

[23][24][25][26][27][28], it is perhaps worthwhile to ask the question what generalizations the speakers make regarding the complex, phonetically-arbitrary tone sandhi patterns, as it is possible that a glimpse into how a speaker has internalized the pattern may be more telling about the grammatical nature of the pattern than the pattern itself.

I focus on a specific aspect of phonetic arbitrariness in this paper — the transparent vs. opaque distinction in tone sandhi processes. Following Kiparsky [29], I define a transparent sandhi as one that is driven by a surface-true phonotactic generalization, and in the meantime, the output of the sandhi is also not an undergoer of another sandhi. For instance, the T3 sandhi in Mandarin (2a) is transparent, as it can be driven by a phonotactic ban of a T3 before another T3, and the output of the sandhi T2-T3 is not subject to another sandhi in the language. The spreading pattern in Shanghai is also transparent, as it can be motivated by the avoidance of pronounced contours on the initial syllable, and the resulting tonal sequence also does not offend any other phonotactic generalization. Any non-transparent sandhi is an opaque sandhi. For example, all sandhi processes in the Taiwanese pattern in (2c) are opaque: the sandhis in the circular chain shift fail both conditions for transparency; the 24 → 33 sandhi is phonotactically motivated, as the ban on 24 in nonfinal positions is a surface-true generalization, but it derives an output 33-X that could further undergo the 33 → 21 sandhi.

To investigate the effect of opacity on how speakers internalize tone sandhi patterns, I report results from two types of experiments — nonce-probe tests of productivity (also known as the wug test) [30] and auditory lexical decision with auditory priming [31]. In section 2, I discuss nonce-probe tests on the tone sandhi patterns in Taiwanese, Shanghai, Wuxi, Mandarin, and Hakka in turn and argue that transparent tone sandhi is generally productive in nonce words, while opaque tone sandhi is not. In section 3, I discuss auditory priming results from Taiwanese, Mandarin, and Hakka, which show that tone sandhi words undergoing a transparent sandhi are more strongly primed by an identical first syllable carrying the base tone, while those undergoing an opaque sandhi are more strongly primed by the sandhi tone. Collectively, these results suggest that transparent sandhis are likely derived through productive phonological processes from the base tone, while opaque sandhis are internalized as the allomorph listings of existing morphemes and syllables [32].

2. Nonce-Probe Tests

In a typical nonce-probe test, participants are asked to produce novel words that meet the environment for a phonological process; the propensity for the process to apply to the novel words can be taken as a measure of productivity for the process. In nonce-probe tests of disyllabic tone sandhi, the participants are given the base tones of monosyllables and asked to concatenate the two syllables as a real word, often with the help of a discourse context. I discuss the results from five different sandhi patterns in this section. These patterns allow two comparisons: (a) opaque tone substitution vs. transparent tone spreading and (b) opaque tone substitution vs. transparent tone substitution. We start from the opaque tone substitution pattern in Taiwanese.

2.1. Taiwanese

The tone sandhi pattern on non-checked syllables (CV, CVN) in Taiwanese is given in (2c). To test the productivity of the different sandhis in the pattern, we used a method similar to the ones used by Hsieh [33][34][35] and Wang [36]. Specifically, we elicited the production of two types of

disyllabic words from native speakers: real words and novel words. The real words were existing words that all participants were familiar with. The novel words were composed of an accidental gap syllable and an existing noun, where the first syllable was cued as a novel verb in a discourse context. For the real words, the participants heard the two syllables in their base tones separated by 800ms and were asked to produce the two syllables together as a word as naturally as possible. For the novel words, the participants heard the novel syllable pronounced in its base tone twice and the noun in its base tone once in the discourse set-up; they were then asked to produce the V-N combination as a word as naturally as possible. Twenty-five real words and twenty-five novel words were elicited from the participants. The first syllable included all five unchecked tones, while the second syllable had a 33 tone in all test words. Twenty-six native Taiwanese speakers with a mean age of 38.5 participated in the experiment in Taiwan.

An initial inspection of the production data indicated that the participants' responses on the first syllables were categorically one of the five unchecked tones. The tones on the first syllables were then transcribed by a team of three researchers consisted of one native Taiwanese speaker and two native Mandarin speakers, all phonetically trained. The transcriptions were then classified into "Correct_Sandhi" if the syllable underwent the expected sandhi according to (2c), "No_Sandhi" if the syllable maintained the base tone, or "Others" if the participant provided any other response.

The percentages of the three types of responses for the real and novel words are given in Figure 1.

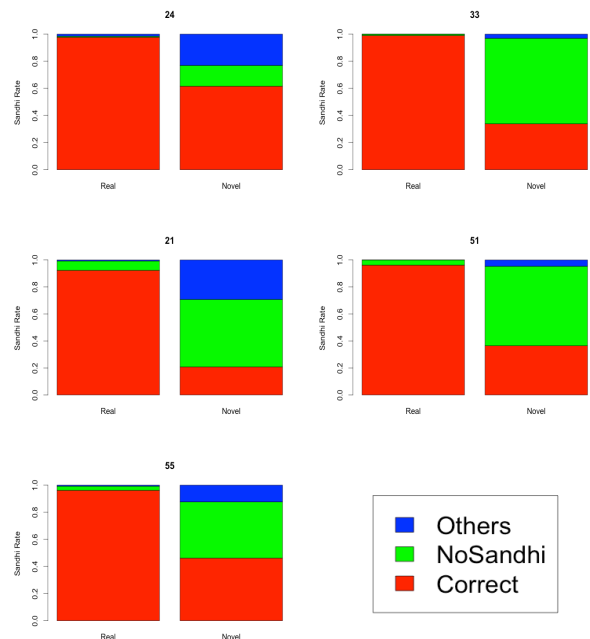


Figure 1: Tone sandhi results on the first syllable of disyllabic real and novel words in Taiwanese.

Linear Mixed-Effects analyses were conducted with word type (real vs. novel) and the base tone on the first syllable (24, 33, 21, 51, 55) as fixed effects and participant, participant by word type, and item as random effects. Likelihood ratio comparisons showed that for "Correct_Sandhi" rate, adding word type ($\chi^2=66.91$, $p<.001$) and s1 base tone ($\chi^2=45.68$, $p<.001$) successively into the model both improved the model, but adding the interaction term did not ($\chi^2=6.17$, $p=.187$). For "No_Sandhi" rate, however, the model with the interaction is the best ($\chi^2=11.97$, $p=.018$), and separate analyses for real and novel words showed that σ_1 base tone has no effect in real

words, but a significant effect for novel words, with the 24→33 sandhi eliciting significant fewer “No_Sandhi” responses than the other sandhis.

These results indicate that none of the opaque tonal substitution processes in Taiwanese is entirely productive, and the participants’ responses often have no sandhi application. The phonotactically motivated sandhi 24→33, however, has an edge in productivity over the other sandhis in that it is less likely for the participants to respond with the no sandhi form. These results are consistent with earlier wug-test results on Taiwanese tone sandhi [33][34][35][36][37][38].

2.2. Shanghai

For Shanghai, we focus on the transparent spreading pattern of the high fall tone in (1a) on non-checked syllables. See [39] for results on other sandhis and further experimental details.

Participants in the Shanghai experiment also provided production data for real and novel disyllabic words, but the novel disyllables were cued as modifier-noun combinations (M-Ns) instead of V-Ns, as V-Ns are generally phrases in Shanghai and do not participate in tone sandhi [5][40]. All tonal combinations were tested in [39], but we only focus on the combinations between 51 and the two tones on non-checked syllables with a voiceless onset (51, 35) due to space limitation. Forty-eight speakers with a mean age of 24.6 from the urban regions of Shanghai participated in the experiment.

An initial inspection of the production data indicated that a classification of the responses into “Sandhi” vs. “No_Sandhi” would be difficult. Therefore, we opted to measure the f_0 of the two syllables using Yi Xu’s *ProsodyPro* Praat script and conducted growth curve analyses [41] using orthogonal quadratic polynomials to compare the f_0 s between real and novel words. The normalized f_0 results for 51-51 and 51-35 are given in Figure 2.

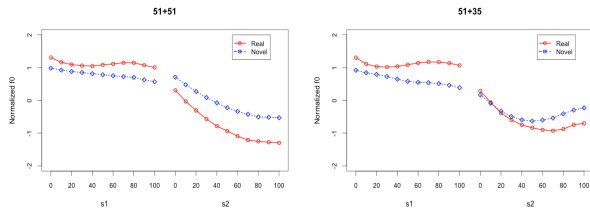


Figure 2: F_0 results for disyllabic real and novel words in Shanghai.

The overall shapes of the f_0 curves in Figure 2 show a falling contour over the two syllables for both real and novel words, indicating that the spreading sandhi is generally productive. Growth curve analyses, however, showed a difference in f_0 between real and novel words on both syllables. There appear to be stronger traces of the base tones in the novel words than in the real words; e.g., the second syllable has a higher fall in 51-51 and a greater rise in 51-35 in the novel words. This suggests that the lack of full productivity of the transparent spreading pattern in Shanghai, if any, lies in the gradient phonetic realization of the sandhi, a pattern quite different from the categorical non-application observed in Taiwanese.

2.3. Wuxi

Wuxi is a Wu dialect closely related to Shanghai. The pattern substitution sandhis in Wuxi involving non-checked syllables with a voiceless onset are given in (3) [6].

- (3) Wuxi tone sandhi:
T1-X: 53-X → 43-34

T3-X: 323-X → 44-55

T5-X: 34-X → 55-31

If we do not ascribe theoretical significance to the small transcription differences between 323 and 434 and between 45 and 34, we can divide the sandhi pattern in Wuxi into two distinct aspects: an opaque circular substitution pattern T1 → T3 → T5 → T1 and the subsequent transparent spreading of the substituted tone. Wuxi, therefore, has elements of both the Taiwanese and Shanghai types of sandhi. The productivity of the Wuxi tone sandhi pattern is tested in [42], and I summarize the results for T1-X, a cognate of the Shanghai 51-X pattern, here. Interested readers should consult [42] for more details.

The same methods were used to elicit the production of both real and novel words in Wuxi, but the novel words included both M-N and V-N items, as no clear difference in sandhi production between the two has been documented (but see [40]). Twenty native speakers with a mean age of 27 participated in the experiment in Wuxi.

Both the acoustic analysis of f_0 and the transcription and the categorization of the sandhi patterns were conducted for the production data. The acoustic f_0 results for 53-53, 53-323, and 53-34 are provided in Figure 3.

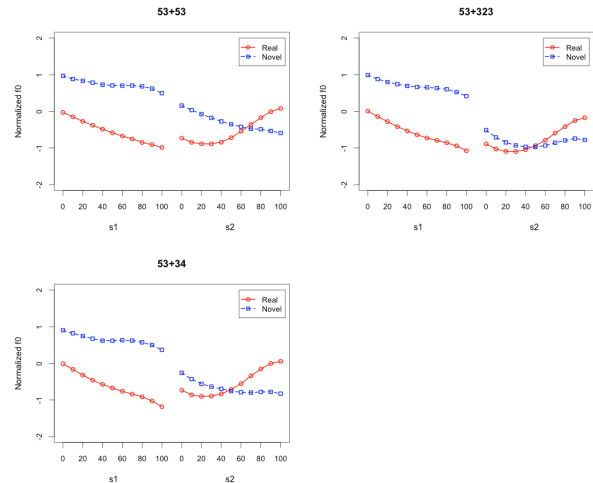


Figure 3: F_0 results for disyllabic real and novel words in Wuxi.

The f_0 pattern here looks markedly different from that in Shanghai. There are large differences in f_0 on both syllables between real and novel words (see [42] for statistical comparisons). It appears that the substitution sandhi only occurred in the real words; in the novel words, the initial fall was spread instead, and there are also traces of the base tones in the surface tone patterns, e.g., the low dipping on the second syllable of 53-323.

The results of the transcription and classification of the sandhi patterns by a phonetically trained native Wuxi speaker are given in Figure 4. These results further support our intuition gained from the f_0 results. The real words underwent the pattern substitution sandhi, as expected. But there is only a very low percentage of correct substitution in novel words, mirroring the Taiwanese tone sandhi pattern. The majority of the responses was classified as having the extension pattern, and “unchanged”, where both syllables kept the base tone, and “partially unchanged”, where at least one of the syllables kept the base tone, also accounted for a good portion of the data. These seem to correspond to the Shanghai pattern we observed in 2.2. I again refer the readers to [42] for statistics on these results.

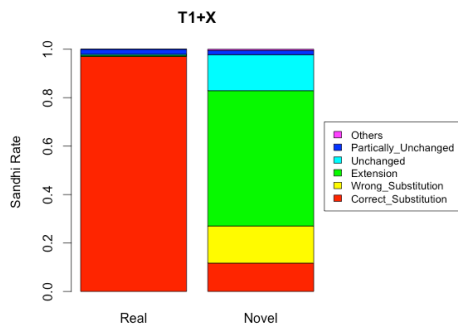


Figure 4: Tone sandhi classification results for disyllabic real and novel words in Wuxi.

The f_0 and the classification results together indicate that the two aspects of Wuxi tone sandhi have different productivity properties: similar to Taiwanese, opaque substitution lacks full productivity and often categorically fails to apply to novel words; and similar to Shanghai, transparent spreading, either from the base tone or from the substituted tone, is generally productive, but may apply incompletely in a phonetically gradient fashion.

2.4. Interim Summary

What we have seen so far is that the opaque substitution and transparent spreading have different productivity patterns. It is important to note that there is no compelling reason for us to assume that the lexical propensity of these tone sandhi patterns is different among the different dialects. In fact, the lexical statistics likely levy against the transparent sandhi in Shanghai, as it only applies to compound words, and V-N disyllables often do not undergo sandhi [5]. In Wuxi, on the other hand, the substitution sandhi applies to a wider range of grammatical categories [6]. Moreover, the different behavior of the two aspects of Wuxi sandhi cannot be accounted for by frequency as both aspects are simultaneously involved in the sandhi process in Wuxi words. Therefore, we have strong reasons to believe that it is the opacity of the sandhi that determines its productivity behavior.

However, there is an additional difference between the opaque substitution sandhi in Taiwanese and the transparent spreading sandhi in Shanghai: consistent with typological generalizations [3][4], the substitution pattern is right-dominant, and the spreading pattern is left-dominant. To rule out the possibility that their productivity difference is rooted in directionality rather than opacity, I discuss two additional case studies of productivity below: Mandarin and Hailu Hakka, both of which have transparent, right-dominant tone sandhi.

2.5. Mandarin

The productivity of the T3 sandhi pattern in Mandarin (2a) was investigated in [43]. The experiment tested the production of real words as well as four types of nonce words — pseudo words in which both syllables were existing morphemes, but the combinations were nonwords, and novel words in which the first syllable, the second syllable, or both syllables were accidental gaps in the syllabary. Participants heard the two syllables in their base tones separated by 800ms and produced the two syllables together as a word as naturally as possible. Thirty native speakers of Beijing Mandarin ranging from 19 to 37 years of age participated in the experiment in Beijing.

The production data showed that the T3 sandhi consistently applied in all nonce word types. F_0 results

indicated that there was incomplete application of the sandhi in nonce words, as the pitch pattern of the sandhi tone in nonce words showed more base tone properties (lower and later turning point) than in real words (see [43] for more details). This is a similar productivity pattern to what we have seen for the transparent sandhi in Shanghai.

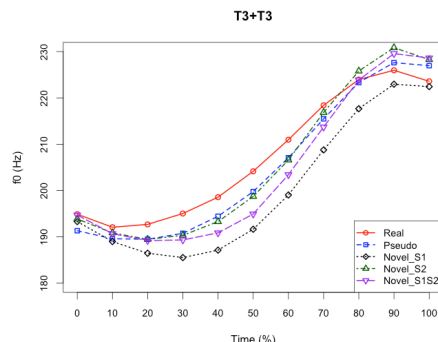


Figure 5: F_0 results for the first syllable of disyllabic real words and four types of novel words in Mandarin.

2.6. Hailu Hakka

A final element to consider in the transparency vs. opacity comparison is the nature of the tone sandhi trigger: albeit both right-dominant, the Mandarin T3 sandhi is triggered by a following tone, while the Taiwanese sandhi pattern is triggered by position. To complete the argument that it is indeed opacity that causes categorical unproductivity, I discuss a productivity study of a sandhi pattern in Hailu Hakka that is both positionally triggered and transparent [44].

I focus on the 13 → 33 sandhi in (2b) investigated in [44]. Participants provided production data for both real and novel words, where the novel words were M-N or V-N combinations with a novel modifier or verb and an existing noun, after being provided the base tones of the two syllables. The base tone combinations tested were 13-33 and 13-53. Nineteen native speakers with a mean age of 58.6 participated in the experiment in Hsinchu, Taiwan.

The normalized f_0 results for the first syllable of the 13-X disyllables are given in Figure 6. Growth curve analysis with orthogonal quadratic polynomials revealed no difference between the real and the novel words, indicating that the sandhi applied productively to the novel words.

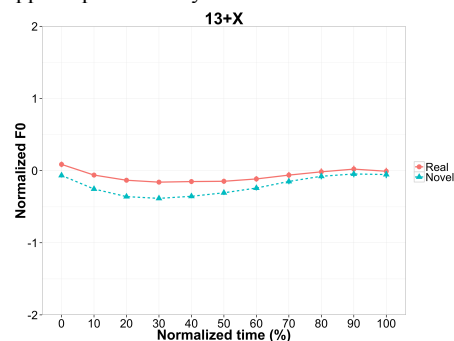


Figure 6: F_0 results for the first syllable of disyllabic real and novel words in Hailu Hakka.

Together with the Taiwanese results, the Hailu Hakka results here suggest that the positional nature of the sandhi trigger does not determine its productivity property, as both sandhi patterns are positionally triggered, yet they behave differently in the nonce-probe tests. These results further confirm that opacity is indeed the culprit for the unproductivity we observed for Taiwanese and Wuxi sandhi.

2.7. Discussion

Taken together, the nonce-probe tests of tone sandhi patterns surveyed here indicate that phonological opacity plays a crucial role in determining how native speakers internalize the sandhi: transparent sandhis are likely derived through productive phonological derivations from the base tone, while opaque sandhis are likely due to allomorph listings of existing morphemes and syllables (see [32] for a similar view). Phonotactic motivations, however, could give the sandhi a productive edge even if it is opaque, as shown in the 24 → 33 sandhi result in Taiwanese. These results indicate that opaque patterns — a specific instance of phonetic arbitrariness — are underlearned.

In the following section, we discuss a series of studies that investigate the nature of tone sandhi from the perspective of spoken word recognition. The goal is to address the question whether the speakers’ phonological knowledge that we deduced from the nonce-probe tests is consistent with what they use in the process of spoken word recognition.

3. Auditory Priming

In auditory lexical decision, participants judge whether an experimental item they hear is a word or not. The latency with which the participants respond “yes” to a word is influenced by properties of the word itself, such as its frequency, as well as the exposure to an earlier item (prime). A prime that shares phonological elements with the word target has been commonly found to facilitate the response to the target (e.g., *MEAN* primes *BEAN*) (see [45] for a review).

We use auditory lexical decision with auditory priming to test whether a disyllabic word undergoing tone sandhi on the first syllable is primed by a monosyllable sharing the base tone or the sandhi tone of the first syllable. By comparing the priming behavior of disyllables undergoing transparent and opaque sandhis, we can see whether the two types of sandhis are processed differently in spoken word recognition as predicted by our nonce-probe test results.

3.1. Taiwanese

We start with the priming study of two of the sandhi patterns in Taiwanese, 51 → 55 and 24 → 33, reported in [46]. Recall that both sandhi patterns are opaque, but 24 → 33 can potentially be motivated by a phonotactic generalization. Eighteen words undergoing each of these sandhis were used as targets (e.g., /pij⁵¹-tsun²⁴/ 翻船 ‘to capsize a boat’). Each target was preceded by three types of monosyllabic primes by 250ms in a Latin-square design: underlying prime (e.g., /pij⁵¹/ 翻 ‘to capsize’), surface prime (e.g., /pij⁵⁵/ 冰 ‘ice’), and control prime (e.g., /pij²¹/ 併 ‘to combine’). Sixty filler words and ninety-six nonwords with a balanced mixture of tones and prime types were also included in the experiment. The participants needed to judge whether the disyllable is a word or not in Taiwanese as quickly and as accurately as possible upon hearing the prime and the target. Thirty-six native Taiwanese listeners in the age range of 30-55 participated in the experiment in Taiwan.

The logged reaction times (logRT) for the correct responses, trimmed to exclude those falling outside two standard deviations from the mean for each participant, were analyzed using Linear Mixed-Effects models with sandhi type and prime type as fixed effects and participant and item as random effects.

The logRT results are shown in Figure 7. A significant interaction between sandhi type and prime type motivated separate analyses for 51 → 55 and 24 → 33. For 51 → 55,

only the surface primes elicited significant facilitation compared to the control primes ($\beta=-.030$, $SE=.007$, $t=-4.45$, $p<.001$), while the underlying primes did not ($\beta=-.011$, $SE=.007$, $t=-1.66$, $p=.097$). For 24 → 33, however, both the underlying and the surface primes elicited significant priming (underlying primes: $\beta=-.036$, $SE=.006$, $t=-5.68$, $p<.001$; surface primes: $\beta=-.023$, $SE=.006$, $t=-3.65$, $p<.001$).

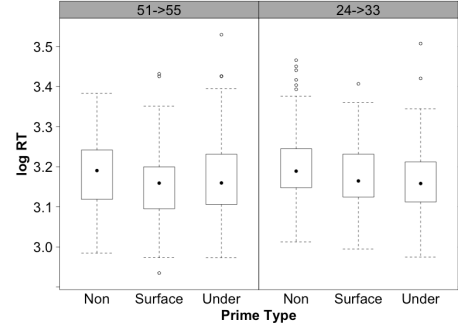


Figure 7: *LogRT results for disyllables undergoing the 51 → 55 and 24 → 33 sandhis in Taiwanese, separated by the underlying prime (Under), surface prime (Surface) and control prime (Non) conditions.*

3.2. Mandarin

We then discuss a priming study of the tonally-triggered transparent T3 sandhi in Mandarin, reported in [47]. Thirty disyllabic T3 sandhi words were used as targets, and in a Latin-square design, each target was preceded by an underlying (T3) prime, a surface (T2) prime, or a control prime, all of which shared the same segments with the first syllable of the word. Sixty filler words and ninety nonwords with a balanced mixture of tones and prime types were also included in the experiment. Thirty-three native Taiwan Mandarin listeners participated in the experiment in Taiwan.

The logRT results, given in Figure 8, showed that only the underlying primes elicited significant facilitation compared to the control primes ($\beta=-.030$, $SE=.005$, $t=-6.36$, $p<.001$), while the surface primes did not ($\beta=-.0005$, $SE=.005$, $t=-.10$, $p=.920$).

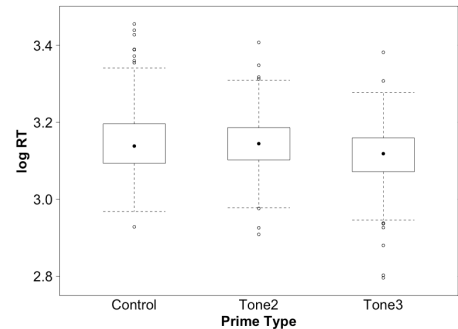


Figure 8: *LogRT results for T3 sandhi words in Mandarin, separated by the underlying prime (T3), surface prime (T2) and control prime conditions.*

3.3. Hailu Hakka

Finally, we discuss a priming study of the positionally-triggered transparent sandhi 13 → 33 / __ X in Hailu Hakka reported in [44]. Twenty disyllabic 13-X words were used as targets, and in a Latin-square design, each target was preceded by four types of monosyllabic primes, the first three of which shared the same segments as the first syllable of the word: underlying prime (13), surface prime (33), segmental prime (a tone other than 13 or 33), and unrelated prime (different

syllable from the first syllable with a tone other than 13 or 33). Eighty filler words and one hundred nonwords with a balanced mixture of tones and prime types were also included in the experiment. Thirty-two native Hailu Hakka listeners participated in the experiment in Hsinchu, Taiwan.

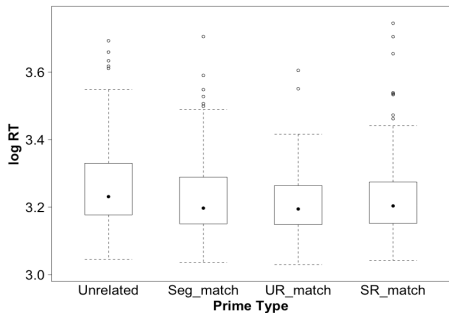


Figure 9: LogRT results for the 13 → 33 sandhi words in Hailu Hakka, separated by the underlying prime (UR_match), surface prime (SR_match), segmental prime (Seg_match), and unrelated prime conditions.

The logRT results, given in Figure 9, showed that, compared to the unrelated primes, all prime types that shared the same segments as the first syllable of the words elicited significant priming, a finding consistent with earlier literature (e.g., [48]). But compared to the segmental primes, only the underlying primes elicited faster reaction time ($\beta=-.003$, $SE=.010$, $t=-2.602$, $p=.0096$), while the surface primes did not ($\beta=-.011$, $SE=.010$, $t=-1.072$, $p=.284$). As the segmental primes in Hailu Hakka correspond to the control primes in the Taiwanese and Mandarin experiments, the results here are similar to the Mandarin results, but different from the Taiwanese results.

3.4. Discussion

The results of the auditory priming experiments in Taiwanese, Mandarin, and Hailu Hakka show that a word undergoing a transparent tone sandhi (Mandarin, Hailu Hakka) is consistently primed by a syllable carrying the base tone, a word undergoing an opaque tone sandhi with a potential phonotactic motivation (Taiwanese 24 → 33) can be primed by either the base tone or the sandhi tone, and a word undergoing an opaque tone sandhi without phonotactic motivation is only primed by the sandhi tone. These results match the productivity gradation that we observed in the nonce-probe tests and provide converging evidence that transparent tone sandhis involve productive phonological processes from the base tone, while opaque sandhis involve allomorph listings of existing morphemes and syllables.

4. General Discussion

The nonce-probe and auditory priming studies summarized here indicate that opaque tone sandhis are not internalized in the same way as transparent tone sandhis by native speakers. This has significant consequences on how we should construct the synchronic analyses of these patterns as analysts. Take the Wuxi pattern as an example: the transparent spreading aspect of the sandhi can potentially be accounted for by the interaction between markedness constraints such as *TONE, *CONTOUR and faithfulness constraints such as MAX(Tone) and FAITH-ALIGN (which penalizes spreading, see [4]), but the opaque aspect of the sandhi needs to be encoded with listed sandhi tones on various levels of representation (e.g., syllable, morpheme, word) and constraints that force the listed forms to be used [49]. An implementation of this, which allows both

the lexical patterns and the experimental results to be modeled, can be found in [42]. Other works that appeal to listedness to account for opaque tone sandhi patterns include [37] and [38].

We can only speculate on how the opaque and other phonetically arbitrary tone sandhi patterns arise diachronically and where they might be going. But dialectal comparisons may provide some clues. The pattern substitution sandhi in Wuxi, for instance, may have resulted from a diachronic shift from right-dominant sandhi, a commonly attested pattern in Southern Wu dialects, where the tone on the initial syllable was paradigmatically substituted, to left-dominant sandhi, where the substituted tone is subsequently spread rightward [6][14]. On the other hand, Wuxi has been reported to have pattern extension sandhi as well in limited grammatical contexts [6], and a comparison between cognate tones in Wuxi and Shanghai indicates that Shanghai has simply extended the application of pattern extension to all phonological words. Finally, Shanghai has also been reported to have the substitution pattern [5]; words undergoing substitution were typically described as exceptions to the general spreading pattern, and these words have become increasingly rare in our experience working with younger Shanghai speakers. These observations are consistent with our results that pattern extension is more productive than pattern substitution.

5. Conclusions

The complex, often phonetically arbitrary patterns of tone sandhi are the results of stages of diachronic change, much of which we are still yet to understand. What I hope to have shown here is that the study of tone sandhi can benefit greatly from experimental investigations that more directly tap into the speakers' knowledge that they use in linguistic tasks such as forming new words and recognizing spoken words. While I have only focused on one extreme case of phonetic arbitrariness (opacity) and two experimental methods in this paper, it is certainly my hope that the scope of the investigation can be extended to other potential sources of overlearning and underlearning and other psycholinguistic and neurolinguistic methods (e.g., [50][51][52][53]). This type of data can potentially provide a more accurate window into how the speakers internalize the patterns they are exposed to than the descriptive patterns themselves. By getting the right data, we move one step closer to understanding the nature of the tonal grammar, in particular, in recognizing that building a synchronic analysis for tone sandhi systems is still difficult, but perhaps difficult in a different way from what we originally envisioned: what we need more is likely not additional formal machineries that allow all tone sandhi patterns, phonetically arbitrary or not, to be derived as base-tone ~ sandhi-tone mappings, but a quantitative and flexible model that allows us to reconcile the experimental results with the lexical patterns, and in the meantime, capture the variability and gradience observed in the data.

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