What's in a word:
Observing the contribution of underlying and surface representations

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Abstract

Abstract underlying representations play a crucial role in capturing predictable relations among different phonetic categories in phonological theory. Tone sandhi is a tonal alternation phenomenon in which a tone changes to a different tone in certain phonological environments. This study investigates whether Taiwanese listeners are more sensitive to the surface form of the tones or the underlying tonal representations of tone sandhi words. An auditory lexical decision experiment was conducted to examine priming effects between monosyllabic primes and disyllabic target words (tone sandhi T51 → T55 and sandhi T24 → T33). Each target was preceded by either a surface-tone prime (e.g., ping55-ping55tsun24; pue33-pue33jong51), an underlying-tone prime (e.g., ping51-ping55tsun24; pue24-pue33jong51), or an unrelated control (e.g., ping21-ping55tsun24; pue21-pue33jong51). Results showed significant differences in the natue of the priming effects across the two sandhi types, with productivity of the tone sandhi rule influencing how listeners process and represent tone sandhi words.

Keywords

Priming

Tone sandhi

Underlying representation

Surface representation

Productivity

Introduction

Across different cognitive domains, comprehension is thought to involve categorization, requiring mapping from one or more continuous perceptual dimensions to a set of meaningful categories. Language comprehension is particularly well-suited to explore this mapping of how the brain represents concepts and the nature of the cognitive processes involved in retrieval of information. Indeed, phonological variation in the form of different phonetic shapes of words poses a challenge for theories of speech perception and language comprehension in general and requires an account of the way in which perceived surface forms are mapped onto putatively more abstract underlying representations.

During spoken word recognition, the acoustic input often does not match the corresponding stored representation in a straightforward fashion due to different factors such as coarticulation, gender, and speaking rate (Weber & Scharenborg, 2012). Variation due to phonological alternation has received much less attention in spoken word recognition. For example, the phoneme /t/ is typically unreleased in final position (e.g., note [noʊt̚]), aspirated in the initial position of a stressed syllable (e.g., no[t^h]ation), and realized as a voiced alveolar flap between a stressed and an unstressed vowel (e.g., no[ɾ]able). Tone sandhi is a phonological alternation phenomenon where a tone changes to another tone due to the influence of an adjacent tone (Cheng, 1968). In these cases, the surface form of a tone sandhi word differs from its underlying representation. The existence of such underlying representations has been a contested issue. One claim is that there are abstract underlying representations, which undergo various changes in order to generate surface forms that we actually hear. Given that there is an incomplete match between the surface representation and underlying representation, how tone sandhi words are represented and accessed in speakers' lexicon is of paramount importance for models of word recognition. The current study aims to investigate how speakers process tone sandhi words in order to understand the contribution of underlying representations and surface forms.

Two contrasting views concerning how tone sandhi words are represented in the mental lexicon have been proposed (Zhou & Marslen-Wilson, 1997). In Mandarin tone sandhi, a tone 3 changes to a tone 2 in the context of a tone 3 (T3 → T2/__T3). An underlying or canonical representation view states that tone sandhi words are represented as the concatenation of the citation forms of their constituent morphemes. Therefore, according to the underlying representation view, the Mandarin sandhi word [pɑw2 ɕjɛn3] "insurance", would be represented as /pɑw3 ɕjɛn3/ in Mandarin speakers' lexicon. On the other hand, a surface representation view posits that tone sandhi words are stored based on their surface form (represented as /pɑw2 ɕjɛn3/). Zhou and Marslen-Wilson's (1997) experimental research on the processing of tone sandhi in Mandarin produced conflicting results, showing inhibition for disyllabic primes with tone 2 on the first syllable preceding tone 3 sandhi targets (cohort competition for the surface form) as well as facilitation for disyllabic primes with tone 3 on the first syllable preceding tone 3 sandhi targets (morpheme activation for the underlying form). These data patterns were not consistent with either of the two views.

To further investigate how Mandarin tone 3 sandhi words are processed, Chien, Sereno and Zhang (2016) conducted an auditory-auditory priming lexical decision experiment. Each disyllabic Mandarin tone 3 sandhi target (e.g., /fu3 dao3/ 輔導, "to counsel") was preceded by one of three corresponding monosyllabic primes, namely, a tone 2 prime (e.g., /fu2/ 服, "to assist"), a tone 3 prime (e.g., /fu3/ 輔, "to guide"), or a control prime (e.g., /fu1/ 敷, "to put on"). Results showed that tone 3 primes (underlying form overlap with the first syllable of the tone 3 sandhi targets) facilitated participants' lexical decision responses, while tone 2 primes (surface form overlap with the first syllable of the tone 3 sandhi targets) did not show facilitation relative to the unrelated control primes. Moreover, these priming effects occurred regardless of the targets' word frequency. The frequency of the sandhi words did not affect the nature of the priming. Chien, Sereno and Zhang (2016) concluded that Mandarin tone 3 sandhi words are represented as /tone 3 tone 3/ in listeners' mental lexicon.

Further evidence for an underlying-tone lexical representation comes from production experiments that showed that the surface representation [tone 2 tone 3] of tone 3 sandhi words can be productively derived from the underlying representation /tone 3 tone 3/ via the tone 3 sandhi rule. Zhang and Lai (2010) asked Mandarin speakers to combine two isolated tone 3 monosyllables together and produce them as a disyllabic word, even though the combination is not an existing word of Mandarin. The F0 height and contour of the first syllable of the disyllables showed that Mandarin tone 3 sandhi applied without exception to the resulting combinations.

Tone sandhi in Taiwanese, a Southern Min dialect of Chinese, is more complex (Lin, 1994). For Taiwanese disyllabic words, tone sandhi is manifested in a circular chain-shift fashion in the non-phrasal final position for open syllables or syllables ending with a nasal coda, as shown in Figure 1. For the syllable 馬 /ma51/ "horse", the citation tone of the syllable changes from a high-falling tone (ma51) to a high-level tone (ma55) when it precedes another syllable (上 /sjoŋ33/). Thus, the surface form of this Taiwanese disyllabic sandhi word 馬上 /ma51 sjoŋ33/ "immediately" is [ma55 sjoŋ33].

$$\begin{tikzcd} {[55]} \arrow[r] & {[33]} \arrow[d] & {[24]} \arrow[l] \\ {[51]} \arrow[u] & {[21]} \arrow[l] \end{tikzcd}$$

Figure 1. Taiwanese tone sandhi circle

Zhang, Lai, and Sailor (2011) investigated the productivity of Taiwanese tone sandhi using a similar nonword probe test to the Mandarin study cited above. Their results showed that Taiwanese tone sandhi was not as productive as Mandarin tone 3 sandhi. While Taiwanese tone sandhi 24 → 33 elicited more complete application (around 80%), tone sandhi 51 → 55 yielded only 40 percent application. Zhang et al. (2011) suggested that the lower productivity for Taiwanese tone sandhi may be due to the phonologically opaque nature (Kiparsky, 1973) of Taiwanese tone sandhi (a circular chain shift). Zhang et al. (2011) further suggested that the reason why 51 → 55 is relatively less productive compared to 24 → 33 is due to phonotactic constraints: it is phonotactically legal for tone 51 to occur in the non-phrasal final position while it is illegal for tone 24 to occur in that position in Taiwanese (see Figure 1). The relatively unproductive nature of Taiwanese tone sandhi in novel words suggested that Taiwanese speakers may be less sensitive to tone sandhi rules.

Given the complexity of the sandhi patterns in Taiwanese, it is possible that Taiwanese speakers store the surface representations of tone sandhi words directly in their mental lexicon rather than deriving them from their underlying representations. The current study investigated how Taiwanese native speakers process tone sandhi words.

Methods

An auditory lexical decision priming experiment was conducted with monosyllabic primes and disyllabic Taiwanese tone sandhi targets. Two tone sandhis were examined (51 → 55 and 24 → 33). Each tone sandhi disyllabic target was preceded by either a surface tone prime, an underlying tone prime, or an unrelated control prime.

Participants

Thirty-six native Taiwanese speakers (19 M; 17 F) participated (ranging from 30-55 years old). None of them had any reported language impairments.

Stimuli

Thirty-six disyllabic Taiwanese tone sandhi words were selected from an online Taiwanese dictionary (“教育部臺灣閩南語常用詞辭典”, http://twblg.dict.edu.tw/holodict_new/default.jsp) as critical targets (see Appendix 1). Eighteen of them had the tonal melody 55-24 (i.e., 51 → 55 in the first syllable), while eighteen of them had the tonal melody 33-51 (i.e., 24 → 33 in the first syllable). Since there is no large Taiwanese frequency corpus, a familiarity rating task was conducted to determine the subjective familiarity of the sandhi targets (36 participants rated the stimuli, ranging from 1 [“never heard or said”] to 7 [“very often heard and said”], Flege, Takagi, and Mann, 1996). The average subjective familiarity rating was 5.55 (SD = 1.25) for the 51 → 55 sandhi targets and 5.47 (SD = .98) for the 24 → 33 sandhi targets. To approximate lexical frequency, which the familiarity rating experiment aimed to estimate, we averaged all participants’ responses for each individual target item and included these average ratings in the subsequent statistical analyses of the reaction time data from the lexical decision experiment.

Each disyllabic target was preceded by one of three monosyllabic primes that shared the same segmental content with the first syllable of the target: a surface tone prime, which is identical to the first syllable in the surface tone, an underlying tone prime, which shares the underlying tone with the first syllable, and an unrelated tone prime with a tone different from both the underlying and surface tones. The three types of monosyllabic primes were all real Taiwanese words. Examples of each prime condition for each sandhi target type are shown in Figure 2.

51 → 55 sandhi:

Prime Type	
surface prime	[ping55] “ice”
underlying prime	[ping51] “to turn over”
control prime	[ping21] “to combine”

→ [ping55 tsun24] /ping51 tsun24/ “shipwreck”

24 → 33 sandhi:

Prime Type	
surface prime	[pai33] “to lose”
underlying prime	[pai24] “to arrange”
control prime	[pai21] “to worship”

→ [pai33 kai51] /pai24 kai51/ “to mediate”

Figure 2. For each sandhi target type (51 → 55; 24 → 33), there are three prime conditions.

In addition to the 36 critical sandhi targets, 60 disyllabic words (selected from the Taiwanese dictionary and Taiwanese Spoken Corpus, Myers and Tsay, 2013) served as filler words. Thirty of them were preceded by monosyllabic primes whose segments, but not tones, matched the first syllables of the disyllables on the surface, and 30 of them by monosyllabic primes sharing neither segments nor tones with the first syllables of the disyllables. They all consisted of smooth syllables (open syllables or syllables with a nasal coda). Ninety-six disyllabic nonword targets were also included. They all consisted of two existing morphemes whose combination did not make an existing word. Each nonword was also preceded by a Taiwanese monosyllabic word: 12 were preceded by primes having the same segments and tones as their first syllables on the surface, 54 by primes sharing only the same segments with the first syllables, and 30 by primes sharing neither segments nor tones with the first syllables. The numbers of tones were balanced across critical targets, filler words, and nonwords.

Stimulus recording

A 29-year-old female native Taiwanese speaker, without any reported history of language impairments, recorded the stimuli in an anechoic chamber at the University of Kansas with a cardioid microphone (Electrovoice, model N/D767a) and a digital solid-state recorder (Marantz, model PMD671), using a sampling rate of 22,050 Hz.

Procedure

An auditory-auditory priming lexical decision experiment was conducted. For the lexical decision task, stimuli were fully randomized and presented via Paradigm (Tagliaferri, 2015) over headphones (Beats Executive Over-Ear Headphones). Eight practice trials were presented first and then the 192 main trials. For the 192 main trials, 36 of them were critical trials and presented using a Latin Square design, such that each participant only heard a critical target once, preceded by its corresponding surface tone prime, underlying tone prime, or unrelated control prime. The remaining 156 trials were shared across all participants.

For each trial, participants first heard the monosyllabic prime. After a 250 ms interval, they heard the disyllabic target, either a word or a nonword. The participants' task was to judge whether the disyllabic target was a real word or not by clicking the left button of the mouse, representing "yes", or the right button of the mouse, representing "no", as quickly and accurately as possible. The ITI was 3000 ms. The total duration of the experiment was around 30 minutes. Reaction times and errors obtained from the lexical decision task were subjected to statistical analyses.

Results

Statistical analyses were conducted on reaction times and errors obtained from the lexical decision task. Reaction times were measured from target onset. The overall error rate was 12.9% (*SD* = 1.9) (892 trials/6912 trials). For the reaction time analyses on the critical targets, incorrect responses (8.8%) and responses over two standard deviations from the mean (3.0%) were excluded.

A series of linear mixed-effects analyses were conducted on participants' log-transformed reaction times and errors using the lme4 package in R (Bates, Maechler, Bolker, and Walker, 2014). Likelihood ratio tests were performed to evaluate effects of Prime (Surface, Underlying, Control), Sandhi Type (51 → 55, 24 → 33), Familiarity, Prime * SandhiType, Prime * Familiarity, Sandhi Type * Familiarity, and Prime * Sandhi Type * Familiarity.

Participants' log-transformed reaction time to the sandhi targets was the dependent variable. Prime and Sandhi Type were categorical fixed factors, while Familiarity was a continuous fixed variable. For Prime, Control was selected as the baseline to which Surface and Underlying were compared in order to examine facilitation and inhibition effects. Participant and Item were random variables. Seven random-intercepts-only models (A, B, C, D, E, F, and G) were created and compared using likelihood ratio tests to determine the effects of the fixed variables, as shown in Table 1. lmerTest (Kuznetsova, Brockhoff, and Christensen, 2015) was used to compute p-values for the mixed-effects model coefficients for these analyses and for all subsequent analyses.

Due to the complexity of the results, a summary of the data patterns will be presented first, followed by detailed statistics. In summary, we found significant effects of Familiarity, Prime * Sandhi Type, and Prime * Sandhi Type * Familiarity on reaction time. For the two-way interaction between Prime and Sandhi Type, the 51 → 55 sandhi showed a surface priming effect and a trend for an underlying priming effect, while the 24 → 33 sandhi showed both surface and underlying priming effects, with the underlying priming effect being significantly stronger. For the three way interaction among Prime, Sandhi Type, and Familiarity, the 51 → 55 sandhi showed an effect of Familiarity and a trend for the Prime * Familiarity interaction, while the 24 → 33 sandhi showed significant effects of both Familiarity and Prime * Familiarity. The results, overall, demonstrate different facilitative patterns for the Surface and Underlying conditions between the two different Taiwanese tone sandhis and that the priming effects are regulated differently by Familiarity between the two sandhis.

Model	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
A	Prime	N/A	N/A	N/A	N/A	N/A	N/A
B	Prime	Sandhi Type	N/A	N/A	N/A	N/A	N/A
C	Prime	Sandhi Type	Familiarity	N/A	N/A	N/A	N/A
D	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	N/A	N/A	N/A
E	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	N/A	N/A
F	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	Sandhi Type * Familiarity	N/A
G	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	Sandhi Type * Familiarity	Prime * Sandhi Type * Familiarity

Model Comparison	χ^2	*df*	*p* value
B vs A	.709	1	$p = .4$
C vs B	33.161	1	$p < .001$
D vs C	12.92	2	$p = .002$
E vs D	3.275	2	$p = .195$
F vs E	0	1	$p = 1$
G vs F	14.338	2	$p < .001$

Table 1. Reaction time likelihood ratio tests: model comparisons

Results generated from the likelihood ratio tests showed an effect of Familiarity by comparing Model C and Model B ($\chi^2 = 33.161$, df = 1, $p < .001$), indicating that participants responded to familiar targets significantly faster than to unfamiliar targets. Results also showed a significant two-way interaction of Prime * Sandhi Type by comparing Model D and Model C ($\chi^2 = 12.92$, $df = 2$, $p = .002$), and a significant three-way interaction of Prime * SandhiType * Familiarity by comparing Model G and Model F ($\chi^2 = 14.338$, $df = 2$, $p < .001$).

A model that only differed from Model G by an additional by-Participant random slope in PrimeTone (prime tone 51, prime tone 55, and prime tone 21 for the [T55 T24] target; prime tone 24, prime tone 33, and prime tone 21 for the [T33 T51] target) was also created, and likelihood ratio comparison showed that this model did not significantly improve over Model G ($\chi^2 = 5.231$, $df = 20$, $p = .999$), indicating that the more complex random effect structure was not warranted.

Additional linear mixed-effects analyses were conducted to examine the significant two-way Prime * Sandhi Type interaction. Two additional analyses were conducted for targets with tone sandhi 51 → 55 and for targets with tone sandhi 24 → 33, with participants' Log-transformed Reaction Time as the dependent variable, Prime as a categorical fixed factor (Surface, Underlying, Control), and Participant and Item as random variables.

For targets with tone sandhi 51 → 55, Surface tone primes elicited significantly faster reaction times than did Control primes ($\beta = -.030$, $SE = .007$, $t = -4.45$, $p < .001$), and there was a trend for Underlying tone primes to yield faster reaction times than did the Controls ($\beta = -.011$, $SE = .007$, $t = -1.66$, $p = .097$). Reaction times for the Surface prime condition were also significantly faster than those for the Underlying prime condition ($\beta = .020$, $SE = .007$, $t = 2.92$, $p = .004$). As shown in Figure 3, the facilitation priming revealed that for the targets with tone sandhi 51 → 55, Surface tone primes (+120 ms facilitation priming effect) significantly facilitated participants' lexical decision responses. While Underlying tone primes (+32 ms facilitation priming effect) showed significantly less facilitation than Surface tone primes, a facilitation effect (relative to Control primes) was still evident.

For targets with tone sandhi 24 → 33, Underlying primes elicited significantly faster reaction times compared to the Control prime condition ($\beta = -.036$, $SE = .006$, $t = -5.68$, $p < .001$) and Surface primes yielded significantly faster reaction times than did the Control primes as well ($\beta = -.023$, $SE = .006$, $t = -3.65$, $p < .001$). Furthermore, the Underlying condition elicited significantly faster reaction times than did the Surface condition ($\beta = -.013$, $SE = .006$, $t = -2.07$,

p = .039). As shown in Figure 3, for targets with tone sandhi 24 → 33, both Underlying and Surface prime conditions significantly facilitated participants' lexical decision responses; however, the facilitation effect yielded by the Underlying condition (+136 ms facilitation priming effect) was significantly stronger than that observed in the Surface condition (+93 ms facilitation priming effect), the reverse of what was found for tone sandhi 51 → 55.

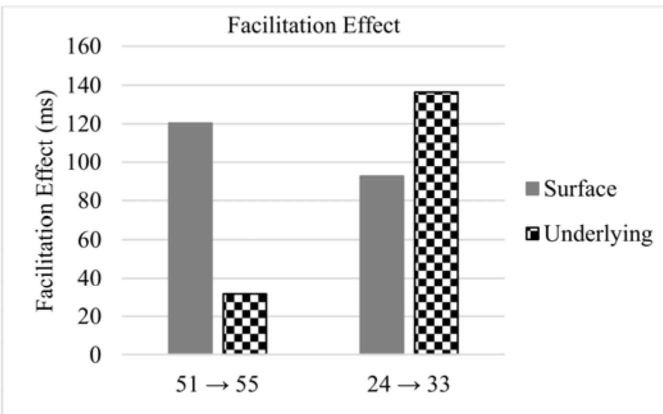

Figure 3. Facilitation effects for the Surface and Underlying prime conditions (relative to baseline Control condition) for targets with tone sandhi 51 → 55 and 24 → 33

In order to further examine the significant three-way interaction of Prime * Sandhi Type * Familiarity, two series of likelihood ratio tests were conducted on participants' log-transformed reaction times within tone sandhi 51 → 55 (Models H, I, and J) (see Table 2) and 24 → 33 (Models K, L, and M) (see Table 3) respectively, with Prime (Surface, Underlying, Control) and Familiarity (continuous) as fixed variables and Participant and Item as random variables.

Model	Factor 1	Factor 2	Factor 3
H	Prime	N/A	N/A
I	Prime	Familiarity	N/A
J	Prime	Familiarity	Prime * Familiarity

Model Comparison	χ^2	*df*	*p* value
I vs H	16.84	1	$p < .001$
J vs I	5.147	2	$p = .076$

Table 2. Reaction time likelihood ratio tests for tone sandhi 51 → 55: model comparisons

Model	Factor 1	Factor 2	Factor 3
K	Prime	N/A	N/A
L	Prime	Familiarity	N/A
M	Prime	Familiarity	Prime * Familiarity

Model Comparison	χ^2	*df*	*p* value
L vs K	15.491	1	$p < .001$
M vs L	12.432	2	$p = .002$

Table 3. Reaction time likelihood ratio tests for tone sandhi 24 → 33: model comparisons

Results showed an effect of Familiarity for both tone sandhi 51 → 55 (Model I vs Model H) and tone sandhi 24 → 33 (Model L vs Model K), indicating that participants responded to familiar targets significantly faster than to unfamiliar targets, regardless of Sandhi Type.

In addition, a trend for the Prime * Familiarity interaction (Model J vs Model I) was observed for tone sandhi 51 → 55. Using the Control prime as the baseline, parameter estimates for Model J showed that neither the Underlying nor the Surface prime had a signficantly different Familiarity slope from the Control prime (Underlying:Familarity: $\beta = -.004$, $SE = .006$,

t = -0.741, p = 0.459; Surface:Familiarity: β = -.009, SE = .006, t = 1.486 , p = 0.138); but switching the baseline to the Underlying prime showed that there is a significant difference between the Underlying and Surface Familiarity slopes (β = -.014, SE = .0061, t = 2.245, p = 0.025).

An interaction between Prime and Familiarity was also obtained for tone sandhi 24 → 33 (Model M vs Model L). Using the Control prime as the baseline, parameter estimates for Model M showed that the Control prime had a signficantly different Familiarity slope from the Surface prime (β = -.025, SE = .007, t = -3.549, p < .001), and a marginally significantly different Familiarity slope from the Underlying prime (β = -.012, SE = .007, t = -1.826, p = 0.068). Switching the baseline to the Underlying prime showed that there is also a marginally significant difference between the Underlying and Surface Familiarity slopes (β = -.012, SE = .007, t = -1.787, p = 0.074). These results can be seen in Figure 4.

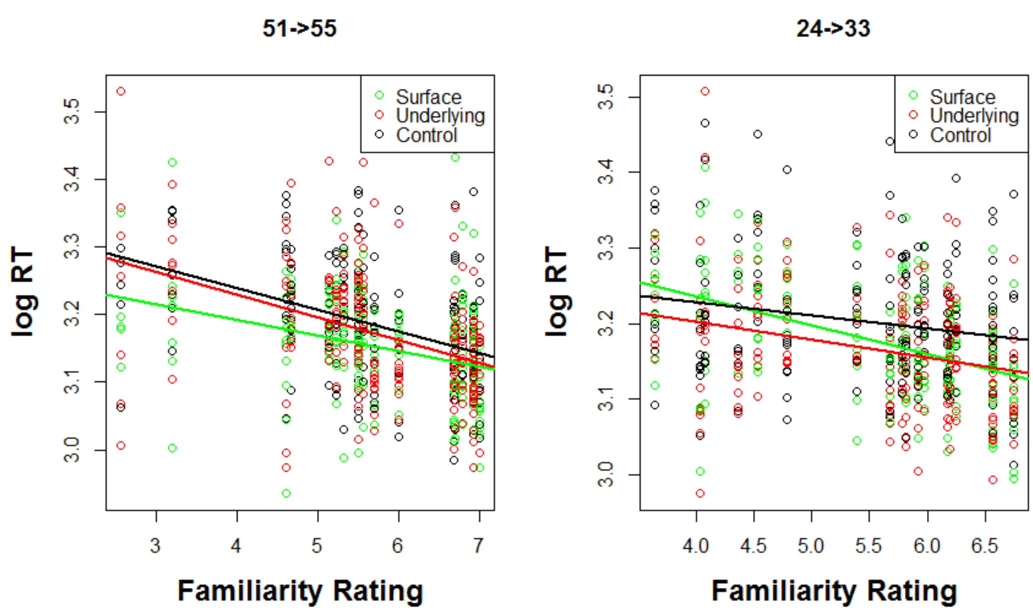

Figure 4. Reaction times elicited in the Surface, Underlying and Control prime conditions for tone sandhi 51 → 55 and 24 → 33 as a function of Familiarity

Another way of visualizing the results is to plot the facilitation effects for both Surface and Underlying forms relative to the Control condition for the two sandhi patterns, as in Figure 5. The different facilitatory patterns across the two sandhi types confirmed the three-way interaction obtained above, showing different patterns across Surface and Underlying conditions as a function of Familiarity for words with tone sandhi 51 → 55 compared to words with tone sandhi 24 → 33. As shown in Figure 5, the slope of the surface facilitation is steeper than that for the underlying facilitation, with familiarity affecting the surface form more than that of the underlying form across both sandhi types.[1]

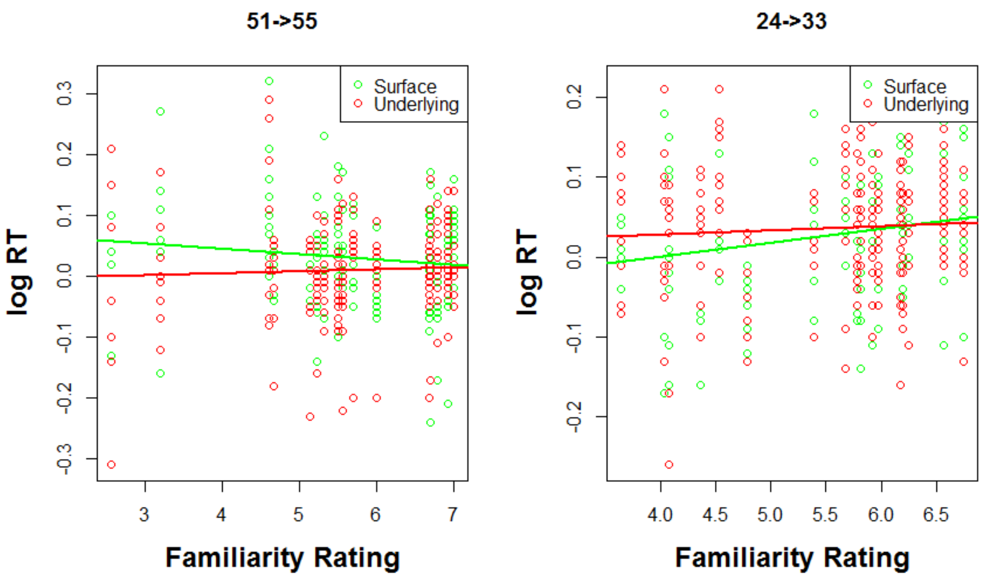

Figure 5. Facilitation effects for tone sandhi 51 → 55 and 24 → 33 as a function of Familiarity

[1] Instead of conducting separate analyses for the two sandhi patterns to further investigate the nature of the interaction terms in the model, we also conducted a nested analysis in which Prime * Familiarity was nested under Sandhi Type. This allows the model to provide separate coefficients for Prime, Familiarity, and Prime:Familiarity for 51 → 55 and 24 → 33 words while keeping both in the same model with a common intercept. The coefficients were near identical to our results from the split analysis, and none of the significant terms was affected. We thank Stephen Politzer-Ahles for making this suggestion.

We also conducted a series of analyses in which we excluded the Control prime and directly compared the priming effects of the Surface and Underlying primes. Such analyses would eliminate the Control condition as a possible source of the differential priming effects, since it could potentially be claimed that the contour of the control prime 21 may be more similar to 51, resulting in surface tone 55 showing more priming, and that the contour of the control prime 21 may be more similar to 33, resulting in underlying tone 24 showing more priming. The analyses excluding the Control prime showed a similar pattern to the results reported above, with a significant three-way interaction among Prime, Sandhi Type, and Familiarity. Separate analyses for the two sandhi patterns showed that, for targets with tone sandhi 51 → 55, reaction times for the Surface prime condition were significantly faster than those for the Underlying prime condition ($\beta = -.019$, $SE = .0065$, $t = -2.921$, $p = .0037$), and the Familiarity slope is significantly steeper for the Underlying prime than for the Surface prime ($\beta = .0153$, $SE = .006$, $t = 2.563$, $p = .0108$). For targets with tone sandhi 24 → 33, reaction times for the Underlying prime condition were significantly faster than those for the Surface prime condition ($\beta = .0127$, $SE = .0061$, $t = 2.075$, $p = .0387$), and the Familiarity slope is steeper for the Surface prime than the Underlying prime ($\beta = -.0137$, $SE = .007$, $t = -2.014$, $p = .045$). This demonstrates that the pattern of priming data cannot be due to the characteristics of the control prime itself but, instead, is due to the nature of the sandhi.

Overall, our reaction time results showed that the contribution of the surface and underlying representations depended on the nature of the sandhi characteristics in Taiwanese, with familiarity modulating the amount of priming especially for the surface priming effect.

Linear mixed-effects analyses were also conducted on participants' errors. A set of likelihood ratio tests were performed to examine main effects of Prime (Surface, Underlying, Control), Sandhi Type (51 → 55, 24 → 33), Familiarity (continuous), Prime * Sandhi Type, Prime * Familiarity, Sandhi Type * Familiarity, and Prime * Sandhi Type * Familiarity. For Prime, Control was chosen as the baseline to which Surface and Underlying were compared. Subject and Item were random factors. Models N, O, P, Q, R, S, and T were generated (see Table 4). Results determined Model P to be the best model because models with more variables could not explain more variance in participants' error data.

The results from Model P showed that Familiarity is a factor in influencing participants' error rates in the lexical decision task, with less familiar targets eliciting more errors ($\beta = .994$, $SE = .106$, $z = 9.359$, $p < .001$). However, no effect of Prime was observed, indicating that neither the Surface condition ($\beta = -.421$, $SE = .234$, $z = -1.8$, $p = .07$) nor the Underlying condition ($\beta = .061$, $SE = .249$, $z = .244$, $p = .807$) elicited fewer errors than the Control condition and Sandhi Type was not significant either ($\beta = -.133$, $SE = .235$, $z = -.566$, $p = .572$), suggesting a similar number of errors for targets with tone sandhi 51 → 55 and 24 → 33.

Model	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
N	Prime	N/A	N/A	N/A	N/A	N/A	N/A
O	Prime	Sandhi Type	N/A	N/A	N/A	N/A	N/A
P	Prime	Sandhi Type	Familiarity	N/A	N/A	N/A	N/A
Q	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	N/A	N/A	N/A
R	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	N/A	N/A
S	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	Sandhi Type * Familiarity	N/A
T	Prime	Sandhi Type	Familiarity	Prime * Sandhi Type	Prime * Familiarity	Sandhi Type * Familiarity	Prime * Sandhi Type * Familiarity

Model Comparison	χ^2	*df*	*p* value
O vs N	.244	1	$p = .621$
P vs O	49.331	1	$p < .001$
Q vs P	1.103	2	$p = .576$
R vs Q	.447	2	$p = .8$
S vs R	.603	1	$p = .437$
T vs S	.781	2	$p = .677$

Table 4. Error rate likelihood ratio tests: model comparisons.

Discussion

The current study investigated how Taiwanese speakers represent and process Taiwanese words with tone sandhi 51 → 55 and tone sandhi 24 → 33. A priming methodology was used in which participants heard monosyllabic prime words followed by disyllabic tone sandhi targets. We found significant facilitation effects due to the overlap between the primes and the first syllables of disyllabic tone sandhi targets. For targets with tone sandhi 51 → 55 and 24 → 33, both underlying and surface tone primes facilitated participants' lexical decision responses compared to an unrelated control prime condition.

Interestingly, however, significant differences in the magnitude of the priming across the two Taiwanese sandhi types were observed. While both sandhi types exhibited facilitatory priming effects, the contribution of underlying and suface forms across sandhi types was distinct. For targets with tone sandhi 24 → 33, underlying tone primes showed significantly more facilitation than surface tone primes while for targets with tone sandhi 51 → 55, surface tone primes showed significantly more facilitation than underlying tone primes.

Productivity studies have shown similar differences. Zhang et al. (2011) examined productivity of Taiwanese tone sandhi and found measurable differences in productivity across tone sandhis. While Taiwanese tone sandhi 24 → 33 elicited nearly complete application in a nonword production test (80%), tone 51 → tone 55 sandhi yielded only 40% application. They argued that tone sandhi 24 → 33 is more productive compared to tone sandhi 51 → 55 since it is phonotactically illegal for tone 24 to occur in the non-phrasal final position while it is legal for tone 51 to occur in that position in Taiwanese (see Figure 1). These productivity differences in Taiwanese tone sandhi were observed in our priming data as well. For the more productive tone 24 → tone 33 sandhi, the underlying primes showed significantly greater facilitation effects compared to surface primes while for the less productive 51 → 55 sandhi, surface tone primes showed significantly greater priming effects compared to underlying primes. Taiwanese words with different tone sandhi characteristics were processed differently.

The current Taiwanese data can be compared to Mandarin tone sandhi, which is extremely productive and applies without exception to novel disyllable combinations (Zhang and Lai, 2010). For Mandarin tone 3 sandhi, Chien, Sereno and Zhang (2016) observed only underlying facilitation using similar priming methods. Together, these Mandarin and Taiwanese data show an influence of sandhi rule productivity on participants' sensitivity to the surface and underlying representations of tone sandhi words, with more productive sandhi eliciting more underlying priming, and less productive sandhi yielding more surface priming.

Differences were also found across languages for the influence of frequency on the priming effects. For the productive Mandarin sandhi, showing only underlying priming, there was no frequency modulation of the priming effect (Chien, Sereno and Zhang, 2016). However, for Taiwanese, which showed a varied contribution of underlying and surface priming across sandhi types, frequency effects on priming were observed. As shown in Figure 4, while surface priming is predominant for the less productive 51 → 55 sandhi and underlying priming is predominant for the more productive 24 → 33 sandhi, the slope of the surface facilitation effect in both sandhis is steeper than that for the underlying facilitation, with familiarity affecting the surface form and the lower frequency items more than the underlying form across both sandhi types. Therefore, the contribution of the surface and underlying representations depends on the nature of the sandhi characteristics in Taiwanese and, interestingly, the effect of frequency on the facilitation is different for the surface and underlying representations, with familiarity modulating the amount of priming especially for low familiarity surface forms.

The current priming results show that facilitation effects can be elicited across different sandhi types. This is consistent with the results in Zhou and Marslen-Wilson (1997) in which disyllabic primes with tone 3 on the first syllable facilitated participants' lexical decision responses due to morpheme-level activation between the primes and the tone 3 sandhi targets. Our results, however, also show that tone sandhi processing is directly associated with Taiwanese speakers' sensitivity to the linguistic pattern of tone sandhi, and the observed differential sensitivity to underlying representations and surface forms is directly related to the degree of productivity of the sandhi phonological rules. The current priming study on Taiwanese, together with that on Mandarin (Chien, Sereno and Zhang, 2016), shows a relationship between priming and productivity, instantiated in a gradient fashion, with the very productive Mandarin tone 3 sandhi eliciting only underlying facilitation, the relatively productive Taiwanese tone sandhi 24 → 33 producing mainly underlying but some surface facilitation, and the least productive Taiwanese tone sandhi 51 → 55 yielding very little underlying facilitation and mainly surface facilitation, especially for the least familiar sandhi words. These findings suggest that words undergoing different sandhi rules across different languages or even within the same language are processed and represented distinctively depending on their productivity. Moreover, these findings provide clear evidence for the contribution of productivity as distinct from the influence of frequency.

The differences in tone sandhi productivity between the two Taiwanese sandhis and between Taiwanese and Mandarin potentially stem from the different phonological properties of the sandhi patterns. The productivity difference between the 24 → 33 and 51 → 55 sandhis in Taiwanese has been ascribed to the presence of a potential phonotactic generalization for the former (a rising 24 cannot occur in nonfinal positions) and the lack of one for the latter (as 51 does appear nonfinally as the sandhi tone of 21) (e.g., Zhang et al. 2011). The productivity difference between the tone 3 sandhi in Mandarin and the two sandhis in Taiwanese, on the other hand, likely stems from the fact that not only does the Mandarin tone 3 sandhi have a phonotactic motivation, but the resulting sandhi tone (tone 2) is also not an undergoer of another sandhi in the same context. In other words, both tone sandhis in Taiwanese are involved in a chainshift, while the tone 3 sandhi in Mandarin is not. This difference corresponds to a transparent-opaque difference in phonological rules made in early phonological literature (e.g., Kiparsky, 1973). The productivity results, therefore, suggest that speakers' phonological knowledge is shaped by the phonotactic constraints on the different sandhis and the transparency of the sandhis. The fact that the priming results on these sandhi patterns mirror the productivity results indicates that the phonological nature of the pattern is not only relevant to the formal account of speakers' phonological knowledge and production, but also important in our understanding of online spoken word recognition. A potential hypothesis that stems from these results is that beyond opacity, other properties of the phonological pattern that may hinder its learning and affect its productivity, e.g., structural complexity, phonetic arbitrariness, and exceptionality, will also affect the representation accessed in spoken word recognition in similar ways.[2]

The present data shed some light on psycholinguistic models of representation and lexical access. Some psycholinguistic models of spoken word recognition assume that lexical representations consist of abstract phonological codes that only preserve essential information for the recognition of spoken words, but omit surface acoustic-phonetic details resulting from speech rate, talker, coarticulation and phonological alternation (McClelland and Elman, 1986; Norris, 1994; Luce and Pisoni, 1998). For feature-based models of spoken word recognition (such as TRACE and NAM), elemental linguistic features of speech sounds are used in the recognition process. A normalization process then operates to extract the information that is critical for word recognition. In these models, variation in the speech input is abandoned early before entering the encoding process. This process is considered economical for the lexicon because it does not need to store an infinite number of variable representations of words. Contrary to this abstractness account, others (e,g, Goldinger, 1996, 1998) have proposed a more

[2] An alternative explanation for the different priming results between the two Taiwanese sandhi patterns pointed out by an anonymous reviewer is that the underlying 24 is only associated with one other tone (33) in the sandhi system, while the underlying 51 is associated with two (55, 21); therefore, 24 elicits stronger priming than 51 of their respective tone sandhi target. But this fails to account for why there is a priming difference between underlying 51 and surface 55 on surface [55-24] (underlying /51-24/) targets, as both 51 and 55 have two tones associated with them in the sandhi system. This also fails to account for the difference between Mandarin tone 3 sandhi and Taiwanese 24 → 33, as in both, the underlying tone prime is only associated with one other tone in the sandhi system.

episodic approach to word recognition. In these exemplar models, surface acoustic-phonetic information does play a role in speech perception, and surface physical details of words are stored in the mental lexicon rather than being discarded for a more abstract representation. Studies supporting this view observed that listeners found it more difficult to recognize (Goldinger, 1996), identify (Mullennix, Pisoni, and Martin, 1989), and recall (Goldinger, Pisoni, and Logan, 1991) stimuli that were spoken by multiple talkers rather than by a single talker, indicating that surface acoustic-phonetic information does have an impact on lexical processing, suggesting that episodic representations of words are represented and preserved in memory.

More recent models propose that lexical representations seem to incorporate both abstract and episodic information (Goldinger, 2007; Cutler and Weber, 2007; Norman and O'Reilly, 2003; Connine, Random, and Patterson, 2008; Schacter, 1992; Fodor, 1983), with Goldinger (2007) recently proposing a *complementary systems* approach in which both abstract and surface information of the speech input is encoded in memory traces. The current data seem to support such a hybrid account in that both surface and underlying representations contribute to the effect of priming, with the degree of priming of each representation being influenced by the nature of sandhi systems.

In summary, the present study demonstrates that disyllabic Taiwanese tone sandhi words are represented differently, related both to their productivity differences as well as their frequency characteristics. We found facilitation effects due to the overlap between primes and the first syllables of disyllabic tone sandhi targets, with significant differences observed in the nature of the priming across the two Taiwanese sandhi types. While both sandhi types exhibited facilitatory priming effects, the contribution of each forms across sandhi types was distinct. For targets with tone sandhi 24 → 33, underlying tone primes showed significantly more facilitation than surface tone primes while for targets with tone sandhi 51 → 55, surface tone primes showed significantly more facilitation than underlying tone primes. Moreover, only the surface priming is modulated by frequency for both sandhi types, while the underlying priming is not. The present results clearly demonstrate that words with different tone sandhi characteristics are represented and processed differently in the mental lexicon.

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Appendix 1. Critical tone sandhi targets

kai55-too24 (改途), ping55-tsun24 (翻船), po55-tshi24 (保持), poo55-kiong24 (補強), tiam55-mia24 (點名), tang55-thuan24 (黨團), kui55-sin24 (鬼神), the55-ling24 (體能), te55-ki24 (短期), tsu55-tshi24 (主席), kau55-ge24 (狗牙), kiam55-pui24 (減肥), tsim55-thau24 (枕頭), king55-te24 (揀茶), koo55-khuan24 (股權), tsuan55-hing24 (轉型), pun55-tsinn24 (本錢), khau55-khim24 (口琴), pai33-kai51 (排解), pue33-jong51 (培養), ping33-ting51 (平等), te33-kuan51 (茶館), tsian33-king51 (前景), tiunn33-soo51 (場所), tshiang33-tsui51 (沖水), tai33-tiunn51 (台長), tang33-kong51 (銅管), tau33-po51 (投保), tiau33-khuan51 (條款), to33-tsau51 (逃走), ki33-kha51 (奇巧), tsinn33-kui51 (錢鬼), tsai33-tsu51 (財主), kio33-ting51 (橋頂), tsiong33-tshu51 (從此), penn33-tshiu51(平手)