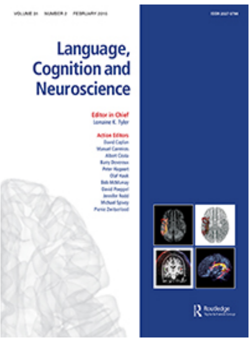


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# Priming the representation of Mandarin tone 3 sandhi words

Yu-Fu Chien, Joan A. Sereno and Jie Zhang

Department of Linguistics, University of Kansas, 427 Blake Hall, 1541 Lilac Lane, Lawrence, KS 66045, USA

**ABSTRACT**

Phonological alternation poses problems for spoken word recognition. In Mandarin Tone 3 sandhi, a Tone 3 syllable changes to a Tone 2 syllable when followed by another Tone 3 syllable. A traditional phonological account assumes that the initial syllable of Mandarin disyllabic sandhi words is Tone 3 (T3) underlyingly, but becomes Tone 2 (T2) on the surface. In an auditory–auditory priming lexical decision experiment, each disyllabic tone sandhi target word (e.g., chu3-li3) was preceded by one of three monosyllabic primes: a T2 prime (Surface-Tone overlap) (chu2), a T3 prime (Underlying-Tone overlap) (chu3), or a control prime (Baseline condition) (chu1). Results showed that Tone 3 primes (Underlying-Tone) elicited significantly stronger facilitation effects for the sandhi targets than Tone 2 primes (Surface-Tone), with little effect of target frequency. The data are examined in terms of the contribution of underlying representations for models of spoken word recognition.

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Mandarin Chinese; tone sandhi; phonological representation; priming; spoken word recognition



During the process of spoken word recognition, acoustic inputs map onto phonemes (or tonemes), and phonemes (or tonemes) onto words in speakers' mental lexicon. However, in real speech situations, the acoustic input does not always match its corresponding phonological representation in the speakers' mental lexicon in a straightforward way due to a variety of factors such as co-articulation, variation induced by speech rate, and phonological alternation. Phonological alternation, whereby a morpheme takes on different surface realisations in different phonological contexts, poses challenges to theories concerning lexical access and spoken word recognition. Mandarin tone 3 sandhi is an example of a productive phonological alternation.

Mandarin is a tone language where the pitch of syllables distinguishes word meanings, as shown in Figure 1. For example, /ma/ with tone 1 (a high-level tone) refers to "mother" (媽); /ma/ with tone 2 (a high-rising tone) means "hemp" (麻); /ma/ with tone 3 (a low-dipping tone) refers to "horse" (馬), while /ma/ with tone 4 (a high-falling tone) means "scold" (罵).

In disyllabic compounds, Mandarin words can undergo tonal alternation. Mandarin tone 3 sandhi is one such tonal alternation, in which an initial tone 3 (the low-dipping tone) syllable changes into a tone 2 (the high-rising tone) syllable when it is followed by another tone 3 syllable. For example, the lexical tone of the morpheme 保 /pɑw3/ "to maintain" changes from tone 3 to tone 2 if it is followed by another tone 3 morpheme 險 /ɕjɛn3/ "danger". Therefore, the surface representation of the tone 3 sandhi word 保險 "insurance" is [pɑw2 ɕjɛn3]. When Mandarin speakers encounter a tone 2 syllable in speech, the tone 2 syllable may be either an underlying tone 2 or underlying tone 3 syllable. The tone 3 sandhi phenomenon raises questions regarding how Mandarin native speakers process tone 2 and tone 3 syllables during online processing, how tone 2 and tone 3 syllables map onto their phonological representations, and how Mandarin tone 3 sandhi words are represented in Mandarin native speakers' mental lexicon.

Unlike most spoken word recognition models for Indo-European languages that focus on segments, Mandarin word recognition models must acknowledge both segmental and tonal information (Moore & Jongman, 1997; Taft & Chen, 1992; Ye & Connine, 1999; Zheng, Minett, Peng, & Wang, 2012). Sereno and Lee (2014) specifically investigated the contribution of Mandarin tonal and segmental information to lexical activation. In their experiments, tonal and segmental overlap between primes and targets was manipulated. Four prime-target pairs were created: prime and target were identical in segment and tone (ST) (e.g., ru4-ru4), prime and target shared the same segmental information (S) (e.g., ru3-ru4), prime and target overlapped in terms of their tones (T) (e.g., sha4-ru4), or prime and target differed in both their tones and segments (UR) (e.g., qin1-ru4), with target tones balanced across conditions (cf. Lee, 2007). Sereno and Lee (2014) found a significant facilitation effect for the ST and S conditions and an

**CONTACT** Yu-Fu Chien y078c178@ku.edu

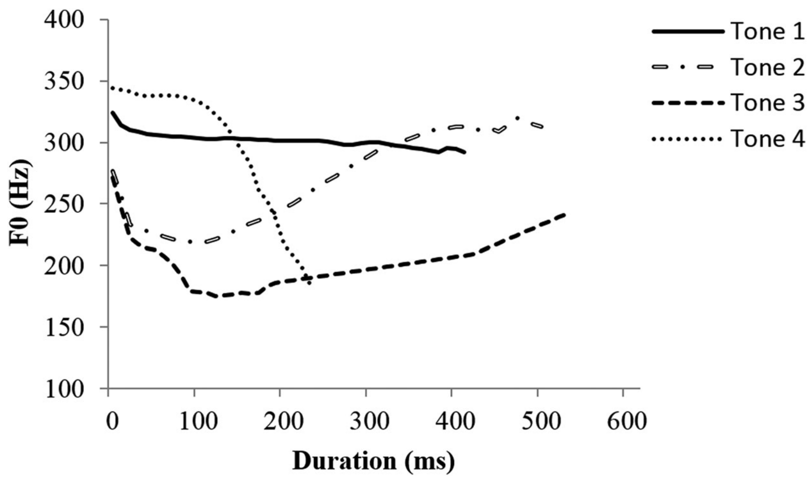


**Figure 1.** The fundamental frequency of the four Mandarin tones in /ma/.



inhibition effect for the T condition relative to the control condition (UR). Segmental information facilitates while tonal information is inhibitory. Furthermore, the results of the S condition revealed that reaction times were speeded when the offset F0 of the prime contrasted with the onset F0 of the target (such as a tone3-tone1 pair), suggesting that lower level acoustic–phonetic information might contribute to the segmental priming effect. A contrast effect in tone perception has also been shown in previous studies (Moore & Jongman, 1997; Sereno, Lee, & Jongman, 2011). Sereno and Lee (2014) concluded that segmental information plays a more critical role in constraining Mandarin lexical activation than does tonal information and the nature of the tonal mismatch influences segmental priming in these monosyllabic targets.

In examining the processing of Mandarin disyllable words, Zhou and Marslen-Wilson (1994) investigated compound words in auditory lexical decision. In their experiments, disyllabic words and non-words were examined, where word frequency, morpheme frequency, and syllable frequency were systematically manipulated, with either the first or the second constituent of the disyllabic words held constant. The results showed that disyllabic word frequency, rather than morpheme frequency, syllable frequency or the combination of these two, was a key factor in influencing subjects' lexical decision latencies, although when compounds were matched for frequency, their first syllable frequency did influence reaction time. Zhou and Marslen-Wilson's data suggest that properties of the internal units of compounds contribute to a lesser extent in Mandarin lexical decision.

Zhou and Marslen-Wilson (1995) conducted an auditory–auditory paired priming task and a repetition priming task to further investigate Mandarin compound processing. Five conditions were constructed for both the paired priming and repetition priming tasks, where the prime and the target were exactly identical (identical condition), sharing the same morpheme (morphological condition), sharing the same syllable (homophone condition), having the same character but not the same morpheme (character condition), or completely unrelated (baseline condition). The results of both tasks showed that the identical and morphological conditions always elicited facilitation effects regardless of the number of intervening items between prime and target or whether the first or the second constituent of the disyllable was manipulated. However, the facilitation effect was reduced when the prime and the target were matched on their first constituent. Zhou and Marslen-Wilson suggested that the reduced facilitation effect was attributed to cohort competition at the word level, curtailing the facilitation effect resulting from re-activation of the recurring morphemes between primes and targets on the morpheme level. The homophone and character conditions elicited an inhibition effect when the prime and target shared their first syllable, a facilitation effect when the prime and the target shared their second syllable, and a null effect when the second syllable of the prime and the first syllable of the target were matched. The authors proposed that the inhibition effect in the homophone and character conditions also resulted from cohort competition at the word level, while the facilitation effect observed in the four conditions when the second constituent of the primes and the targets were matched could be attributed to morpheme-level facilitation. The null effect found in the homophone and character conditions could be explained by the fact that word-level competition and morpheme-level facilitation cancelled each other out. They concluded that Mandarin compounds should be represented as a whole and their individual constituents (e.g., morphemes) should also be represented.

Mandarin disyllabic compounds often undergo tonal alternation. Zhou and Marslen-Wilson (1997) specifically investigated Mandarin tone 3 sandhi, in which a tone 3 syllable changes into a tone 2 syllable when it is followed by another tone 3 syllable. Zhou and Marslen-Wilson compared two views regarding how Mandarin tone 3 sandhi compound words are represented in Mandarin speakers' mental lexicon — a "surface representation view" (represented as /tone 2 tone 3/) in which tones on the surface are stored directly as the underlying representation and a "canonical representation view" (represented as /tone 3 tone 3/) in which the concatenation of the citation form is the underlying representation.

To investigate these competing positions, Zhou and Marslen-Wilson (1997) conducted two lexical decision experiments, using auditory–auditory priming. Each tone 3 sandhi target (e.g., /ts͡ʰaj3 tɕ͡ʰy3/ 採取 "to adopt") was preceded by three kinds of disyllabic primes based on the tones of their first syllables, namely, a tone 2 prime (e.g., /ts͡ʰaj2 xwa2/ 才華 "talent"), a tone 3 prime (e.g., /ts͡ʰaj3 xoŋ2/ 彩虹 "rainbow"), and a control prime (e.g., /tʰjɛn1 ɤ2/ 天鵝 "swan"). The first syllable of the tone 2 prime matched the first syllable of the tone 3 sandhi target both on the segmental level and on the tonal level in the surface representation, while the first syllable of the tone 3 prime matched the first syllable of the tone 3 sandhi target both on the segmental level and on the tonal level in the underlying representation. In terms of the control prime, the first syllable of the control prime had no relationship with the first syllable of the tone 3 sandhi target, phonetically or semantically. The results of their Experiment 1 showed an inhibition effect (29 ms), with the tone 2 primes yielding significantly slower reaction times than did the control primes as a result of cohort lexical competition due to the fact that tone 2 primes matched the initial syllable of the targets on the surface. In contrast, a facilitation effect (52 ms) was found for the tone 3 prime condition, with the tone 3 primes eliciting significantly faster reaction times than did the control primes. Zhou and Marslen-Wilson (1997) proposed that the facilitation effect observed in the tone 3 prime condition came from the fact that tone 3 primes activated all words beginning with tone 3 syllables and their corresponding monosyllabic tone 3 morphemes, including those used as the first syllables of the tone 3 sandhi targets. Based on these data, Zhou and Marslen-Wilson (1997) claimed some support for the surface representation view.

Zhou and Marslen-Wilson (1997), however, suggested that the canonical representation view could also explain the results of their Experiment 1 under the assumption of strategic control of access processes (i.e., participants could develop strategies in the lexical decision task) (McQueen & Sereno, 2005). Given strategic processes, they suggested that words beginning with a tone 2 syllable and words starting with a tone 3 syllable can both be activated in parallel after subjects heard the tone 3 sandhi targets because the tone 3 sandhi targets could activate words beginning with a tone 3 syllable in their underlying representation and words starting with a tone 2 syllable in their surface representation. After the presentation of the tone 3 primes, the lexical access system would be biased towards a tone 3 interpretation with respect to the initial syllables of the sandhi targets. This tone 3 bias turned out to be beneficial since the tone 3 interpretation of the first syllable of the sandhi targets matched exactly the underlying tone 3 of the first syllable of the sandhi targets, giving rise to the facilitation effect. As for the tone 2 primes, after the presentation, the lexical access system would be biased towards a tone 2 interpretation with respect to the initial syllables of the sandhi targets. This tone 2 interpretation, however, turned out to be harmful because this interpretation cannot be mapped onto the first underlying tone 3 syllable of the sandhi targets, leading to processing burden, and hence an inhibition effect.

In order to provide additional evidence for one representational view over another, a second experiment, also using an auditory–auditory priming lexical decision task, was conducted (Zhou & Marslen-Wilson, 1997). Unlike the first experiment, all targets in the second experiment began with a tone 2 syllable, both in the underlying and in the surface representation. For each target (e.g., /ts͡ʰaj2 pʰan4/ 裁判 "referee"), four primes were presented, namely, a tone 2 prime (/ts͡ʰaj2 tʂ͡ʰan3/ 財產 "property"), a tone 3 prime (/ts͡ʰaj3 xoŋ2/ 彩虹 "rainbow"), a sandhi prime (/ts͡ʰaj3 tɕ͡ʰy3/ 採取 "to adopt"), and a control prime (/y4 ljɑw4/ 預料 "to predict"). The results of the second experiment showed an overall inhibition effect in the tone 2 prime, tone 3 prime, and the sandhi prime conditions, with reaction times in these three conditions significantly slower than those in the control prime condition. In addition, reaction times in the tone 2 prime (881 ms) and the sandhi prime (882 ms) conditions were comparable, but were significantly faster than those in the tone 3 prime condition (904 ms). Zhou and Marslen-Wilson (1997) concluded that neither the surface representation view nor the canonical representation view is a viable alternative for how Mandarin speakers represent tone 3 sandhi words in their mental lexicon.

In Zhou and Marslen-Wilson (1997), disyllabic primes immediately preceded disyllabic targets. It is possible (stimuli were not provided in Zhou & Marslen-Wilson, 1997) that the second syllable of the disyllabic primes might have played a role in the priming effects due to the segmental and tonal overlap between the second syllable of the primes and the first syllable of the following target. Moreover, since Mandarin compound words are represented as a whole and their individual morphemes may be represented as well (Zhou & Marslen-Wilson, 1995), it is hard to determine whether the priming effect, either inhibition or facilitation, is attributed to the individual morphemes of the disyllabic word, or to the disyllabic word as a whole. For these reasons, the present experiment will use monosyllabic primes in examining tone sandhi.

An additional issue that is known to contribute to tone sandhi representation is frequency of occurrence. Recent studies have shown that lexical frequency does contribute to the realisation of sandhi tones across Chinese languages. For example, in a production experiment, Zhang and Liu (2015) investigated the productivity of Tianjin tone sandhi using a nonce-probe test and found that words of higher frequency lead to higher tone sandhi productivity in Tianjin Chinese. For instance, in sandhis where the sandhi tone is expected to be higher than the base tone (e.g., L → LH / __L), the sandhi tone realisation for words with higher frequency was higher in fundamental frequency (F0) than that for words with lower frequency, indicating that words of higher frequency had their surface tone realised farther away from the underlying tone than did words of lower frequency. Zhang and Liu (2015) suggested that this result might be because higher frequency words give rise to stronger lexical listing for the sandhi. Yuan and Chen (2014) investigated the acoustic characteristics of the first syllable of Mandarin tone 3 sandhi words in telephone conversations and news broadcasts. Their results showed that the first syllable of higher frequency tone 3 sandhi words exhibited a smaller F0 rise than that of lower frequency tone 3 sandhi words, thus showing a greater similarity between the first syllable of tone 3 sandhi words and an underlying tone 3 for higher frequency words — an opposite effect to Zhang and Liu (2015). It is possible that the different results between Zhang and Liu (2015) and Yuan and Chen (2014) are due to a task difference: the subjects in Zhang and Liu's study were auditorily primed by the underlying tones, as the nonce-probe experiment required the subjects to concatenate individual syllables given in their underlying tones; the data in Yuan and Chen (2014), however, came from settings with no such priming influence. The effect of frequency may be different for these different types of data. But given these findings, it seems warranted to further investigate the effect of frequency in the processing of tone 3 sandhi words in Mandarin.

## The current study

The aim of the current study is to investigate how Mandarin tone 3 sandhi words are processed and whether word frequency plays a role in determining how tone 3 sandhi words are accessed. An auditory–auditory priming lexical decision task was used to directly examine the influence of monosyllabic primes on disyllabic tone 3 sandhi targets. Three prime conditions were contrasted: a Tone 2 prime condition, which overlaps with the tone 3 sandhi target on the surface, a Tone 3 prime condition, which overlaps with the tone 3 sandhi target underlyingly, and an unrelated control prime condition. In addition, lexical frequency of tone 3 sandhi targets was investigated to determine whether frequency of occurrence differentially influences the processing of tone 3 sandhi.

## Methods

### Subjects

Thirty-three native Mandarin speakers (28 male, 5 female) living in Taiwan were recruited for this study. None of them reported any language impairments or cognitive disabilities. Their ages ranged from 20 to 32 years at the time of testing.

### Stimuli

Thirty disyllabic tone sandhi words were selected as critical targets. They were all chosen from a corpus entitled Digital Resources Center for Global Chinese Teaching and Learning (Cheng et al., 2005). Each tone sandhi target (e.g., /fu3 dao3/ 輔導, "to counsel") was preceded by one of the three corresponding monosyllabic primes: a tone 2 prime (e.g., /fu2/ 服, "to assist"), a tone 3 prime (e.g., /fu3/ 輔, "to guide"), and a control prime (always a tone 1) (e.g., /fu1/ 敷, to put on). Thus, each tone sandhi target's first syllable overlapped with its corresponding tone 2 prime both on the segmental level and on the tonal level in the surface representation. Each tone sandhi target's first syllable overlapped with its corresponding tone 3 prime both on the segmental level and on the tonal level in the underlying representation. Each tone sandhi target's first syllable overlapped with its corresponding control prime on the segmental level, but was different from the control prime in terms of tone, both in the surface representation and in the underlying representation.

For the tone sandhi targets, 15 of them were high-frequency tone 3 sandhi words, with a mean word frequency of 898/5 million (SD = 566), a mean log-transformed word frequency of 2.88 (SD = 0.23), a mean log-transformed first syllable frequency of 3.18 (SD = 0.29) (defined as the sum of the frequencies of all homophones to the first syllable either as a tone 2 or as a tone 3 syllable), and a mean log-transformed second syllable frequency of 2.97 (SD = 0.36) (defined as the sum of the frequencies of all homophones to the second syllable). Fifteen of them were low-frequency tone 3 sandhi words, with a mean word frequency of 24/5 million (SD = 13), a mean log-transformed frequency of 1.32 (SD = 0.21), a mean log-transformed first syllable frequency of 3.04 (SD = 0.34), and a mean log-transformed second syllable frequency of 2.90 (SD = 0.38). All of the critical targets, their log-transformed word frequencies, log-transformed first syllable frequencies, and log-transformed second syllable frequencies are displayed in Appendix 1. Both first syllable and second syllable frequencies were controlled and also examined separately in the analyses in order to evaluate the contribution of internal syllabic units to the priming effects (Zhou & Marslen-Wilson, 1994).

In addition to the tone 3 sandhi targets, 60 filler disyllabic target words that were not sandhi compounds were selected from the same corpus (see Appendix 2). For the 60 disyllabic words, 11 of them were preceded by monosyllabic primes having the same tone and same segments as the first syllable (ST match) (e.g., guan1-guan1men2 or fan4-fan4wan3). The numbers of the tones of the first syllables of the 11 targets were 2 for tone 1, 3 for tone 2, 3 for tone 3, and 3 for tone 4. Thirteen of the 60 disyllabic words were preceded by the monosyllabic primes sharing only segments, but not tones with the first syllables of their corresponding targets (S match) (e.g., mao1-mao3ding1 or da4-da1che1). The remaining 36 disyllabic targets were preceded by monosyllabic primes sharing neither segments nor tones with the first syllable of their corresponding targets (ST mismatch) (e.g., tou1-ba2guan4 or hong2-ji1ben3). The numbers of tones of the first syllables of those 36 disyllabic targets were balanced, with 9 for each of the four tones.

Ninety disyllabic non-words (see Appendix 2) consisting of two legal monosyllables in Mandarin were also included. The combinations of the two monosyllables were not Mandarin words (i.e., novel compounds). Among the 90 disyllabic non-words, 21 of them were preceded by the monosyllabic primes having the same segments and tone as the first syllables of their corresponding targets (ST match); 33 of them were preceded by the monosyllabic primes having only the same segments, but not tones as the first syllables of their corresponding targets (S match); 36 of them were preceded by the monosyllabic primes sharing nothing in common either on the segmental level or on the tonal level with the first syllables of their corresponding targets (ST mismatch). For the 90 disyllabic non-word targets, 22 of them began with a tone 1 syllable; 22 of them began with a tone 2 syllable; 23 of them began with a tone 3 syllable; 23 of them began with a tone 4 syllable. For the 90 monosyllabic primes of those targets, 23 of them were tone 1; 22 of them were tone 2; 22 of them were tone 3; 23 of them were tone 4.

## *Stimulus recording*

A female native Taiwan Mandarin speaker produced the stimuli. The stimuli were recorded in an anechoic chamber 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, at the University of Kansas. Stimuli were segmented using Praat (Boersma & Weenink, 2013).

## *Procedure*

An auditory–auditory priming lexical decision experiment was conducted. Participants were first asked to fill out a questionnaire regarding their language background and sign a consent form. Then they were invited to a quiet room and were seated in front of a computer. All of the stimuli in the experiment were presented randomly over headphones (Beats Executive Over-Ear Headphones) using Paradigm (Tagliaferri, 2005). Twenty practice trials were presented before the 180 test trials.

The 30 critical trials were presented using a Latin Square design, such that each participant only heard a critical target (a tone 3 sandhi target) once, preceded by either its corresponding tone 2 prime, tone 3 prime, or control prime. The remaining 150 trials were shared across all participants.

On each trial, participants heard a monosyllabic prime first. After a 250 ms interval, they heard a disyllabic target, either a word or a non-word. The participants' task was to judge whether the disyllabic target was a real word or a non-word by clicking the left button, representing "yes", or the right button, representing "no", of the mouse as quickly and accurately as possible. All of the participants used their dominant hand to make their responses. The ITI was 3000 ms. The duration of the experiment was about 20 minutes.

## Results

Both reaction times and errors obtained from the lexical decision task were subjected to statistical analyses. All thirty-three subjects' data were included in the statistical analyses, with an overall mean accuracy of 91.30% (SD = 3.76) (5423 trials/5940 trials). For the reaction time analyses, incorrect responses (8.43%) as well as responses over two standard deviations from each subject's mean (.27%) were excluded. Both incorrect responses and outliers were treated as errors.

Linear mixed-effects analyses were conducted on participants' reaction times using the lme4 package in R (Bates, Maechler, Bolker, & Walker, 2014). A series of likelihood ratio tests were conducted to examine the effect of Tone (Tone 2, Tone 3, Control), Frequency (log-transformed word frequency of the tone 3 sandhi targets),[1] First Syllable Frequency (FSFreq), Second Syllable Frequency (SSFreq), as well as the interaction of Tone and Frequency. For Tone, the Control condition was chosen as the baseline to which the Tone 2 and Tone 3 conditions were compared. Frequency, First Syllable Frequency, and Second Syllable Frequency were set as continuous variables. Subject and Item were treated as random variables. The dependent variable in the analyses was the subjects' log-transformed reaction time to the tone 3 sandhi targets. Model A, B, C, and D are created, as shown in Table 1. Effects of Tone, Frequency, First Syllable Frequency, Second Syllable Frequency, and Tone X Frequency interaction were determined by comparing between two models.

Results of likelihood ratio tests showed no effect of First syllable frequency by comparing Model B with Model A, no effect of Second syllable frequency by comparing Model C and Model B, and no effect of Tone X Frequency interaction by comparing Model D with Model C, as displayed in Table 1. The analyses demonstrated that the more complex models did not explain more variance in the reaction time data, indicating that the additional parameters, namely, First Syllable Frequency, Second Syllable Frequency, and the Tone X Frequency interaction did not contribute significantly to the models. Therefore, Model A was determined as the best model.

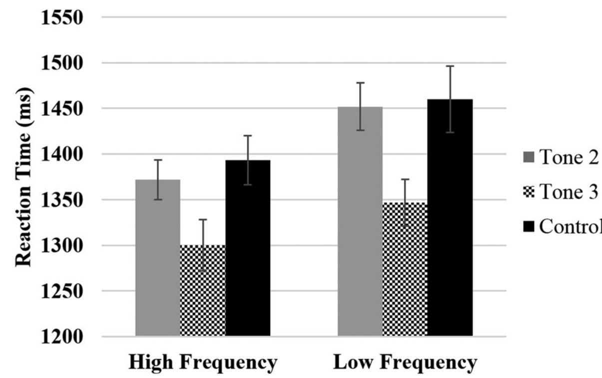


**Figure 2.** Mean reaction time (ms) and error bars for the Tone 2, Tone 3, and Control conditions for the high-frequency and the low-frequency target words in the lexical decision task.

The results generated by model A showed significantly faster reaction times for the Tone 3 condition relative to the Control condition, $\beta = -.030$, SE = .005, $t = -6.36$, $p < .0001$, but no reaction time differences for the Tone 2 condition when compared to the Control condition, $\beta = -.0005$, SE = .005, $t = -.10$, $p = .920$ (see Figure 2 below). These analyses show a clear facilitatory effect for the Tone 3 primes. The results also revealed a significant effect of Frequency, $\beta = -.015$, SE = .006, $t = -2.32$, $p = .020$, indicating that, as expected, reaction times decreased as word frequency increased.

For the error analyses, both incorrect responses and responses over two standard deviations were included. A set of likelihood ratio tests were conducted to examine the effect of Tone (Tone 2, Tone 3, Control), Frequency (log-transformed word frequency of the tone 3 sandhi targets), First Syllable Frequency (FSFreq), Second Syllable Frequency (SSFreq), as well as the interaction of Tone and Frequency on the participants' error rate (dependent variable). For Tone, the Control condition was chosen as the baseline to which the Tone 2 and Tone 3 conditions were compared. Frequency, First Syllable Frequency, and Second Syllable Frequency were treated as continuous variables. Subject and Item were treated

**Table 1.** Reaction time likelihood ratio tests: model comparisons.

| Model | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 |
|---|---|---|---|---|---|
| A | Tone | Freq. | N/A | N/A | N/A |
| B | Tone | Freq. | FSFreq | N/A | N/A |
| C | Tone | Freq. | FSFreq | SSFreq | N/A |
| D | Tone | Freq. | FSFreq | SSFreq | Tone X Freq |
| Model comparison | $\chi^2$ | *df* | *p* value | | |
| B vs. A | 1.633 | 1 | $p = .201$ | | |
| C vs. B | .348 | 1 | $p = .555$ | | |
| D vs. C | .757 | 2 | $p = .685$ | | |

**Table 2.** Error rate likelihood ratio tests: model comparisons.

| Model | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 |
|---|---|---|---|---|---|
| A | Tone | Freq. | N/A | N/A | N/A |
| B | Tone | Freq. | FSFreq | N/A | N/A |
| C | Tone | Freq. | FSFreq | SSFreq | N/A |
| D | Tone | Freq. | FSFreq | SSFreq | Tone X Freq |
| Model comparison | $\chi^2$ | Df | *p* value | | |
| B vs. A | .183 | 1 | $p = .669$ | | |
| C vs. B | 3.456 | 1 | $p = .063$ | | |
| D vs. C | 1.349 | 2 | $p = .506$ | | |



as random variables. Model A, B, C, and D were created (Table 2) and compared in order to assess the effect of the fixed variables (Tone, Frequency, FSFreq, SSFreq, and Tone X Frequency). Results revealed that First Syllable Frequency (Model B vs. Model A), Second Syllable Frequency (Model C vs. Model B), and the Tone X Frequency interaction (Model D vs. Model C) were not significant factors, indicating that the more complex models failed to explain more variance in the error data. Thus, Model A was determined as the best model.

The results of model A revealed that neither the Tone 3 condition nor the Tone 2 condition yielded significantly lower error rates when compared to the Control condition ($\beta = -.007$, SE = .338, $z = -.021$, $p = .983$; $\beta = -.302$, SE = .323, $z = -.935$, $p = .350$, respectively). Furthermore, there was no main effect of Frequency ($\beta = .650$, SE = .414, $z = 1.571$, $p = .116$). The lack of tone and frequency effects could be due to the overall low error rates across all tone 3 sandhi targets.

## Discussion

The present study investigated how Mandarin tone 3 sandhi words are processed by native speakers. The reaction time data clearly show that Mandarin tone 3 sandhi targets preceded by monosyllabic tone 3 primes elicited significantly faster reaction times than those preceded by both monosyllabic tone 2 primes and control primes. Mandarin monosyllabic tone 3 primes significantly facilitated participants' lexical decision responses to the following Mandarin tone 3 sandhi targets, whereas Mandarin monosyllabic tone 2 primes failed to do so. These data suggest that although tone 3 primes and the first syllable of their corresponding tone 3 sandhi targets did not share the same surface tones, their underlying tonal overlap facilitated subjects' lexical decisions. Moreover, even though the monosyllabic tone 2 primes and their corresponding tone 3 sandhi targets were matched on the surface, the tone 2 overlap did not facilitate subjects' responses to the following Mandarin tone 3 sandhi targets. Our data support a view in which native speakers access the underlying representation /tone 3 tone 3/ when they access tone 3 sandhi disyllabic words. Mandarin native speakers at some level represent tone 3 sandhi words as /tone 3 tone 3/ in their mental lexicon. The prior presentation of a tone 2, although matching sandhi targets on the surface, does not seem to facilitate recognition of the tone 3 sandhi words.

Recall that in their first experiment, Zhou and Marslen-Wilson (1997) obtained an inhibition effect when tone 3 sandhi targets were preceded by disyllabic primes beginning with a tone 2 syllable and a facilitation effect when the targets were preceded by disyllabic primes starting with a tone 3 syllable. These data are consistent with those in Zhou and Marslen-Wilson (1995), where disyllabic targets preceded by disyllabic primes yielded a facilitation effect if the first syllable of the primes and the first syllable of the targets shared the same morpheme (morphological condition), but an inhibition effect if they were homophonous (homophone condition). Our data pattern similarly to these data in the direction of the effect: facilitation for underlying match relative to surface match. These results are consistent with the data found in the phonological priming literature (e.g., McQueen & Sereno, 2005; Radeau, Morais, & Segui, 1995) that has shown facilitation due to phonological overlap, both in onset (more than 1 phoneme) and offset positions. There seems to be a processing benefit due to phonological overlap between primes and targets, with segmental overlap, and in the present case, both segmental and tonal overlap, dominating the lexical competition. Although the primes in both Zhou and Marslen-Wilson's experiments were all disyllabic words while ours were monosyllabic words, the tone 3 primes in Zhou and Marslen-Wilson (1997) and the current study both elicited significant strong facilitation effects. However, the disyllabic tone 2 primes of Zhou and Marslen-Wilson (1997) resulted in significant inhibition. In the current study, such competition was not observed, most likely due to the fact that the primes were all monosyllables that were fully embedded in the targets. In addition, the use of a short ISI and the inclusion of a number of filler items seemed to reduce the likelihood of use of strategic processes.

It is also interesting to compare our results to the Mandarin production results in Politzer-Ahles and Zhang (in press) using odd-man-out implicit priming, a paradigm in which a set of words is responded to faster if they are phonologically homogeneous than when phonologically heterogeneous. In their experiments, three of the four words were identical and began with a tone 3 syllable (e.g., qi3-ye4), whereas the fourth word in each set was either a completely unrelated word (Unrelated) (kong1-tiao2), a word sharing the same first syllable as the other three words (Homogeneous) (qi3-shen1), a word beginning with a tone 2 syllable (Heterogeneous) (qi2-zhi4), or a word beginning with an underlying tone 3 syllable in the sandhi context (Sandhi) (qi3-dian3). Their results showed that, for the three words shared by all sets, there was a facilitation effect for the subjects' production latencies in the Homogeneous set relative to the Unrelated baseline, but not in the Heterogeneous or the Sandhi sets. Politzer-Ahles and Zhang argued that these results supported the view that sandhi-undergoing compounds are stored as /tone 3 tone 3/ and later turned into [tone 2 tone 3] before articulatory encoding. This is consistent with our results under the assumption that the lexical decision task taps into lexical storage, not the articulatory encoding of the lexical item. In a second experiment, Politzer-Ahles and Zhang tested data where three of the four words began with a tone 2 syllable (e.g., tu2-di4). Subjects' speech production latencies showed that the Homogeneous set elicited significantly faster reaction times than the Sandhi set, whereas the Sandhi set did not significantly differ from the Heterogeneous set. According to the reduced priming effect for the Sandhi set, Politzer-Ahles and Zhang (in press) proposed that although tone sandhi applies before articulatory encoding occurs, there still seems to be some trace of the underlying representation during speech production. This is also consistent with the results of the current study, which similarly revealed that the underlying representations of Mandarin tone 3 sandhi words play a more important role during lexical access, even though the methodologies used in these two studies are quite different.

Our results are also consistent with those of a nonce-probe study on the productivity of Mandarin tone 3 sandhi by Zhang and Lai (2010). In that study, subjects were asked to produce nonce words with two tone 3 syllables in Mandarin based on auditory prompts. Their results showed that although there were phonetic differences in the surface tones between real and nonce words, tone 3 sandhi consistently applied to nonce words, indicating that it is productive. Together with Politzer-Ahles and Zhang (in press) and Zhang and Lai (2010), our study suggests that Mandarin tone 3 sandhi words are represented in their underlying tones, and that there is a productive mechanism that derives the sandhi tone prior to articulatory encoding.

Previous studies examining Dutch also provide evidence supporting the contribution of the underlying representation during online processing (Jongman, Sereno, Raaijmakers, & Lahiri, 1992; Lahiri, Jongman, & Sereno, 1990). Jongman et al. (1992) used the characteristics of Dutch where both vowel length and final obstruent voicing are contrastive underlyingly. However, in syllable final position, the final obstruents are neutralised on the surface. Therefore, vowel length becomes the only cue to distinguish /zat/ ([zat] "drunk") from /za:d/ ([za:t] "seed") on the surface. In their experiment, a vowel length continuum, [at] to [a:t], was created and attached to syllable onset consonants to form two pairs of real words. Words in each pair differed by vowel length and obstruent final voicing underlyingly, such as /zat/-/za:d/ and /stad/ ([stat] "city") -/sta:t/ ([sta:t] "state"). In an auditory vowel-identification task, Jongman et al. (1992) found that when encountering an ambiguous [a], listeners identify the slightly longer [a] as an underlying /a:/ in the /zat/-/za:d/ pair, whereas listeners identify the same vowel as an underlying /a/ in the /stad/-/sta:t/ pair because they considered the slightly lengthened [a] to be due to the following underlying voiced obstruent. Based on the results, Jongman et al. (1992) concluded that the categorisation of the ambiguous vowel in Dutch is influenced by the underlying representation of the following syllable final obstruent. Hearing the same acoustic continua, listeners' perceptual boundary of /a/-/a:/ was shifted depending on the underlying phonological representation of the obstruent following the vowel. They proposed that the underlying representation is used by listeners online in speech perception. The current study adds to this evidence, showing that in cases of phonological alternation, the underlying representation contributes both segmentally and suprasegmentally.

With regard to the frequency effect, the present results expectedly showed that overall high-frequency tone 3 sandhi targets elicited significantly faster reaction times than did low-frequency tone 3 sandhi targets. Additionally, the first syllable and second syllable frequency analyses showed no effect of syllable frequency on response times, indicating that the word frequency of the tone 3 sandhi compounds, rather than the individual syllable frequency, was the critical factor in lexical access. While Zhou and Marslen-Wilson (1994) found a small first syllable frequency effect only when overall compound frequency was held constant, the current data do not show an independent contribution of syllable frequency to the priming effects.

In the present study, no interaction was found between tone and frequency. These results suggest that both high- and low-frequency Mandarin tone 3 sandhi words are represented as /tone 3 tone 3/ in the native speakers' mental lexicon. Regardless of frequency, underlying representations, rather than their surface representations, seem to be accessed during online lexical processing. The fact that the tone 3 primes in this study facilitated the processing of the tone 3 sandhi targets even though their surface representations did not match suggests that Mandarin native speakers *do* process tone 3 sandhi words computationally and make phonological inferences for the first tone 2 syllable on the surface based on whether or not the second syllable is a tone 3.

## Conclusion

The current study investigated how Mandarin tone 3 sandhi words are represented in the native speakers' mental lexicon. Our data showed faster reaction times and a stronger facilitation effect in the Tone 3 condition than in the Tone 2 condition. These data indicate that Mandarin tone 3 sandhi words are represented as /tone 3 tone 3/ and this representation is accessed during online processing by Mandarin speakers. The /tone 3 tone 3/ representation is used not only for higher frequency tone 3 sandhi words, but also for lower frequency tone 3 sandhi words.

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## Note

1. Analyses were also conducted treating Frequency as a categorical variable (High Frequency, Low Frequency). The results of the linear mixed-effects analyses were identical to those for Frequency treated as a continuous variable.

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## Appendix 1. Critical high-frequency and low-frequency target sandhi stimuli

High-frequency tone 3 sandhi targets

| Target | Pinyin | Log Word Frequency | Log First syllable Frequency T2 + T3 | Log Second Syllable Frequency |
|---|---|---|---|---|
| 產品 | chan3 pin3 | 3.39 | 2.75 | 2.68 |
| 處理 | chu3 li3 | 3.28 | 3.11 | 3.49 |
| 只有 | zhi3 jiu3 | 3.07 | 3.59 | 3.84 |
| 主管 | zhu3 guan3 | 3.02 | 3.20 | 3.00 |
| 引起 | yin3 qi3 | 3.00 | 2.90 | 3.15 |
| 也許 | ye3 xu3 | 2.97 | 3.50 | 2.86 |
| 彼此 | bi3 ci3 | 2.85 | 2.94 | 3.18 |
| 領導 | ling3 dao3 | 2.79 | 2.98 | 2.83 |
| 採取 | cai3 qu3 | 2.77 | 3.16 | 2.79 |
| 選舉 | xuan3 ju3 | 2.77 | 2.89 | 2.58 |
| 輔導 | fu3 dao3 | 2.73 | 3.20 | 2.84 |
| 演講 | yan3 jiang3 | 2.71 | 3.37 | 2.43 |
| 想法 | xiang3 fa3 | 2.66 | 3.30 | 3.15 |
| 以往 | yi3 wang3 | 2.64 | 3.73 | 2.78 |
| 保險 | bao3 xian3 | 2.56 | 2.77 | 2.64 |

Low-frequency tone 3 sandhi targets

| Target | Pinyin | Log Word Frequency | Log First Syllable Frequency T2+T3 | Log Second Syllable Frequency |
|---|---|---|---|---|
| 扭轉 | niu3 zhuan3 | 1.76 | 2.22 | 2.53 |
| 審理 | shen3 li3 | 1.69 | 2.87 | 3.49 |
| 可口 | ke3 kou3 | 1.59 | 3.42 | 2.72 |
| 賭場 | du3 chang3 | 1.48 | 2.99 | 3.85 |
| 雅典 | ya3 dian3 | 1.32 | 2.72 | 2.97 |
| 喜酒 | xi3 jiu3 | 1.32 | 3.12 | 3.02 |
| 腳本 | jiao3 ben3 | 1.30 | 2.75 | 3.09 |
| 婉轉 | wan3 zhuan3 | 1.28 | 2.99 | 2.53 |
| 顯眼 | xian3 yan3 | 1.23 | 2.85 | 2.89 |
| 廠長 | chang3 zhang3 | 1.20 | 3.48 | 2.64 |
| 體檢 | ti3 jian3 | 1.20 | 3.36 | 2.77 |
| 海產 | hai3 chan3 | 1.15 | 3.31 | 2.68 |
| 養老 | yang3 lao3 | 1.15 | 2.96 | 2.95 |
| 乞討 | qi3 tao3 | 1.11 | 3.60 | 2.26 |
| 打手 | da3 shou3 | 1.00 | 2.97 | 3.07 |

## Appendix 2. Disyllabic filler word target stimuli with prime words. Also, disyllabic non-word target stimuli with prime words

*Filler words*

tie1-tie1xin1, guan1-guan1men2, tou1-ba2guan4, lio1-su2qi4, ling1-shou2shi4, mao1-mao3ding1, qiao1-qiao3yan2, pao1-pao3lu4, shao1-shi3yong4, shai1-ku3qing2, shang1-kou3she2, tong1-shau4ye2, shou1-shang4tai2, xing1-duo4xing4, ma2-gu1qie3, hong2-ji1ben3, qiao2-hu1qi4, pao2-pao2xiao4, yan2-yan2 liao4, quan2-quan2shen1, shou2-shou3zhen1, shu2-shu3tiao2, chao2-chao3jia4, ting2-zhen3tou2, tiao2-xue3kuo2, qian2-po3xing2, liao2-ru4kou3, mei2-zong4ku3, ming2-luo4tuo2, dian3-shu1zhuang1, ku3-gao1zhang3, bu3-qian1shou3, ren3-tiao2zhong3, ling3-han2leng3, shui3-lan2se4, zhu3-zhu3yao4, ran3-ran3se4, chuang3-chuang3dang4, ma3-ren4zhen1, qiang3-shui4jiao4, ku3-ling4wai4, da4-da1che1, jiang4-jiang1jun1, hu4-tian1jia1, dong4-ting1ke1, kua4-xing1qiu2,fang4-fan2jian1, ben4-liao2tian1, ban4-ming2men2, xue4-qi2shi2, yuan4-yuan2lai2, wan4-wan3an1, pin4-pin3de2, kao4-hu3ren2, bao4-gui3guai4, kan4-guo3dong4, huo4-huo3ban4, ju4-ju4ji2, fan4-fan4wan3, huan4-huan4qi4

*Non-words*

fei1-fei1kong1, tan1-tan1lian2, yao1-yao1kao3, chong1-chong1qian4, han1-han2liu1, fen1-fen2ba3, su1-su2shi3, kuang1-yin2mei3, ke1-lai2qian3, xiu1-mang2zhu3, qing1-qing3mei2, shai1-shai3ku1, zao1-zao3shai4, kan1-mu3kan1, zhou1-sa3pang2, tui1-kan3nen4, kai1-kai4tang1, mi1-mi4shu3, jang1-yan-g4lian4, xiao1-fen4mi1, fu1-pang4ba2, tian1-kong4-nian3, qi2-qi1shou1, xia2-xia1yin2, zhai2-zhai1li3, chuan2-qi1pu2, bo2-pi1tao3, chen2-zhuo1gou4, rao2-rao2jia3, zei2-zei2quan3, yin2-yin2da3, bie2-bie2gui3, wen2-wen2pu3, chao2-chao3ren4, luo2-luo3ba2, yao2-yao3bei4, fo2-pu3shua1, ba2-shu3wen2, qiou2-man3li4, chuang2-chuang4ni3, tu2-tu4hua1, miao2-shi4sui1, qiang2-yun4lin2, zhao2-di4xiou3, gong3-gong1miao3, huang3-huang1he4, yuan3-peng1shao2, suo3-gan1niao3, li3-sou1fa4, chou3-chou2tong3, wei3-wei2bian3, er3-er2zhi3, jie3-nu2ai3, ji3-chu2gu3, ban3-mi2kou3, bao3-bao3qu1, kong3-kong3zha1, chuang3-chuang3qing2, zou3-zou3ya4, yao3-yao3dian4, lao3-lao4ti2, niao3-niao4an4, can3-can4shou1, bei3-shi4tu1, rao3-deng4tai2, kao3-gu4shu3, si4-xi1ma2, shang4-shang1wen3, tou4-dou1ku4, shan4-guo1chu2, fu4-shan1zou3, mi4-tang1yin4, men4-men2lian3, da4-da2ai3, mo4-shu2si3, shou4-ni2wan3, tai4-zhe2gan3, qian4-qian3shei2, ba4-ba3kan1, chang4-chang3ku4, wo4-jian3lao1, xiou4-geng3fa2, xia4-zhen3bu4, zhang4-zhang4qu1, du4-du4mai2, mu4-mu4nian2, si4-si4bei3, lu4-lu4bi4, can4-can4wa4