Phonetically Identical Forms can Have Different Phonological Behaviors

Naiyan Du
Michigan State University

1 Introduction

Since at least the mid-1980s, the effect of incomplete neutralization has been documented in a variety of languages including Catalan (Dinnsen & Charles-Luce, 1984), Dutch (Warner et al., 2004), Japanese (Braver & Kawahara, 2016), Polish (Slowiaczek & Dinnsen, 1985; Slowiaczek & Szymanska, 1989) and Russian (Dmitrieva, 2005; Kharlamov, 2012; Matsui, 2015). For example, in German it is traditionally described that the phonological voicing contrast for obstruents is neutralized in syllable-final positions (Jespersen, 1913; Trubetzkoy, 1939; Wiese, 2000; Zifonun et al., 1997). The phonological rule is stated in (1). However, careful phonetic and perceptual examinations (Port & O'Dell, 1985; Roettger et al., 2014; inter alia) have shown that the neutralization is incomplete phonetically. In other words, underlying voiceless stops, derived voiceless stops and underlying voiced stops all have unique phonetic forms.

(1) [-sonorant] → [-voice]/ ____#

Note: # indicates the syllable boundary.

It is difficult to reconcile the observed effect of incomplete neutralization with the traditional formal phonology where categorical phonological representation and modular feed-forward model are assumed (Bermúdez-Otero, 2007; Chomsky & Halle, 1968; Keating, 1996, Pierrehumbert, 2002). Under such a framework, the phonological representations are discrete elements that does not contain any gradient phonetic information, and phonetics only have access to the output of phonology. As a result, underlying features that undergo phonological neutralization process should disappear completely in surface representations and in phonetics. However, in the case of German final devoicing, it seems that the [+voice] feature in the underlying representation still plays a role in phonetics to create an intermediate status of "semi-voiced".

One solution that is gaining increasing attention to the puzzle posted by incomplete neutralization is to introduce gradience into phonology (McCollum, 2019). Under such a theory, the assumption of categorical phonological representation in traditional formal phonology is completely dropped, and fine-grained gradient information is allowed inside phonology. Although a consensus has not been reached by previous studies (Lionnet, 2017; Pierrehumbert et al., 2000; Silverman, 2006; Tucker & Warner, 2010; inter alia) on how to incorporate gradience inside formal phonology, as McCollum (2019) pointed out, at least some form of continuously valued variables should be allowed. To apply this theory in German final devoicing, phonology should not only direct a underlyingly voiced segment to devoice, but also demand to what the degree the devoicing process should occur to distinguish the derived voiceless segment from its underlying counterpart.

Despite the fact that observed effect of incomplete neutralization can get a straightforward explanation by incorporating gradience into phonology, the proposed new theory also becomes much stronger and predicts much more possible grammars. To appreciate this statement, under traditional formal phonology, only one grammar is possible for final obstruent devoicing process like that in German, namely the [+voice] feature in the underlying representation should disappear completely in the surface. In contrast, under the proposed new theory of gradient phonology, an infinite number of grammars are possible, differentiating on the degree to which the devoicing is demanded to happen.

* I would like to thank Karthik Durvasula, Yen-Hwei Lin and audience of AMP 2021 for comments and feedbacks.

Proceedings of *AMP 2021*

However, in this paper, I argue that since phonetic reality does not have a corresponding relationship with phonological behavior, the observation of incomplete phonetic neutralization does not has any necessary implication on phonological behavior and does not by itself argue against categorical phonological representation.

I will provide two pieces of evidence from Huai'an Tone Sandhi process supporting my claim in this paper. First, I will show that the phonetic difference between derived Tone 3 and its underlying counterpart is compatible with their identical phonological behavior of triggering another tone sandhi process. The fact that the Tone 3 output of Tone 4 sandhi process can trigger Tone 3 sandhi process in Huai'an provides evidence that Tone 4 Sandhi process results in a complete neutralization in the phonology. Yet despite being clearly phonologically neutralized, I will show that there is incomplete neutralization in the phonetics for Tone 4 Sandhi process. So phonetic neutralization does not have to be complete for a complete phonological neutralization, which suggests categorical phonological neutralization processes are quite compatible with incomplete phonetic neutralization.

Second, I will show although there is almost no phonetic difference between derived Tone 3s from lexical Tone 4 Sandhi and post-lexical Tone 4 Sandhi, they have different phonological behaviors in the sense that post-lexically derived Tone 3 triggers Tone 3 Sandhi process at a higher rate across the boundary between subject and predicate than lexically derived Tone 3. Therefore, even the phonetic uniformity does not ensure identical phonological behavior.

For the rest of this paper, I will elaborate the feeding order of two tone sandhi processes in Huai'an at both lexical and post-lexical levels in Section 2 with more background information. Section 3 will present the experiment in Huai'an. And Section 4 will be a short discussion.

2 Background

Huai'an has four phonemic tones, labelled as Tone 1, Tone 2, Tone 3 and Tone 4. Following the tradition of tone description in Chinese languages, in Table 1, the four tones are given in tone letters (Chao, 1930) in a scale of 1 to 5 where 1 is the lowest pitch and 5 is the highest pitch and followed by a contour description in words.

Phonemic Tone	Tone Letter	Contour Description
Tone 1	42	high falling
Tone 2	24	high rising
Tone 3	212	low/low rising
Tone 4	55	high level

Table 1: Descriptions of Phonetic Tones in Huai'an

For the rest of the paper, to make it easier on the reader, I will only use the T plus tone number in examples to refer to tones. For example, "T3" refers to Tone 3.

The 3 tone sandhi rules that are related to the current paper as show (2):

(2) Two Tone Sandhi Rules in Huai'an

T3 + T3 → T2 + T3

T4 + T4 → T3 + T4

Note: both tone sandhi processes are optional in Huai'an.

Crucially, the Tone 3 output of tone 4 sandhi patterns at both lexical and post-lexical levels can feed into the low-register tone sandhi process. Examples are shown in (3):

(3) Feeding Order in Huai’an Mandarin

a.

o	pa-tsæ̃
1sg	forcibly occupy
$[DP[VP]]_{TP}$	
“I forcibly occupy (something).”	
UR	T3 T4 T4
SR1	T2 T3 T4
SR2	T3 T3 T4
SR3	T3 T4 T4

b.

o	to	ʐəɯ
1sg	chop	meat
$[DP[V[DP]_{VP}]]_{TP}$		
“I chop meat.”		
UR	T3 T4 T4	
SR1	T2 T3 T4	
SR2	T3 T3 T4	
SR3	T3 T4 T4	

In (3)a, the last two syllables form a single word and the combine with the monosyllabic subject to become a sentence. Therefore the Tone 3 is derived at lexical level. While in (3)b, each syllable forms a separate word by itself, so the Tone 3 is clearly derived at post-lexical level. The wordhood of the last two syllables in (3)a is confirmed by the test of Conjunction Reduction (Huang, 1984). Conjunction Reduction is argued by Huang to apply to coordinated phrases but not to coordinated words in both English and Chinese languages. To give an example in English, it is grammatical to say “I love mom and dad”, but it is ungrammatical to say “New York and Orleans” to mean the city New York and the city of New Orleans. To apply this test in Huai’an, for the two examples in (3), it is possible to apply Conjunction Reduction for (3)b, as shown in (4)a. But it is not possible to apply to (3)a, as shown in (4)b. Although both [pa-tsæ̃] and [pa-lɪn] are words, it is not possible to extract their common part and conjunct the left.

(4) a.

o	to	ʐəɯ	hu	tsʰæ̃
1sg	chop	meat	and	vegetables

“I chop meat and vegetables”

b.

*o	pa	tsæ̃	hu	lɪn
1sg	forcibly	occupy	and	bully

Intended: “I forcibly occupy and bully.”

The feeding order suggests that Tone 4 Sandhi results in a Tone 3 category that is phonologically the same as an underlying Tone 3. Despite the categorical phonological behavior of the derived Tone 3 in Huai’an, For the next section, I will show that there is incomplete phonetic neutralization of derived Tone 3 and underlying Tone 3 at both lexical and post-lexical levels. In addition, I will show that although lexically derived Tone 3 is almost phonetically the same with post-lexically derived Tone 3, they trigger the Tone 3 Sandhi across the boundary between subject and predicate at different rates.

3 The Experiment

3.1 *Participants* I recruited 4 native speakers of Huai'an Mandarin by personal relations in Huai’an City. The age range is from 53 to 58 years old. Among them, 1 is female and 3 are male. All the participants are born and raised in Huai'an City.

3.2 *Stimuli* The stimuli are first divided into two groups. Group 1 is composed tri-syllabic sentences with monosyllabic subject and a disyllabic verb like that in (3)a and Group 2 is composed of tri-syllabic sentences with each syllable forming a separate word like that in (3)b. Each group is further divided into three sets as shown in (5):

(5) Three Sets of Stimuli in the Experiment

Underlying T3: /T3 T3 T4/ → [T2 T3 T4]

Derived T3: /T3 T4 T4/ → [T2 T3 T4] or [T3 T3 T4] or [T3 T4 T4]

Underlying T4: /T2 T4 T4/ → [T2 T3 T4] or [T2 T4 T4]

The rightmost syllables are always Tone 4. The middle syllables can be underlyingly Tone 4 that can optionally undergo Tone 4 Sandhi to become Tone 3 or underlyingly Tone 3 that cannot undergo any tone sandhi in this context. The first syllables can be underlyingly Tone 3 that can undergo Tone 3 Sandhi to become Tone 2 with reference to the middle syllables which are derived Tone 3 from Tone 4 or underlyingly Tone 3, the first syllable can also be underlyingly Tone 2 that does not undergo any tone sandhi in Huai'an. The crucial second syllable is only composed of Stop plus Vowel, which makes it easy to annotate the vowel and measure the pitch. Inside one set, the stimuli are differentiated by tones and are largely identical in segments, the only place segments may vary is the Place of Articulation of the second syllable or the third syllable but never manner of articulation of any syllables, which minimizes the influence of the variation on the measurements of pitch. The full stimuli list is summarized in the Appendix.

Each participant produced 4 repetitions of 40 test sentences at natural speech rate with 8 fillers, which means the total number of utterances a participant has read is 192.

3.3 *Procedure* Each participant was recorded by a trained research assistant in a quiet room that was either located in the participants' home or workplace using audacity (version 2.3.2) and a Popu Line BK USB microphone on a Lenovo laptop. The participants were instructed to read under normal rate using their everyday voice. The participants were also encouraged to read through the stimuli list to be familiar with the reading materials before producing them.

3.4 *Measurement* The recordings were also manually annotated by the author. An example is shown in Figure 1:

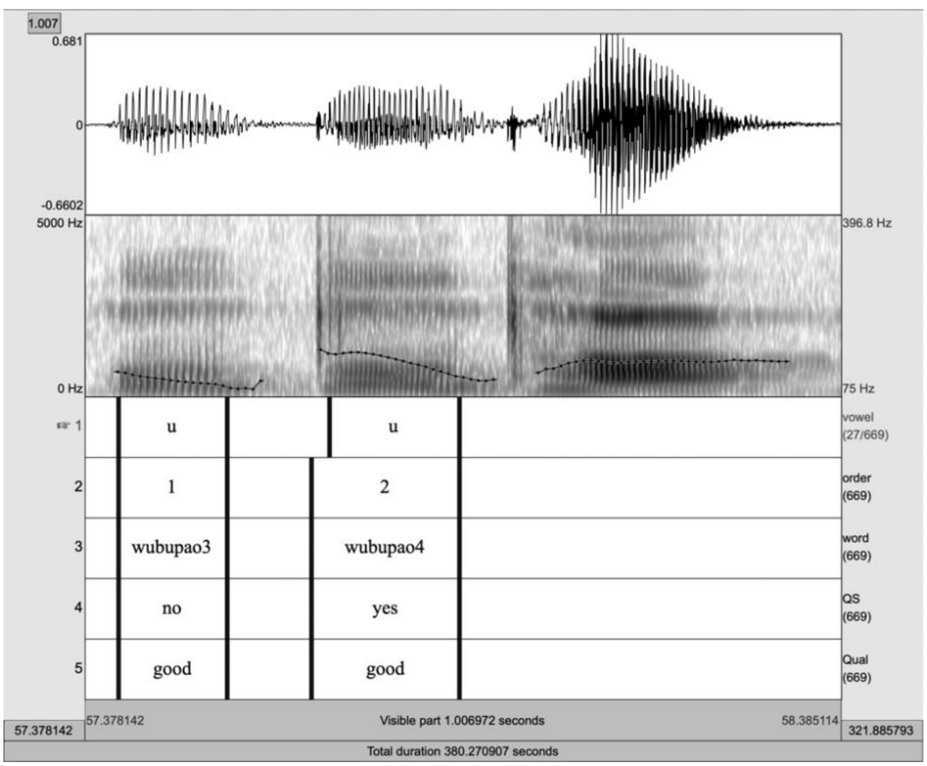

Figure 1: Annotation of Experiment (Tone 4)

The annotation file has five tiers in total. The first tier marks the quality of the vowel of the current syllables, the second tier indicates the position of the current syllables inside the utterances where a first syllable is marked '1' and a middle syllable is marked '2', the third tier contains the pinyin of the whole utterance and the underlying tone of the current syllables. The forth tier is whether the current syllables undergo tone sandhi. And the last tier indicates the quality of the recording on the current utterance. I only use productions of recordings that are marked 'good' like in the previous experiment. Pitch was extracted at

5% steps (20 steps in total) with a script in Praat (Boersma & Weenink, 2021), and pitch contour is drawn in R (R Core Team, 2021) using 'smooth' method in ggplot2 (Wickham, 2016).

3.5 *Result* I first show here that the Tone 4 Sandhi at both lexical and post-lexical levels are in fact phonetically incomplete despite that derived Tone 3 from Tone 4 Sandhi can trigger Tone 3 Sandhi.

The pitch contours of Group 1 (lexical level) and Group 2 (post-lexical level) are shown side by side in Figure 2 and Figure 3. In both figures, lexical data is to the left and post-lexical data is to the right. Figure 2 depicts the contours of raw pitch while Figure 3 depicts contour of z-score transformed pitch. In each plot, the rectangle line represents the contours of underlying Tone 4, the circle line represents underlying Tone 3 and the triangle line represents derived Tone 3. Based on visual inspection of the data, the three-way comparison among the contours of Underlying Tone 3, Derived Tone 3 and Underlying Tone 4 again clearly shows that the incomplete neutralization in pitch contour was quite large in all plots in Figure 2 and Figure 3.

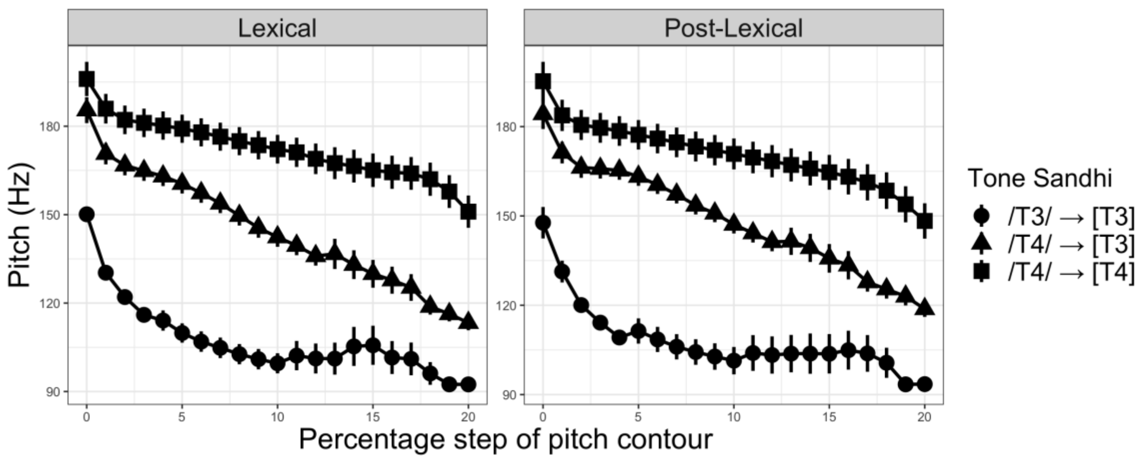

Figure 2: Side-by-Side Contours Comparison (Raw Pitch)

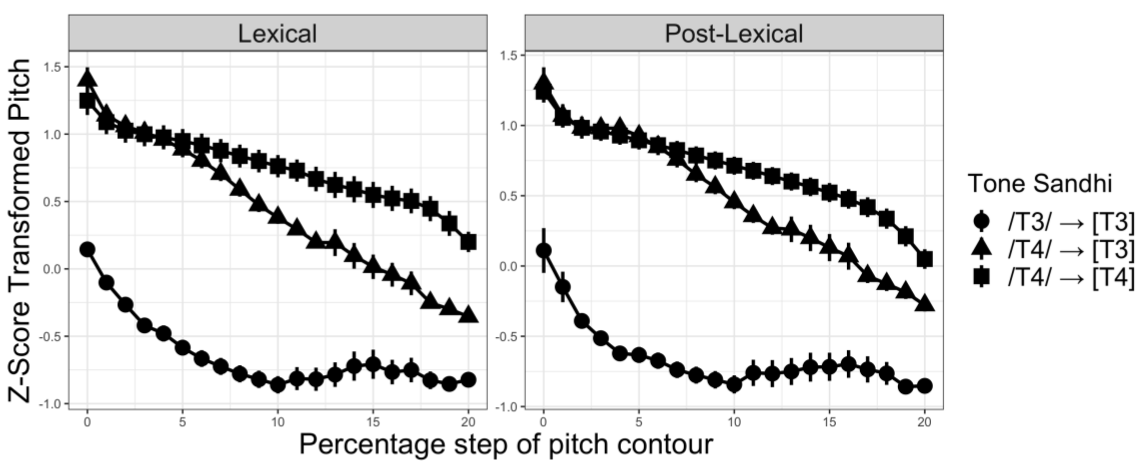

Figure 3: Side-by-Side Contours Comparison (Z-Score Transformed)

To confirm the description, simple linear regression is run on the means of last three steps of the contours, the results are shown from Table 2 to Table 5. Table 2 and Table 3 correspond to the two plots in Figure 2 where Table 2 shows the result of lexical level and Table 3 shows the result of post-lexical level. Table 4 and Table 5 correspond to the two plots in Figure 3 where Table 4 shows the result of lexical level and Table 5 shows the result of post-lexical level. All p values in these tables are much smaller than 0.05, which suggests that Underlying Tone 4, Derived Tone 3 and Underlying Tone 3 are significantly different at the tonal offset position.

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
/T4/ → [T3]	116.52	3.64		
/T3/ → [T3]	-19.97	4.92	-6.58	2.42e-10
/T4/ → [T4]	40.85	6.20	6.32	1.05e-09

Table 2: Linear Regression of Lexical Level (Raw Pitch)

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
/T4/ → [T3]	112.50	4.45		
/T3/ → [T3]	31.07	7.81	3.98	8.83e-05
/T4/ → [T4]	-21.69	6.02	-3.60	0.00037

Table 3: Linear Regression of Post-Lexical Level (Raw Pitch)

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
/T4/ → [T3]	-0.31	0.06		
/T3/ → [T3]	-0.52	0.08	-6.58	2.42e-10
/T4/ → [T4]	0.63	0.10	6.32	1.05e-09

Table 4: Linear Regression of Lexical Level (Z-Score Transformed Pitch)

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
/T4/ → [T3]	-0.20	0.07		
/T3/ → [T3]	0.41	0.12	3.37	0.000871
/T4/ → [T4]	-0.56	0.09	-6.00	5.99e-09

Table 5: Linear Regression of Post-Lexical Level (Z-Score Transformed Pitch)

Second, I show that despite no significant phonetic difference between lexically derived Tone 3 and post-lexically derived Tone 3, their phonological behavior are different in the sense that their abilities of triggering Tone 3 Sandhi across the boundary between subject and predicate are different.

The contours of underlying Tone 4, derived Tone 3 and underlying Tone 4 at lexical and post-lexical levels are placed on top of each other and differentiated by shape in Figure 4 and Figure 5. In each figure, the circle contours are at lexical level and the triangle contours are at post-lexical level. So Figure 4 (raw pitch) is built by making the left plot in Figure 2 all circle and right plot all triangle and place them on top of each other. Figure 5 (z-score transformed pitch) is made out of Figure 3 with the same idea.

In both Figure 4 and Figure 5, the tonal contours at lexical level are highly similar to their counterparts of post-lexical level despite the observation that the degree of neutralization at post-lexical level is slightly smaller than that of lexical level. The difference between underlying Tone 4 and derived Tone 3 at post-lexical level is slightly smaller than that at lexical level. When measured in raw pitch, the difference at lexical level is only 9 Hz larger than that at post-lexical level.

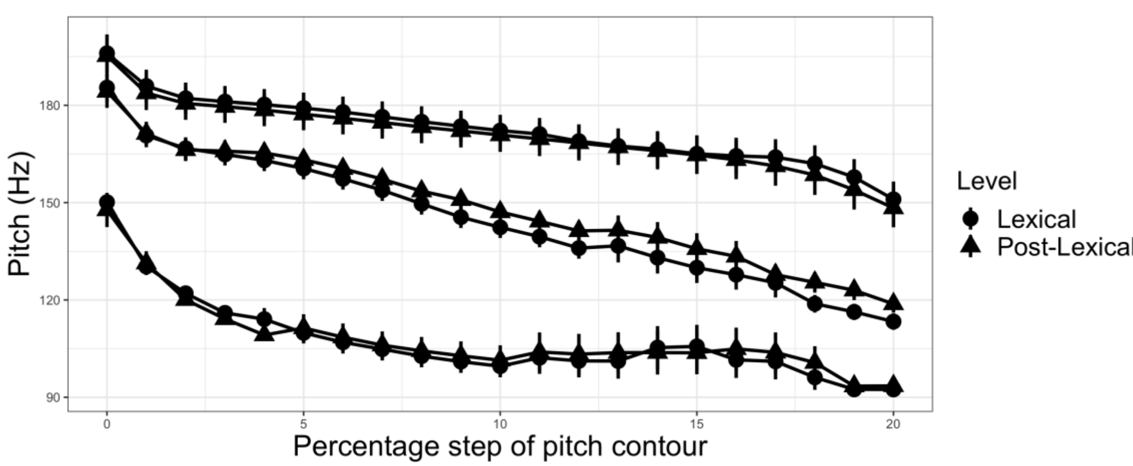

Figure 4: On-Top Contours Comparison (Raw Pitch)

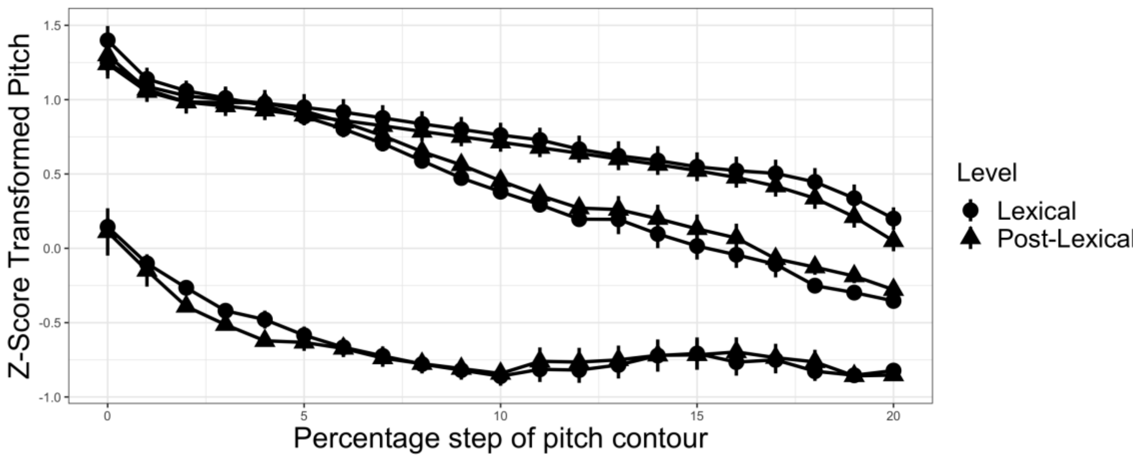

Figure 5: On-Top Contours Comparison (Z-Score Transformed Pitch)

The similarity of derived Tone 3s at lexical and post-lexical levels is also confirmed by simple linear regression. The result on raw pitch is shown in Table 6, and the result on z-score transformed pitch is shown in Table 7. The p value for z-score transformed pitch is 0.09, which may be considered to be marginally significant, suggesting that the degree of neutralization at post-lexical level is smaller than that at lexical level.

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
Lexical	116.52	2.83		
Post-Lexical	5.98	3.96	1.51	0.13

Table 6: Linear Regression of Different Levels (Raw Pitch)

Coefficients	Estimate	Standard Error	t value	Pr(>|t|)
Lexical	-0.31	0.04		
Post-Lexical	0.10	0.06	1.69	0.09

Table 7: Linear Regression of Different Levels (Z-Score Transformed Pitch)

Although there is no significant phonetic difference between derived Tone 3 contours at lexical and post-lexical levels or the degree of incomplete neutralization may even be smaller than at post-lexical level than lexical level, post-lexically derived Tone 3 has a higher rate of triggering Tone 3 Sandhi across the boundary between subject and predicate than lexically derived Tone 3, which suggests that post-lexically derived Tone 3 behaves phonologically more like a underlying Tone 3 than lexically derived Tone 3. The triggering rates data are shown in Table 8.

Tone Condition	Level	Triggered/Total	Triggering Rate
Derived Tone 3	lexical	13/64	20.31%
Derived Tone 3	Post-Lexical	21/66	31.82%
Underlying Tone 3	lexical	86/91	94.51%
Underlying Tone 3	Post-Lexical	77/78	98.72%

Table 8: Abilities of Different Tones Triggering Tone 3 Sandhi

4 Conclusion

To repeat, there are two findings of the current paper, I will review and offer explanation to them separately for this section.

The first finding is that the phonetic difference between derived Tone 3 and its underlying counterpart is compatible with their identical phonological behavior of triggering another tone sandhi process, which means phonetic neutralization does not have to be complete for complete phonological neutralization. The explanation that the author prefers right now is the co-activation of lexical items proposed by Ernestus and

Baayen (2006). Based on emerging evidence that the lexical information contains fine-grained phonetic information (Brown & McNeill, 1966; Bybee, 1994; Goldinger, 1996, 1997; Palmeri et al., 1993; Pisoni, 1997), Erunetus and Baayen argue that incomplete neutralization is caused by co-activation by related lexical items. In Huai'an, since Tone 4 sandhi is an optional rule in the first place, for a disyllabic word composed of two Tone 4 syllables, two surface representations are possible, namely Tone 3 plus Tone 4 and Tone 4 plus Tone 4. It is possible that these two forms are activated simultaneously in the phonology-phonetics interface and an intermediate derived Tone 3 is created.

The second finding is that although there is almost no phonetic difference between derived Tone 3s from lexical Tone 4 Sandhi and post-lexical Tone 4 Sandhi, they have different phonological behaviors in the sense that post-lexically derived Tone 3 triggers Tone 3 Sandhi process at a higher rate across the boundary between subject and predicate than lexically derived Tone 3. The tentative explanation lies on Duanmu's proposal (2007) on the interaction between stress and tone sandhi domain. Duanmu proposes that tone sandhi domain may be built according to the position of stresses in Mandarin languages. Since Mandarin languages are trochaic, a disyllabic word may induce a stress on the first syllable in Huai'an. Therefore, for the trisyllabic stimuli used in the experiment, the second syllable may carry a stress when the last two syllables form a word. Then tone sandhi domain tends to group the stressed syllable and the following unstressed syllable together according to Duanmu, which may leave the first syllable unparsed. Under such a situation, there is no way for the second syllable to trigger Tone 3 Sandhi on the first syllable.

For future, I will of course need to increase the statistical power of the experiment with more speakers so that the results can be convincing. I also need to think about why different phonetic cues neutralize differently in the case of Huai'an Tone 4 Sandhi.

5 Appendix: Stimuli of the Experiment

Group 1: Lexical Level

IPA	pinyin	UR	SR	vowel	type
u pɛ su	wugaishu	244	244/234	ɛ	UR as T4
u pɔ suŋ	wubaosong	244	244/234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	244	244/234	ɛ	UR as T4
u kɔ fu	wugaofu	244	244/234	ɔ	UR as T4
u pa tsæ̃	wubazhan	244	244/234	a	UR as T4
u kɛ su	wubaishu	344	344/334/234	ɛ	UR as T4
u pɔ suŋ	wubaosong	344	344/334/234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	344	344/334/234	ɛ	UR as T4
u kɔ fu	wugaofu	344	344/334/234	ɔ	UR as T4
u pa tsæ̃	wubazhan	344	344/334/234	a	UR as T4
u kɛ su	wugaishu	234	234	ɛ	UR as T4
u pɔ suŋ	wubaosong	234	234	ɔ	UR as T4
u kɛ tɕĩ	wugaijian	234	234	ɛ	UR as T4
u pɔ xu	wubaohu	234	234	ɔ	UR as T4
u ta tsæ̃	wudazhang	234	234	a	UR as T4
u kɛ su	wugaishu	334	234	ɛ	UR as T4
u pɔ suŋ	wubaosong	334	234	ɔ	UR as T4

u kɛ tɕĩ	wugaijian	334	234	ɛ	UR as T4
u pɔ xu	wubaohu	334	234	ɔ	UR as T4
u ta tsæ̃	wudazhang	334	234	a	UR as T4

Group 2: Post-Lexical Level

IPA	pinyin	UR	SR	vowel	type
u tɛ su	wugaisu	244	244/234	ɛ	UR as T4
u pɔ suŋ	wubaosong	244	244/234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	244	244/234	ɛ	UR as T4
u kɔ fu	wugaofu	244	244/234	ɔ	UR as T4
u pa tsæ̃	wubazhan	244	244/234	a	UR as T4
u tɛ su	wugaisu	344	344/334/234	ɛ	UR as T4
u pɔ suŋ	wubaosong	344	344/334/234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	344	344/334/234	ɛ	UR as T4
u kɔ fu	wugaofu	344	344/334/234	ɔ	UR as T4
u pa tsæ̃	wubazhan	344	344/334/234	a	UR as T4
u kɛ su	wugaisu	234	234	ɛ	UR as T4
u pɔ suŋ	wubaosong	234	234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	234	234	ɛ	UR as T4
u kɔ fu	wugaofu	234	234	ɔ	UR as T4
u ta fæ̃	wudafan	234	234	a	UR as T4
u kɛ su	wugaisu	334	234	ɛ	UR as T4
u pɔ suŋ	wubaosong	334	234	ɔ	UR as T4
u tɛ tɕĩ	wudaijian	334	234	ɛ	UR as T4
u kɔ fu	wugaofu	334	234	ɔ	UR as T4
u ta fæ̃	wudafan	334	234	a	UR as T4

References

Bermúdez-Otero, Ricardo. 2007. Diachronic phonology. In Paul de Lacy (Eds.), *The Cambridge handbook of phonology*. 497–517. Cambridge: Cambridge University Press.

Boersma, Paul, & David Weenink. 2021. Praat: doing phonetics by computer [Computer program]. Version 6.1.41, retrieved 25 March 2021 from http://www.praat.org/.

Braver, Aaron, & Shigeto Kawahara. 2016. Incomplete neutralization in Japanese monomoraic lengthening. *Proceedings of the Annual Meetings on Phonology*, *2*.

Brown, Roger, & David McNeill. 1966. The "tip of the tongue" phenomenon. *Journal of Verbal Learning and Verbal Behavior*, *5*(4), 325–337.

Bybee, Joan L. 1994. A view of phonology from a cognitive and functional perspective. *Cognitive Linguistics*, *5*(4), 285–305.

Chomsky, Noam, & Morris Halle. 1968. *The sound pattern of English*. New York: Harper and Row.

Dinnsen, Daniel A., & Jan Charles-Luce. 1984. Phonological neutralization, phonetic implementation and individual differences. *Journal of Phonetics*, *12*(1), 49–60.

Dmitrieva, Olga. 2005. *Incomplete neutralization in Russian final devoicing: Acoustic evidence from native speakers and second language learners* [PhD Thesis]. University of Kansas, Linguistics.

Duanmu, San. 2007. *The phonology of standard Chinese*. OUP Oxford.

Ernestus, Mirjam, & Harald Baayen. 2009. The functionality of incomplete neutralization in Dutch: The case of the past-tense formation. *Laboratory phonology 8*, 27–50. De Gruyter Mouton.

Goldinger, Stephen D. 1996. Words and voices: Episodic traces in spoken word identification and recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(5), 1166–1183.

Goldinger, Stephen D. 1997. Words and voices: perception and production in an episodic lexicon. In Keith Johnson & John W. Mullennix (Eds.), *Talker variability in speech processing*, 33–66. San Diego, CA: Academic Press.

Huang, C.-T. James. 1984. Phrase structure, lexical integrity, and Chinese compounds. *Journal of the Chinese Language Teachers Association*, *19*(2), 53–78.

Jespersen, Otto. 1913. *Lehrbuch der phonetik*. BG Teubner.

Keating, Patricia A. 1996. The phonology-phonetics interface. In Ursula Kleinhenz (Eds.), *Interfaces in phonology*. 262–278. Berlin: Akademie-Verlag.

Kharlamov, Viktor. 2012. *Incomplete neutralization and task effects in experimentally-elicited speech: Evidence from the production and perception of word-final devoicing in Russian* [PhD Thesis]. Université d'Ottawa/University of Ottawa.

Lionnet, Florian. 2017. A theory of subfeatural representations: The case of rounding harmony in Laal. *Phonology*, *34*(3), 523–564.

Matsui, Mayuki. 2015. *Roshiago ni okeru yuuseisei no tairitsu to tairitsu no jakka: Onkyo to chikaku.[Voicing contrast and contrast reduction in Russian: Acoustics and perception]* [PhD Thesis]. Doctoral dissertation, Hiroshima University.

McCollum, Adam. 2019. Gradient morphophonology: Evidence from Uyghur vowel harmony. *Proceedings of the Annual Meetings on Phonology*, *7*.

Palmeri, Thomas. J., Stephen D. Goldinger, & David B. Pisoni. 1993. Episodic encoding of voice attributes and recognition memory for spoken words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(2), 309–328.

Pierrehumbert, Janet B. 2002. Word-specific phonetics In *Laboratory Phonology VII*, 101–139. Berlin: Mouton de Gruyter.

Pierrehumbert, Janet B., Mary E. Beckman, & D. Robert Ladd. 2000. Conceptual foundations of phonology as a laboratory science. *Phonological Knowledge: Conceptual and Empirical Issues*, 273–304.

Pisoni, David B. 1997. Some thoughts on 'normalization'in speech perception. In Keith Johnson & John W. Mullennix (Eds.), *Talker variability in speech processing*, 9–32. New York: Academic Press.

Port, Robert F., & Michael L. O'Dell. 1985. Neutralization of syllable-final voicing in German. *Journal of Phonetics*, *13*(4), 455–471.

R Core Team. (2021). R: A language and environment for statistical computing. [Computer program] Version 1.4.1106, retrieved 25 March 2021 from https://www.rstudio.com.

Roettger, Timo B., Bodo Winter, Sven Grawunder, James Kirby, & Martine Grice. 2014. Assessing incomplete neutralization of final devoicing in German. *Journal of Phonetics*, *43*, 11–25.

Silverman, Daniel. 2006. *A critical introduction to phonology: Of sound, mind, and body*. A&C Black.

Slowiaczek, Louisa M., & Daniel A. Dinnsen. 1985. On the neutralizing status of Polish word-final devoicing. *Journal of Phonetics*, *13*(3), 325–341.

Slowiaczek, Louisa M., & Helena J. Szymanska. 1989. Perception of word-final devoicing in Polish. *Journal of Phonetics*, *17*(3), 205–212.

Trubetzkoy, Nikolai. S. 2010. *Grundzüge der phonologie*. De Gruyter.

Tucker, Benjamin V., & Natasha Warner. 2010. What it means to be phonetic or phonological: The case of Romanian devoiced nasals. *Phonology*, *27*(2), 289–324.

Warner, Natasha, Allard Jongman, Joan Sereno, & Rachèl Kemps. 2004. Incomplete neutralization and other sub-phonemic durational differences in production and perception: Evidence from Dutch. *Journal of Phonetics*, *32*(2), 251–276.

Wiese, Richard. 2000. *The phonology of German*. Oxford University Press on Demand.

Wickham, Hadley. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. ISBN 978-3-319-24277-4, https://ggplot2.tidyverse.org.

Zifonun, Gisela, Ludger Hoffmann, Bruno Strecker, Ursula Brauße, & Joachim Ballweg. 1997. *Grammatik der deutschen Sprache* (Vol. 1). Walter de Gruyter.