | 黄绳<br>*yellow rope*<br>皮鞋<br>*leather shoes* | 卖茶<br>*sell tea*<br>造船<br>*make ships* |
| LHL-LH | 杨桃<br>*starfruit*<br>黄豆<br>*soya bean* | 黄树<br>*yellow trees* | 卖饭<br>*sell rice* |
| | **[[LC] N]** | | **[[V N] N]** |
| LHL-HH-HH | 黄瓜籽<br>*cucumber seed* | | 造纸厂<br>*paper mill* |
| LHL-HH-LHL | 黄瓜皮<br>*cucumber skin* | | 卖花人<br>*flower seller* |
| LHL-LHL-HH | 杨梅籽<br>*berry seed* | | 造船厂<br>*shipyard* |
| LHL-LHL-LHL | 杨桃皮<br>*starfruit skin* | | 卖茶人<br>*tea seller* |

### 2.2. Speakers and recordings

We recruited eight native Xiangshan speakers, including four females and four males, with ages ranging from 47 to 53 and a mean age of 50. All participants were born and raised in Xiangshan and reported using Xiangshan as their primary language for over 75% of their daily communication. The recordings were conducted by the first author in March and April 2021, using an H4n Zoom recorder at a sampling rate of 44.1k Hz. The participants were instructed to read the selected tokens in a semi-randomised order as naturally as possible. Each token was displayed in an individual slide using Microsoft PowerPoint to avoid any potential list effect. All instructions were given in Xiangshan to avoid potential code-switching or influence from other languages.

### 2.3. Data analysis

The recordings were manually segmented and annotated in *Praat* [17] by the first author. For every token, the boundaries of rhymes—which include onset glides, vowels, and nasals—were marked. $F_0$ values at 10 equidistant points within each rhyme were extracted using *ProsodyPro* [18]. The $f_0$ values at the first time point were discarded to eliminate possible perturbations from the onsets. Inter-speaker variations were normalised by calculating the z-scores of logarithmic-transformed $f_0$ values based on each speaker's mean $f_0$ [19]. All the $f_0$ contours were visualised using *R* [20]. The phonetic descriptions of the tone sandhi patterns will be provided in Section 3, followed by theoretical analyses in Section 4.

## 3. Results

In the following sessions, only recurring sandhi patterns in the speech data are discussed. Single occurrences are deemed outliers and are not examined in this paper.

### 3.1. Disyllabic tone sandhi

The findings of this study validate the presence of both left- and right-dominant tone sandhi patterns in disyllables in Xiangshan.

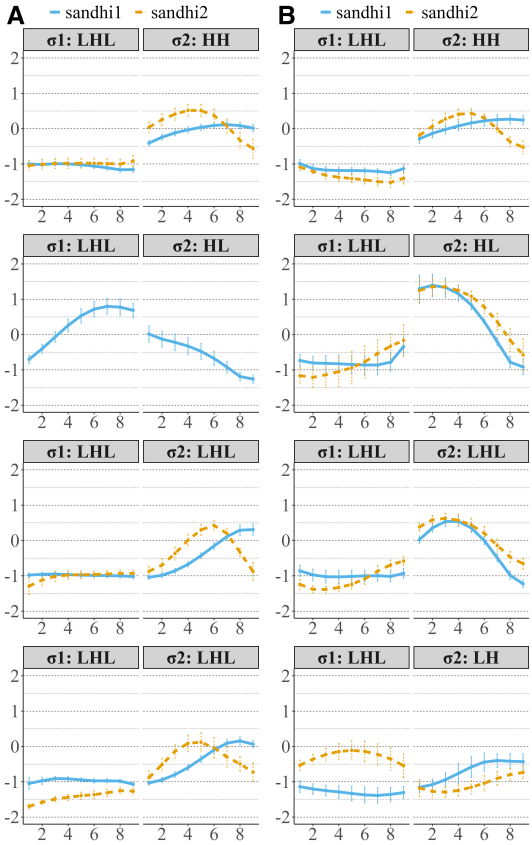


Figure 1: *Sandhi patterns of disyllabic LC and MH (A) and VO (B). The title bars in each sub-panel indicate the syllable positions and citation tones.*

As shown in Figure 1A, the sandhi contours of LHL-HH, LHL-LHL, and LHL-LH citation tone combinations are similar, which surface as either an L-LH contour (sandhi1) or an L-LHL contour (sandhi2). It suggests a left-dominant sandhi for these three tone combinations, where the left tone determines the whole contour for the entire disyllable regardless of the second tone. The actual sandhi derivation does *not* follow a left-to-right one-to-one association as typically adopted by other Northern Wu dialects (e.g., Shanghai [21], [22]). Instead, both tones undergo changes. By contrast, the VO structure generally demonstrates a right-dominant sandhi (Figure 1B). Across all the four tone combinations, the citation tone of the second tone

is largely preserved, whilst the first tone is reduced to an L, an LM, or an LML tone. The only exception is sandhi2 for the LHL-HH tone combination, which does not preserve the second tone but rather changes it to a rise-fall contour. It should be noted that the choice of the sandhi variants mentioned above (i.e., sandhi1 and sandhi2 in each plot) is not correlated with the tone values of the second tones, speakers, items, etc. At this stage, we intend to treat them as free variants.

### 3.2. Trisyllabic tone sandhi

Two tone sandhi variants are found for the [[LC] N] structure, as shown in Figure 2A: an L-L-LM or an L-L-LML contour. These patterns mirror those of the disyllabic LC and MH structures (Figure 1A). All of them exhibit an overall rise (sandhi1) or a rise-fall (sandhi2) contour across the entire sandhi domain, with the rise or rise-fall realised on the final syllable. Essentially, the disyllabic domain within the [[LC] N]] structure seems to be eliminated, leading to an extension of the disyllabic left-dominant sandhi over the whole trisyllable.

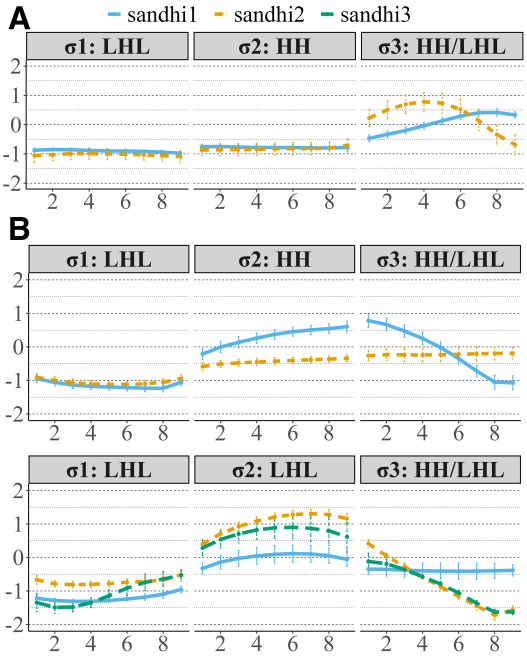


Figure 2: *Sandhi patterns of [[LC] N] (A) and [[V N] N] (B). The title bars in each sub-panel indicate the syllable positions and citation tones.*

The [[V N] N] structure shows more complicated sandhi behaviours, which seem to reflect both left- and right-dominant sandhi. In this scenario, the right-dominant sandhi is first applied to the first two syllables, as bounded by the VO structure. Subsequently, the tone features of the second sandhi tone spread to the third syllable, showing a left-dominant sandhi across the boundary. This is evidenced by a comparison of the trisyllabic sandhi in Figure 2B and the disyllabic VO sandhi in Figure 1B. For example, for the LHL-LHL-HH/LHL combination (Figure 2B, row 2), the first tone becomes either an L or an LM tone. The same changes are found in the disyllabic VO that shares the same tone combination, i.e., LHL-LHL (Figure 1B, row 3). Subsequently, the trisyllable realises the LHL tone of the second syllable over the last two syllables. Although it has three variants, with the last tone realised as either a level (sandhi1) or a falling contour (sandhi2 and sandhi3), all of them can be seen as an extension of the preceding ($\sigma_2$) tone, as the $f_0$ trajectories appear to form a continuum. Similar to the free variants in the disyllables, other factors such as non-initial tones, speakers, etc., do not contribute to the selection of the variants. It justifies classifying the sandhi patterns of the last two syllables as a left-dominant sandhi, as the contours are determined solely by the left tone (in this case, the sandhi tone of the second tone). The other set of citation combinations, i.e., LHL-HH-LHL/HH, shows similar mechanisms (Figure 2B, row 1). It should be noted that the left-dominant sandhi adopts a left-to-right tone re-association mechanism, which is different from the neutralisation mechanism used by the disyllabic LC and MH structures.

It might alternatively be argued that the left-dominant tone extension operating on the final two syllables is based on the *citation* rather than the *sandhi* tone of the second syllable. This is because the sandhi tone of the second syllable, which derives from a right-dominant sandhi, is usually the same as its citation tone. However, the sandhi1 pattern of the LHL-HH-HH/LHL combinations provides extra evidence (Figure 2B, row 1). This variant shows a rise-fall contour on the last 2 syllables, which *cannot* come from the citation tone of the second syllable, i.e., an HH tone, via a re-association mechanism. Instead, it can be derived from the sandhi tone of the second syllable in the VO structure, i.e., an LHL tone (Figure 1B, row 1, sandhi2). Therefore, to achieve a unified account for both sets of citation tone combinations, we consider the sandhi contours of the last two syllables as deriving from the *sandhi* tone of the second syllable in the VO structure. This suggests an overall cyclic application of tone sandhi within the [[V N] N] structure based on the syntactic structures: a right-dominant VO tone sandhi is applied to the first two syllables, followed by a left-to-right tone extension of the second sandhi tone over the last two syllables.

## 4. Theoretical analyses

In this section, alternative theoretical accounts for the observed patterns are explored. An end-based approach and a stress-based metrical approach will be adopted and discussed respectively. We provide evidence that neither approach can perfectly account for the Xiangshan data.

### 4.1. An end-based approach

The end-based approach, rooted in Prosodic Phonology, propose to account for the sensitivity of phonological processes to morpho-syntactic structure by mean of an intermediate level between syntax and phonology, i.e. the prosodic structure [3] (cf. [4]). This approach maps syntactic structures to prosodic structures by aligning the left or right edges of both [5], [6]. In this way, it allows indirect reference from phonology to syntax, as well as non-isomorphic mappings between syntax and prosody. In Shanghai Wu, the left-dominant sandhi domain is claimed to be a prosodic word (PWd), the left edge of which is aligned with the left edge of a lexical item, as specified in (1). Thus, one prosodic word extends from the left edge of a lexical item until the left edge of the next one.

(1) Prosodic Word (PWd) formation [5]:
Prosodic Word: {Left, $Lex^0$}, where $Lex^0$ is a N, V, A, or a compound.

As Xiangshan and Shanghai exhibit similar tone sandhi mechanisms, i.e., left-dominant sandhi in LC and MH, and right-dominant sandhi in VO structure, we could apply the same rule to Xiangshan. The disyllabic MH and the two trisyllabic structures examined in this study would be treated as

compounds in [5], as acknowledged in [12], [13]. But it should be noted that setting the boundary between words and phrases in Chinese has been a longstanding unsolved issue [23], [24]. According to this approach, as shown in (2), Xiangshan forms one single sandhi domain in disyllabic LC and MH, and two separate domains in disyllabic VO. It aligns well with the data where only LC and MH apply a left-dominant sandhi. The trisyllables are predicted to have only one sandhi domain regardless of the internal structures, because they are treated as one single compound. However, our data show different sandhi processes for the two different structures.

(2) Prosodic Word (PWd) formation in Xiangshan

| | Disyllables | | Trisyllables |
|---|---|---|---|
| | LC, MH | VO | [[V N/LC] N] |
| Edge alignment | [$\sigma_1$ $\sigma_2$ | [$\sigma_1$ [$\sigma_2$ | [$\sigma_1$ $\sigma_2$ $\sigma_3$ |
| PWd formation | ($\sigma_1$ $\sigma_2$) | ($\sigma_1$) ($\sigma_2$) | ($\sigma_1$ $\sigma_2$ $\sigma_3$) |

### 4.2. A stress-based metrical approach

A stress-based metrical approach assumes that stress serves as the underlying motivation for tone sandhi. In a left-dominant sandhi domain, only the tones of the stressed syllables are retained, which are then extended over to the unstressed syllables. Stress is assigned to syntactic non-heads, after which left-headed metrical domains (i.e., trochees) are formed from left to right. The relevant rules proposed in [12], [13], [25] are aggregated and re-written in (3). A more detailed version can be found in [25], which breaks down the Nonhead Stress rule to morpheme, compound, and phrase levels, and adds an optional Stress Reduction rule.

(3) a. Nonhead stress: a syntactic nonhead is stressed

b. Cyclic application: apply stress assignment cyclically from compound to phrase level.

c. Clash Resolution: Remove the stress column next to a higher column.

d. Metrical domain formation: form left-headed metrical domain from left to right.

e. Exhaustive parsing: all elements have to be parsed into metrical domains.

(4) a. Disyllabic metrical domain formation in Xiangshan

| | LC | | MH | | VO | |
|---|---|---|---|---|---|---|
| | A | N | A | N | V | N |
| Nonhead stress | * | | * | | | * |
| Domain formation | ( | ) | ( | ) | | ( ) |
| Exhaustive parsing | | | | | ( ) | ( ) |

b. Trisyllabic metrical domain formation in Xiangshan

| | [[LC] N] | | | [[V N] N] | | |
|---|---|---|---|---|---|---|
| | [[A | N] | N] | [[V | N] | N] |
| Stress cycle 1 | [* | ] | | [ | *] | |
| Stress cycle 2 | * [* | *] | | [* | * *] | |
| Clash resolution | * * | | | | * * | |
| Domain formation | ( | | ) | | ( | ) |
| Exhaustive parsing | ( | | ) | ( ) | ( | ) |

The derivations of the tone sandhi domains in Xiangshan according to this metrical approach are shown in (4). Similar to the end-based approach, this account predicts that the disyllabic LC, MH, and the trisyllabic [[LC] N] in Xiangshan form one single sandhi domain. Disyllabic VO structures, on the other hand, have 2 separate domains. These are all attested in the data. The [[V N] N] structure brings the central difference from the end-based approach, as it is parsed into 2 separate domains instead. This seems to align with our data at first glance, since a left-dominant sandhi is applied only in the last two syllables, and a right-dominant sandhi, as characterised by reduction in unstressed syllables, operates on the first syllable. However, this metrical account ignores the cyclic nature of the sandhi applications (see Section 3.2) and instead assumes simultaneous applications of both left- and right-dominant sandhi. More importantly, it cannot explain why the left-dominant sandhi domain in [[V N] N] adopts a left-to-right association mechanism, while that in LC, MH, and [[LC] N] employs an ad-hoc tonal replacement pattern.

## 5. Discussion and Conclusion

Our results confirmed that Xiangshan, just like other Northern Wu Chinese, shows the co-existence of both left- and right-dominant sandhi in disyllables which correlate with morphosyntax. However, it exhibits an asymmetry of sandhi patterns in two syntactically different trisyllabic compounds: [[LC] N] and [[V N] N]. In summary, the disyllabic and trisyllabic sandhi patterns can be generalized as followed:

(5) a. LC, MH *(left-dominant)* LHL + T → L + LH/LHL

b. VO *(right-dominant)*: LHL + T → L/LM/LML + T

c. [[LC] N] *(left-dominant)*:

LHL + $T_1$ + $T_2$ → L + L + LH/LHL

d. [[V N] N] *(right- & left-dominant):*

LHL + $T_1$ + $T_2$ → L/LM/LML + $T_1$ + $T_2$ *(cycle 1)*

→ L/LM/LML + $T_{1A}$ + $T_{1B}$ *(cycle 2)*

An end-based approach and a stress-based metrical approach were both adopted to account for the mechanisms of the sandhi patterns in the data. While the disyllabic patterns fit well in either theory, the trisyllabic patterns pose a challenge to the existing frameworks. The end-based approach fails to capture the differences in the two trisyllabic structures, as it uniformly parses compounds into one sandhi domain regardless of the internal structures. Moreover, the end-based approach would also need to be able to account for the sensitivity of sandhi domains to factors such as speech rate, focus, and a tendency for polysyllabic words to be parsed into disyllabic feet, which could pose further issues [1], [12], [13].

The stress-based approach explored here incorporates more rhythmic and prosodic effects directly, and connects tone sandhi with other universal phenomena such as stress. It has merits in acknowledging a prominence structure underlying the tone sandhi system which is marked by the tonal preservation and tonal loss. Nevertheless, it still fails to account for the sandhi mechanisms of the [[V N] N] structure in Xiangshan, as it cannot explain why the left-dominant pattern adopted by the last 2 syllables differs from that adopted in LC, MH, and [[LC] N]. Furthermore, this approach is often criticised for lacking independent phonetic evidence for 'stress' in Chinese languages [5]. Therefore, care must be taken when we employ the 'stress' notion in Chinese languages, and more phonetic investigations are needed in this regard.

# 6. References


[1] M. Y. Chen, *Tone Sandhi: Patterns across Chinese Dialects*, 1st ed. Cambridge University Press, 2000. doi: 10.1017/CBO9780511486364.

[2] J. Zhang, 'A directional asymmetry in Chinese tone sandhi systems', *J. East Asian Linguist.*, vol. 16, pp. 259–302, 2007.

[3] E. Selkirk, 'Prosodic domains in phonology: Sanskrit revisited', *Juncture*, vol. 7, pp. 107–129, 1980.

[4] M. Nespor and I. Vogel, *Prosodic phonology: with a new foreword*, vol. 28. Walter de Gruyter, 2007.

[5] E. Selkirk and T. Shen, 'Prosodic domains in Shanghai Chinese', in *The Phonology-Syntax Connection*, Chicago: University of Chicago Press, 1990, pp. 313–337.

[6] E. Selkirk, 'On derived domains in sentence phonology', *Phonology*, vol. 3, pp. 371–405, 1986.

[7] M. J. Yip, 'The tonal phonology of Chinese', Massachusetts Institute of Technology, 1980.

[8] M. S. Wright, *A metrical approach to tone sandhi in Chinese dialects*. University of Massachusetts Amherst, 1983.

[9] C. Shih, *The Prosodic Domain of Tone Sandhi in Chinese (Phrasal Phonology, Tonal Typology, Mandarin, Syntax-Phonology Interface)*. University of California, San Diego, 1986.

[10] S. Duanmu, 'Metrical and Tonal Phonology of Compounds in Two Chinese Dialects', *Language*, vol. 71, no. 2, p. 225, Jun. 1995, doi: 10.2307/416163.

[11] S. Duanmu, 'Metrical structure and tone: evidence from Mandarin and Shanghai', *J. East Asian Linguist.*, vol. 8, no. 1, pp. 1–38, 1999.

[12] S. Duanmu, 'A formal study of syllable, tone, stress and domain in Chinese languages', 1990.

[13] S. Duanmu, 'The tone-syntax interface in Chinese: some recent controversies', in *Proceedings of the Symposium "Cross-Linguistic Studies of Tonal Phenomena*, pp221-254. Institute for the Study of Languages and Cultures of Asia and …, 2005, pp. 221–254.

[14] J. Zhang, 'Issues in the Analysis of Chinese Tone', *Lang. Linguist. Compass*, vol. 4, no. 12, pp. 1137–1153, Dec. 2010, doi: 10.1111/j.1749-818X.2010.00259.x.

[15] Y. Shi, 'Tones and Disyllabic Tone Sandhi in Xiangshan Chinese Dialect', University of Cambridge, 2020.

[16] Y. Shi, B. Post, and F. Nolan, 'The phonetics and phonology of corrective focus in Xiangshan Wu Chinese: interaction with disyllabic tone sandhi', in *Proceedings of the 20th International Congress of Phonetic Sciences (ICPhS)*, Prague, Czech Republic, 2023, pp. 1643–1647.

[17] P. Boersma and D. Weenink, 'Praat: doing phonetics by computer'. 2024. [Online]. Available: http://www.praat.org/

[18] Y. Xu, 'ProsodyPro — A Tool for Large-scale Systematic Prosody Analysis', in *Proceedings of Tools and Resources for the Analysis of Speech Prosody (TRASP 2013)*, Aix-en-Provence, France, 2013, pp. 7–10.

[19] X. Zhu, 'F0 normalization: how to deal with between-speaker tonal variations', *Lang. Sci.*, vol. 9, pp. 3–19, 2004.

[20] R Core Team, 'R: A language and environment for statistical computing'. Vienna, Austria, 2018. [Online]. Available: https://www.r-project.org/

[21] B. Xu, Z. Tang, and N. Qian, 'Xinpai Shanghai fangyan de liandu biandiao [Tone sandhi in New Shanghai]', *Fangyan Dialects*, vol. 1981, pp. 145–155, 1981.

[22] R. J. You, 'Shanghaihua yindang [The sound archive of Shanghai]', *Xiandai Hanyu Fangyan Yinku*, 1994.

[23] C.-T. J. Huang, 'Phrase structure, lexical integrity, and Chinese compounds', *J. Chin. Lang. Teach. Assoc.*, vol. 19, no. 2, pp. 53–78, 1984.

[24] S. Duanmu, 'Wordhood in Chinese', *New Approaches Chin. Word Form. Morphol. Phonol. Lex. Mod. Anc. Chin.*, pp. 135–196, 1998.

[25] S. Duanmu, 'Rime length, stress, and association domains', *J. East Asian Linguist.*, vol. 2, no. 1, pp. 1–44, Jan. 1993, doi: 10.1007/BF01440582.