# Form and meaning co-determine the realization of tone in Taiwan Mandarin spontaneous speech: the case of T2-T3 and T3-T3 tone sandhi

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#### Abstract

In Standard Chinese, Tone 3 (the dipping tone) becomes Tone 2 (rising tone) when followed by another Tone 3. Previous studies have noted that this sandhi process may be incomplete, in the sense that the assimilated Tone 3 is still distinct from a true Tone 2. While Mandarin Tone 3 sandhi is widely studied using carefully controlled laboratory speech (Xu, 1997) and more formal registers of Beijing Mandarin (Yuan and Chen, 2014), less is known about its realization in spontaneous speech, and about the effect of contextual factors on tonal realization. The present study investigates the pitch contours of two-character words with T2-T3 and T3-T3 tone patterns in spontaneous Taiwan Mandarin conversations. Our analysis makes use of the Generative Additive Mixed Model (GAMM, Wood, 2017) to examine fundamental frequency (f0) contours as a function of normalized time. We consider various factors known to influence pitch contours, including gender, speaking rate, speaker, neighboring tones, word position, bigram probability, and also novel predictors, word and word sense (Chuang et al., 2024). Our analyses revealed that in spontaneous Taiwan Mandarin, T3-T3 words become indistinguishable from T2-T3 words, indicating complete sandhi, once the strong effect of word (or word sense) is taken into account. For our data, the shape of f0 contours is not co-determined by word frequency. In contrast, the effect of word meaning on f0 contours is robust, as strong as the effect of adjacent tones, and is present for both T2-T3 and T3-T3 words.

*Keywords:* Tone 3 sandhi, tonal assimilation, GAMM, word-specific tonal realization, frequency effect

There is an increasing interest in spontaneous speech in phonetics, psycholinguistics, and related fields. While carefully controlled speech from laboratory experiments can provide valuable insights into specific aspects of speech production, spontaneous speech allows researchers to study authentic language use in everyday conversations. Spontaneous speech differs from laboratory speech in various aspects, such as the choice of words, syntactic patterns, tones and intonation, and phonological assimilation (Tucker and Ernestus, 2016). For instance, the pronunciation of Mandarin tones in spontaneous speech in everyday use differs from how it is described in textbooks and second-language learning classrooms, posing a huge challenge for second language learners of Mandarin.

Mandarin Chinese is a tonal language, with each syllable being distinguished by a specific lexical tone in addition to vowels and consonants. This tonal differentiation contributes to distinguishing between words' meanings. The main acoustic correlate of Mandarin tones is the shape of words' fundamental frequency (f0) contours. Mandarin Chinese has four lexical tones: a high-level tone (T1), a rising tone (T2), a dipping tone (T3), and a falling tone (T4), along with a neutral or floating tone (Chao, 1968). Chao (1968) describes the neutral tone as being unstressed, noticeably weaker in intensity, and shorter in duration. When a syllable is placed in a disyllabic word or connected speech, tone sandhi takes place. Tone sandhi refers to the modulation of a given syllable's lexical tones by the tones of other syllables in its context. Tone 3 sandhi is the most widely studied tone sandhi phenomenon in Mandarin Chinese. In a disyllabic word with the tone pattern T3-T3, the first T3 is typically pronounced as T2, leading to the perception that the T3-T3 tone pattern sounds similar to the T2-T3 tone pattern. There has been a long-standing debate about whether this tone sandhi results in incomplete or complete assimilation of initial T3 to a initial T2 (Yuan and Chen, 2014).

Although Tone 3 sandhi has long been studied for laboratory speech (Shih, 1986; Xu, 1997), its realization in spontaneous speech has been less extensively investigated. It has been observed that in general, several standard acoustic cues for individual tones, such as f0, are greatly influenced by contextual factors or even reduced to a large degree in spontaneous speech, rendering them unreliable (Brenner, 2013). The majority of research in Mandarin Tone 3 sandhi is based on words that are articulated in isolation or words embedded in simple sentences or careful speech elicited in the lab using experimental tasks (Warner, 2011; Wagner et al., 2015). In order to gain a more comprehensive

understanding of the production of Tone 3 sandhi, it is essential to examine it in the speech style that speakers and listeners most frequently and commonly use in everyday settings. The study of Yuan and Chen (2014), however, addresses the realization of Tone 3 sandhi as it is realized in spontaneous spoken Mandarin, using corpora of standard Mandarin telephone speech and Mandarin broadcast news speech. The present study aims to investigate the realization of disyllabic words with T2-T3 and T3-T3 tone patterns in spontaneous spoken Taiwan Mandarin in face-to-face conversations. In what follows, section 1 provides further details on what is currently known about Tone 3 sandhi. Section 2 introduces our materials and the methods we used for data analysis. Results are presented in section 3. Our study concludes with a summary and discussion.

## 1 Incomplete neutralization of Tone 3 sandhi

Most studies have reported incomplete neutralization for Tone 3 sandhi in Mandarin Chinese. The Sandhi Rising tone (SR tone, the first T3 in T3-T3) is found to exhibit lower pitch compared to the Lexical Rising tone (LR tone, T2 in T2-T3), with mean differences ranging from 3.2 Hz to 20 Hz (Cui et al., 2020; Kratochvil, 1984; Myers and Tsay, 2003; Shen, 1990; Xu, 1993, 1997; Zee, 1980). The SR tone has also been described as tending to have less f0 excursion in the pitch contour across various varieties of Mandarin. For instance, Xu (1997) examined disyllabic non-word /ma-ma/ sequences with 16 possible Mandarin bi-tonal combinations embedded in carrier sentences produced by Beijing Mandarin native speakers. This study revealed that although both exhibited similar fall-rise-fall f0 contours, T3-T3 has a slightly lower pitch than T2-T3 throughout both syllables. This observation suggests for laboratory speech, the SR tone does not fully assimilate with the LR tone. However, most studies addressing Tone 3 sandhi in Taiwan Mandarin have reported that the SR tone and the LR tones are more similar to each other than in other varieties such as Beijing Mandarin. These differences in realization may remain visible but are not well supported from statistical analysis (Cheng et al., 2013; Fon and Chiang, 1999; Myers and Tsay, 2003; Peng, 2000).

Only a few studies have examined Tone 3 sandhi in connected or spontaneous speech. An early study by Kratochvil (1987) analyzed the speech of a speaker of Beijing Mandarin, who was asked to generate sentences using words presented in list format. Using discriminant analysis as classifier, he found that most of the tokens with the sandhi T3 were grouped with the lexical T3 rather than the lexical T2. This study concluded that speakers of Mandarin are adjusting the underlying T3, but the resulting SR tone is yet not equivalent to a T2.

More recently, Yuan and Chen (2014) analyzed the realization of Tone 3 sandhi in Mandarin bi-character words in connected speech from a large corpus of telephone conversations and formal news broadcasts. They found that, despite the remarkable similarity, the LR tone displays higher and longer f0 rising than the SR tone. This low-level acoustic difference in the magnitude and the time period of f0 rise is consistent with previous results obtained using carefully controlled speech. Following up on the study by Xu (1997), Wu et al. (2021) analyzed Mandarin disyllabic words with 16 tonal combinations, but used large corpora of journalistic speech. They found that the SR tone in the T3-T3 sequence is often realized as other tones, suggesting that the tone sandhi rule in connected speech is more likely to be a tendency rather than an absolute rule. In addition to differences in the speech signal, differences between the SR and the LR tone have also observed in EEG waveforms (Chen et al., 2022). The authors argue that different stages of encoding are involved in the production of Tone 3 sandhi.

For a variety of reasons, the way that tones are realized in connected speech is different from the canonical form. Previous research has shown that tonal context is a crucial factor in tone (Xu, 1997). When placed in context, the realization of a given tone is greatly influenced by its preceding tone and following tone, resulting in tonal co-articulation. In addition to the influence of tonal context, speaking rate and the position of a word in the utterance also play a role (Wu et al., 2021; Yuan and

Church, 2021). The faster a speaker talks, the less time is available for implementing changes in the muscles governing the vibration of the vocal cords, resulting in reduced pitch excursions (Cheng et al., 2013; Xu and Sun, 2002). Furthermore, a speaker's speaking style has been found to be another factors predicting tonal variation, given that speakers has their own speaking (Stanford, 2016).

The realization of tone is often also shaped by paralinguistic and sociolinguistic factors, including dialect, gender and a speaker's emotional state. An analysis of the realization of tones in several automatic speech recognition corpora, registering the speech of some 2300 speakers from seven dialectal backgrounds (Tian et al., 2022), reported that tone sandhi was present not only for speakers of Beijing Mandarin, but also for speakers of other dialects of Mandarin, but with regional variation in the degree of assimilation.

In addition, it has been demonstrated that gender plays a role in tonal realizations (Liang and Meng, 2011). Specifically, Tian et al. (2022) found that male speakers tend to produce a greater f0 rise than female speakers in producing both SR tone and LR tone. A speaker's emotional state is also known to co-determine tonal realization (Chang et al., 2023; Zhang et al., 2006).

Furthermore, T3-T3 tone sandhi has been argued to vary also with lexical frequency (Yuan and Chen, 2014; Tian et al., 2022). The study by Yuan and Chen (2014) found that the SR tone exhibited more f0 difference from the LR tone in more frequent words than in less frequent words. Replicating and extending this study, Tian et al. (2022) also reported a similar effect of word frequency across a range of dialects. One possible source for these frequency effects is that more frequent words tend to be realized with shorter spoken word duration, which in turn predicts reduced pitch excursion. A random forest analysis by Wu et al. (2023) shows that, among variation factors including prosodic position, word frequency, tonal contexts, and part of speech, lexical frequency has the most contribution to the SR tone's pitch realization in naturally occurring journalist speech.

Last but not least, some research has shown that fine phonetic detail may reflect subtle differences in meaning (Pierrehumbert et al., 2002). More recent studies supporting this possibility have investigated the spoken word duration of English heterographic homophones (Gahl and Baayen, 2022), the duration of English syllable-final /s/ (Tomaschek et al., 2021) and the duration of noun-verb conversion pairs (Lohmann, 2018). Chuang et al. (2024) report for conversational Taiwan Mandarin that the precise shape of the T2-T4 tone pattern is in part predictable from their meanings, while controlling for segment-related, speaker-related and contextual factors.

In summary, incomplete neutralization, while commonly found for Beijing Mandarin, is however visible but not significant in Taiwan Mandarin. Tonal variation is co-determined by phonetic factors such as tonal context, speaking rate and speaker variability, by sociophonetic factors such as a speaker's sociolect and gender, by the speaker's emotional state, by frequency of use, and by the details of words' meanings.

The present study is a follow-up of Yuan and Chen (2014), a study that addressed the acoustic characteristics of Tone 3 sandhi in spontaneous spoken Mandarin in large corpora of broadcast news and telephone conversations. The present study, however, investigates the tonal realization of disyllabic words with T2-T3 and T3-T3 in a corpus of face-to-face conversations in Taiwan Mandarin. Figure 1 provides examples of the tone contours of two words, 了解(liao3jie3, *to know*) (upper panels) and 媒體(mei2ti3, *media*) (lower panels) that illustrate the immense variation that characterizes pitch contours in this corpus. In our study, we leverage the power of the generalized additive model (GAM, Wood, 2017) to come grips with this variability and to come to a better understanding of four questions.

First, what is the tonal realization of disyllabic words with T2-T3 and T3-T3 tone pattern in spontaneous Taiwan Mandarin speech? Is there any difference between the tonal realization of the T2-T3 tone pattern and the T3-T3 tone pattern with tone sandhi? At the outset of the research reported below, we had no hypothesis about whether T3-T3 tone sandhi in Taiwan Mandarin is incomplete or complete. Anticipating the results reported below, for the data that we investigated, T3-T3 tone sandhi appears to be complete.



Figure 1: Example pitch contours for selected tokens of 了解(liao3jie3, *to know*) (upper panels) and 媒體(mei2ti3, *media*) (lower panels). Xu (1997) observed for laboratory speech that the f0 contours of T2-T3 and T3-T3 words consist of a slight fall, followed by a rise, and then a fall. A similar pattern is visible for the tokens at the left hand side, but very different realizations are found in the remaining panels.

Second, how does context affect tonal realizations? In the light of the results of the previous studies of Mandarin tones, we expect to replicate the effects of speaking rate, tonal context, the position of a word in its utterance, its conditional probability in context, the gender of the speaker, and speaker-specific habits of realising tone.

Third, does a word's frequency of occurrence co-determine the shape of its pitch contour? Our hypothesis with respect to this question is that once word duration and speaking rate are taken into account, frequency does not further modulate pitch. This hypothesis is motivated by two considerations. First, frequency of use is a lexical property that is time-invariant, and it is unclear to us why it would modulate pitch over time. Second, if frequency of use would have a systematic effect on the realization of pitch, one would expect this modulation to be visible across all tonal patterns in the same way. No such effect has been reported in the existing literature.

Fourth, is the shape of a word's pitch contour co-determined by its meaning? Based on the results obtained by Chuang et al. (2024) for the T2-T4 tone pattern in conversational Taiwan Mandarin, we expect that the fine details of how T2-T3 and T3-T3 tone contours are realized are word-specific and semantic in nature. If indeed words' meanings co-determine their pitch contours, then this in turn raises the question of whether evidence for incomplete neutralization is robust when words and words' senses are taken into account as control variables.

## 2 Materials and methods

## 2.1 Data

Data analysed in the present paper is taken from the Taiwanese Mandarin Spontaneous Speech Corpus (Fon, 2004), which consists of 30 hours of spontaneous conversations from speakers aged between 20 and 60 (31 females and 24 males). From this corpus we extracted 3937 word token with the T2-T3 tone pattern, representing 299 word types, and 4791 word tokens with the T3-T3 tone pattern, representing

269 word types. F0 measurements were obtained using Praat (Boersma and Weenink, 2020).

To ensure that for statistical analysis, sufficient numbers of tokens are available for each word type, words with fewer than 12 tokens were excluded from our dataset. For high-frequency words with more than 200 tokens, we randomly sampled 200 tokens, in order to avoid model predictions from being biased towards high-frequency words (Gahl and Baayen, 2022). As a consequence, every word type has a maximum of 200 tokens and a minimum of 12 tokens. Furthermore, in order to facilitate the statistical analysis of effects of gender, words contributed by only female speakers or only male speakers were excluded. We also made sure that tokens of one word type are contributed by two or more speakers, so as to avoid model prediction being biased by one specific speaker's way of speaking. Tokens with potential f0 tracking errors were removed on the basis of visual inspection. The resulting dataset contains 1462 tokens representing 20 word types with tone pattern T2-T3 and 878 tokens representing 20 word types with tone pattern T3-T3.

#### 2.2 Predictors

In our statistical analyses, the response variable is log-transformed pitch. The log-transformation was motivated by a Box-Cox analysis (Box and Cox, 1964). We modelled pitch as a function of normalized time. Table 1 provides an overview of variables that we considered in the statistical analysis.

Chuang et al. (2024) reported that word type is a strong predictor of tonal realization, outperforming a range of segmental properties of words' forms such as vowel height, onset, and rhyme structure. In the present study, we therefore use *word* as critical predictor, avoiding issues of collinearity that come with adding in segmental properties as predictors.

The study by Chuang et al. (2024) also argues that the effect of word type is semantic in nature. In support of this hypothesis, they show that prediction of pitch contours improves when (orthographic) word is replaced by word sense. Therefore, we made use of the same word sense identification system as used in their study, described in Hsieh et al. (2024), which uses BERT in combination with the Chinese WordNet (Huang et al., 2010). <sup>1</sup>

In our dataset, there are 4 words which have no word sense in the Chinese WordNet. For the remaining 36 words in our dataset, a total of 71 senses was identified. Most of the words have 1 to 3 senses. The distribution of senses is skewed towards the right, with about one-third of the senses having 6 tokens or fewer. To make sure that all senses have sufficient tokens for statistical evaluation, we first removed senses with fewer than 8 tokens. In addition, to prevent model predictions from being biased in favor senses with a large number of tokens, we sampled 40 tokens for each of the more frequently used senses. The resulting second dataset, prepared specifically for assessing the role of sense as opposed to orthographic word, contains in total 1144 tokens of 46 sense types (corresponding to 35 orthographic word types).

#### 2.3 Statistical analysis

One of the major challenges in analysing dynamic speech data, such as pitch contours, formant trajectories and tongue movements, is non-linear change over time (Wieling et al., 2016; Wieling, 2018; Chuang et al., 2021). The Generalized Additive Mixed Model (GAMM, Wood, 2017) has emerged as a flexible and powerful statistical method for analysing non-linear time-series data. It has been successfully applied to the analysis of f0 contours in various languages, including Mandarin (Chuang et al., 2024), Brazilian Portuguese (da Silva Miranda et al., 2020), Papuan Malay (Kaland et al., 2023), and French (Deng et al., 2023).

In this study, we make use of the **mgcv** package (Wood, 2017) for R (Team, 2020), using the bam function to model pitch as a function of time and the predictors listed above. As the distribution of

<sup>&</sup>lt;sup>1</sup>The authors thank Yu-Hsiang Tseng for identifying word sense for the dataset in the current paper.

normalized_tnormalized timeFor each token, time was rescaled between 0 and Speech rate was included as covariate to bring effect of durational differences under statistical control.gendergenderSpeakers were identified as male or female.tone_patterntonal patternRising-dipping (23) or dipping-dipping (33).spoken_freqcorpus frequencyNumber of occurrences of a word type in the Taiw corpus.written_freqword frequencyNumber of occurrences of a word type in the Sini Corpus of Taiwan Mandarin (Ma et al., 2001).tonal_contexttonal contextA factor with 36 levels representing the combinatio of the tone of the syllable immediately preceding token and the tone of the syllable immediately follow ing that token. Immediately preceding or followin pauses were coded with PAUSE instead of a to specification.speech_ratespeaking rateLocal speech rate, defined for a token as the numb of syllables per second calculated over the time p riod of four characters to the left and four character to the right of the token.	Abbreviation in R	Variable	Definition
Speech rate was included as covariate to bring effect of durational differences under statistical control.gendergenderSpeakers were identified as male or female.tone_patterntonal patternRising-dipping (23) or dipping-dipping (33).spoken_freqcorpus frequencyNumber of occurrences of a word type in the Taiw corpus.written_freqword frequencyNumber of occurrences of a word type in the Sini Corpus of Taiwan Mandarin (Ma et al., 2001).tonal_contexttonal contextA factor with 36 levels representing the combinatio of the tone of the syllable immediately preceding token and the tone of the syllable immediately follow ing that token. Immediately preceding or following pauses were coded with PAUSE instead of a to specification.speech_ratespeaking rateLocal speech rate, defined for a token as the numb of syllables per second calculated over the time p riod of four characters to the left and four character to the right of the token	normalized_t	normalized time	For each token, time was rescaled between 0 and 1.
of durational differences under statistical control.gendergenderSpeakers were identified as male or female.tone_patterntonal patternRising-dipping (23) or dipping-dipping (33).spoken_freqcorpus frequencyNumber of occurrences of a word type in the Taiw corpus.written_freqword frequencyNumber of occurrences of a word type in the Sini Corpus of Taiwan Mandarin (Ma et al., 2001).tonal_contexttonal contextA factor with 36 levels representing the combinatio of the tone of the syllable immediately preceding token and the tone of the syllable immediately follow ing that token. Immediately preceding or followin pauses were coded with PAUSE instead of a to specification.speech_ratespeaking rateLocal speech rate, defined for a token as the numb of syllables per second calculated over the time p riod of four characters to the left and four character to the right of that token.			Speech rate was included as covariate to bring effects
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spoken_freq   corpus frequency   Number of occurrences of a word type in the Taiw corpus.     written_freq   word frequency   Number of occurrences of a word type in the Sini Corpus of Taiwan Mandarin (Ma et al., 2001).     tonal_context   tonal context   A factor with 36 levels representing the combinatio of the tone of the syllable immediately preceding token and the tone of the syllable immediately following that token. Immediately preceding or following pauses were coded with PAUSE instead of a to specification.     speech_rate   speaking rate   Local speech rate, defined for a token as the number of syllables per second calculated over the time priod of four characters to the left and four character to the right of that token.	tone_pattern	tonal pattern	Rising-dipping (23) or dipping-dipping (33).
written_freq   word frequency   Number of occurrences of a word type in the Sini Corpus of Taiwan Mandarin (Ma et al., 2001).     tonal_context   tonal context   A factor with 36 levels representing the combinatio of the tone of the syllable immediately preceding token and the tone of the syllable immediately following that token. Immediately preceding or following pauses were coded with PAUSE instead of a to specification.     speech_rate   speaking rate   Local speech rate, defined for a token as the number of syllables per second calculated over the time priod of four characters to the left and four character to the right of that token.	spoken_freq	corpus frequency	Number of occurrences of a word type in the Taiwan corpus.
tonal_context   tonal context   A factor with 36 levels representing the combination of the tone of the syllable immediately preceding token and the tone of the syllable immediately following that token. Immediately preceding or following pauses were coded with PAUSE instead of a to specification.     speech_rate   speaking rate   Local speech rate, defined for a token as the numb of syllables per second calculated over the time priod of four characters to the left and four character to the right of that token.	written_freq	word frequency	Number of occurrences of a word type in the Sinica Corpus of Taiwan Mandarin (Ma et al., 2001).
speech_rate   speaking rate   Local speech rate, defined for a token as the numb of syllables per second calculated over the time p riod of four characters to the left and four character to the right of that token	tonal_context	tonal context	A factor with 36 levels representing the combinations of the tone of the syllable immediately preceding a token and the tone of the syllable immediately follow- ing that token. Immediately preceding or following pauses were coded with PAUSE instead of a tone specification.
to the right of that token.	speech_rate	speaking rate	Local speech rate, defined for a token as the number of syllables per second calculated over the time pe- riod of four characters to the left and four characters to the right of that token.
norm_utt_pos   word position in ut- terance   The normalized position of a token in its utterance     word utterance   represented on a scale from 0 to 1. Words in single word utterances were coded with 1.	norm_utt_pos	word position in ut- terance	The normalized position of a token in its utterance, represented on a scale from 0 to 1. Words in single- word utterances were coded with 1.
bg_prob_prevbigram probabilityThe probability of the occurrence of the target wo of the preceding given the preceding word (following (Gahl, 2008) word	bg_prob_prev	bigram probability of the preceding word	The probability of the occurrence of the target word given the preceding word (following (Gahl, 2008)).
bg_prob_fol   bigram probability   The probability of the occurrence of the following of the following word given the target word.	bg_prob_fol	bigram probability of the following word	The probability of the occurrence of the following word given the target word.
<i>speaker</i> speaker A factor with anonymized speaker identifiers as le els.	speaker	speaker	A factor with anonymized speaker identifiers as levels.
word word A factor with orthographic word, as available in t corpus, as levels. In this study, all words under inve- tigation are two-character words (e.g., 媒體(mei2ti media).	word	word	A factor with orthographic word, as available in the corpus, as levels. In this study, all words under investigation are two-character words (e.g., 媒體(mei2ti3, <i>media</i> ).
<i>sense</i> sense A factor with word sense instead of orthograph word, as levels.	sense	sense	A factor with word sense instead of orthographic word, as levels.
genderXtone genderXtone A factor for the interaction of gender by tone_patter	genderXtone	genderXtone	A factor for the interaction of gender by tone_pattern.

## Table 1: Predictors in the statistical analysis

pitch values has heavy tails, following Chuang et al. (2024), we use a scaled-t model for the errors. According to this model,  $(y - \mu)/\sigma \sim t_{\nu}$ , with  $\sigma$  and  $\nu$  parameters that are estimated alongside the smoothing parameters of the model. In the model specification reported in the next section, the directive family='scat' requests the scaled-t model.

We made use of thin plate regression spline smooths to model the effect of time and its interactions with gender, tone pattern. Thin plate regression splines were also used for taking into account the bigram probabilities of preceding and following words. We used tensor product smooths for modeling interactions of time and continuous predictors such as speech rate, utterance position, and bigram probabilities. We used the ti() directive to single out the effect of the interaction and tease it apart from its corresponding main effects. Factor smooths for time were incorporated for speaker, and separately, for word. These factor smooths (specified as s(time, pred, bs="fs", m=1)) represent nonlinear random effects of subject and word, and include shrunk estimates of by-subject and by-word intercepts.

## **3** Results

The model that we proposed for the present data was obtained by fitting a series of increasingly complex GAMM to the dataset. The best model resulting from this exploratory investigation of the Mandarin pitch contours was specified follows:

```
pitch ~ genderXtone+
s(normalized_t, by=genderXtone) +
s(speech_rate, by=gender, k=5) +
ti(normalized_t, speech_rate) +
s(normalized_t, tonal_context, bs='fs', m=1) +
s(normalized_utt_pos)+
ti(normalized_t, normalized_utt_pos) +
s(bg_prob_prev, k=5) +
ti(normalized_t, bg_prob_prev, by=gender) +
s(bg_prob_fol, k=5) +
ti(normalized_t, bg_prob_fol, by=gender) +
s(normalized_t, speaker, bs='fs', m=1) +
s(normalized_t, word, bs='fs', m=1),
data=dat, family='scat'
```

Table 2 therefore reports the increase in AIC when conceptually related sets of terms in the model are withheld from the GAMM. Invariably, these increases are large, indicating that all terms are contributing to making model predictions more precise. Table 3 provides a summary of this model. As this model does not take into account the autocorrelation in the model residuals, the p-values in Table 3 are therefore potentially anti-conservative; see Chuang et al. (2024) for detailed discussion. In what follows, we first briefly discuss the parametric coefficients of this model, and then report in more detail on the smooth terms of the model.

Model term	Increase in AIC
time : genderXtone	35.25
speech rate	515.29
tonal context	3233.60
word position in utterance	2697.26
bigram probability of preceding word	854.78
bigram probability of following word	257.15
speaker	37403.08
word	11622.49

Table 2: Increase in AIC when one or more conceptually related predictors is removed from the model specification.

## 3.1 Parametric coefficients

The reference level of the genderXtone interaction is the T2-T3 tone pattern for female speakers. The contrast effect for T2-T3 for male speakers indicates that, as expected, the male speakers' T2-T3 contour is realized with a lower overall pitch. The T3-T3 intercept for female speakers does not differ from the general intercept, and the T3-T3 contrast for male speakers is again pointing to a lower overall pitch. Given that the two contrasts for male speakers are very similar (-0.5116 and -0.5393), the parametric coefficients considered jointly simply indicate that, irrespective of tone pattern, male speakers realized pitch contours with lower voices.

## 3.2 Smooth terms

## 3.2.1 Time by gender by tone pattern

The first non-linear term in the model, s(normalized\_t, by=genderXtone) requests four smooths of time, one for each combination of *gender* and *tone\_pattern*. Figure 2 illustrates the partial effect of each gender within the two tone patterns. The panels for the speakers identified as female (orange) are fairly similar, and the same holds for the panels representing the speakers identified as male (blue), suggesting that female and male speakers realize their pitch contours in slightly different ways. At the same time, within each gender group, there is no clear difference between the T2-T3 and the T3-T3 tone pattern.

The interaction of time by gender by tone pattern is supported by a lower AIC compared to a model that only includes a general smooth for time (difference in AIC: 28.64). However, model comparison based on the fREML scores (evaluated using the compareML function from the **itsadug** package) suggests the simpler model (with only one smooth for time, irrespective of gender and tone pattern) is to be preferred. Thus, it is unclear whether the difference in tonal realization between men and women will replicate. What is clear is that there is no evidence for incomplete neutralization of the T3-T3 tone pattern.

## 3.2.2 Speaking rate by time by gender

Figure 3 visualizes the interaction of speaking rate by time by gender, which we modeled with thin plate regression smooths for gender, and a tensor product smooth for the interaction of time by speaking rate. In order to keep the model relatively simple, we did not differentiate this tensor product smooth by gender. The partial effect of speaking rate showed an undulating effect for males but hardly any effect for females. The contour plot for the interaction of time by speech rate suggests that early in the word, a greater speaking rate leads to higher pitch, that in the middle of the word, this pattern

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	5.2871	0.0257	205.8844	< 0.0001
genderXtonemale.23	-0.5122	0.0322	-15.9109	< 0.0001
genderXtonefemale.33	-0.0193	0.0197	-0.9823	0.3260
genderXtonemale.33	-0.5395	0.0377	-14.3083	< 0.0001
B. smooth terms	edf	Ref.df	F-value	p-value
s(normalized_t):genderXtonefemale.23	6.1705	6.7769	11.4109	< 0.0001
s(normalized_t):genderXtonemale.23	4.9361	5.5943	8.4417	< 0.0001
s(normalized_t):genderXtonefemale.33	6.0398	6.7379	7.6195	< 0.0001
s(normalized_t):genderXtonemale.33	4.4693	5.1273	9.5167	< 0.0001
s(speech_rate):genderfemale	3.8280	3.9755	8.0368	< 0.0001
s(speech_rate):gendermale	3.9382	3.9961	59.0482	< 0.0001
ti(normalized_t,speech_rate)	13.8236	15.1968	18.3591	< 0.0001
s(normalized_t,tonal_context)	210.9778	323.0000	11.0770	< 0.0001
s(normalized_utt_pos)	8.6143	8.9515	234.0855	< 0.0001
ti(normalized_t,normalized_utt_pos)	14.3050	15.4408	11.1536	< 0.0001
s(bg_prob_prev)	3.4937	3.8402	124.3146	< 0.0001
ti(normalized_t,bg_prob_prev):genderfemale	14.8264	15.6493	11.6598	< 0.0001
ti(normalized_t,bg_prob_prev):gendermale	11.1383	12.8538	5.0413	< 0.0001
s(bg_prob_fol)	3.8657	3.9839	26.5794	< 0.0001
ti(normalized_t,bg_prob_fol):genderfemale	9.6684	11.5367	7.1417	< 0.0001
ti(normalized_t,bg_prob_fol):gendermale	12.2406	14.0435	7.1298	< 0.0001
s(normalized_t,speaker)	359.8600	493.0000	104.9463	< 0.0001
s(normalized_t,word)	255.1873	358.0000	37.9884	< 0.0001

Table 3: Model summary of GAMM fitted to the pitch contours of Taiwan Mandarin T2-T3 and T3-T3 words.



Figure 2: Plots of the partial effect of the three-way interaction of time by gender by tone pattern. Panel 1 and panel 2 shows the partial effect of tone pattern T2-T3 for female and male speakers respectively, and panel 3 and panel 4 show the partial effect of tone pattern T3-T3 for female and male speakers respectively. The dashed red vertical line indicates the average syllable boundary. The dashed red horizontal line indicates the x-axis.

reverses, and that near the end of the word, this pattern reverses once more. As speaking rate is a control variable, we refrain from seeking explanations for the patterns that the GAMM detected.



Figure 3: Speech rate by gender. Left panel: partial effect for female speakers, center panel: partial effect for male speakers, right panel: interaction of speech rate by time, for both genders.

#### 3.2.3 Tonal context

Figure 4 shows how the pitch contour varies with the 25 levels of tonal context, while keeping all other predictors constant. These context-specific pitch contours show great variability. By way of example, consider the green curve that starts in the lower left and ends in the upper right. This curve represents T2-T3 or T3-T3 words embedded between words ending and beginning with a dipping tone (tone 3). Apparently, the preceding dipping tone has a lowering effect on pitch, while the following dipping tone has a raising effect. We note here that sequences of 4 dipping tones (e.g., in our data, 你可以解釋(*ni3 ke3yi3 jie3shi4*, 'you can explain')) have been reported to show substantial inter-speaker variability.



Figure 4: Plot of the partial effect of the tonal context. In the legend, tonal contexts are indicated by the preceding and following tones.

#### 3.2.4 Time by word position

Words that occur later in an utterance tend to have lower pitch, as expected (see the left panel of Figure 5) (Shih, 2000). The contour plot for the interaction of position by time in this figure is less straightforwardly interpretable, and the very large effects near the end of the word are likely unreliable, given that words in single-word utterances were given 1.0 as word position.



Figure 5: Partial effect of word position in utterance. Left panel: partial main effect; fright panel: interaction of word position by time.

#### 3.2.5 Time by probability by gender

Figure 6 presents the partial effects involving the probabilities of the preceding and following words. The left panels present the main effects of the bigram probabilities of the preceding word (upper row) and the following word (lower row). For both, a general downward trend emerges that is stronger for the probability of the preceding word. These probabilities interacted with time in ways that differed between female and male speakers, as shown by the contour plots in the center and right columns. These interactions, although well-supported by the GAM model, are not interpretable without theoretical guidance, and we therefore refrain from further discussion.<sup>2</sup>

#### 3.2.6 Speaker

In order to take the structural variability associated with individual speakers into account, we included by-speaker factor smooths for time. Figure 7 presents four speaker-specific pitch 'habits', for two females (left two panels) and two males (right two panels). These modulations of the pitch contour are independent of the gender-specific effects reported above (see Figure 2). Speaker 1 has a higher pitch than speaker 2, and within the set of male speakers, speaker 4 has a higher pitch than speaker 3. Each of these four speakers further modulate their pitch contours in their own way.

#### 3.2.7 Word

Figure 8 presents the partial effect of Word for a subset of the words in our dataset. All examples shown concern words with the same canonical tone pattern T3-T3. Within the very same tone pattern, many words have their own f0 fingerprints. For instance, 了解 (*liao3jie3*, 'to understand'), last row, second panel, has a mainly rising signature, 好好 (*hao3hao3*, 'properly') has a u-shaped pattern, and 總統 (*zong3tong3*, 'president') has a rise-fall pattern.

<sup>&</sup>lt;sup>2</sup>There is evidence that the main effects of the bigram probabilities are further modulated by gender, but in order to avoid further model complexity, these interactions were not included. We note here that inclusion of these interactions further improves model fit, but does not affect the partial effects that we report and discuss.



Figure 6: Bigram probabilities. Row 1: Bigram probability of preceding word. Left panel: partial main effect; center panel: interaction of bigram probability, for female speakers; right panel: interaction of bigram probability by time, for male speakers. Row 2: Bigram probability of following word. Left panel: partial main effect; center panel: interaction of bigram probability, for female speakers; right panel: partial main effect; center panel: interaction of bigram probability, for female speakers; right panel: partial main effect; center panel: interaction of bigram probability, for female speakers; right panel: partial main effect; center panel: interaction of bigram probability by time, for male speakers.



Figure 7: Partial effect plots for speaker-specific modulations of the pitch contour, for two female (orange) and two male (blue) speakers. The dashed red vertical line represents the average syllable boundary in disyllabic words. The dashed red horizontal line indicates x-axis.



Figure 8: Partial effects of the factor smooth for Word, illustrated for selected example words of the tonal pattern T3-T3. The dashed grey vertical line represents the average syllable boundary in disyllabic words. The dashed grey horizontal line indicates the x-axis.

Figure 8 displays word-specific tone contours for words with the assimilated tone pattern T3-T3. A similar variety of word-specific tone contours characterizes the T2-T3 pattern. It is noteworthy that the two tone patterns show exactly the same kind of word-specific tone signatures, an observation that dovetails well with the T3-T3 and the T2-T3 tone pattern sharing the same basic contour (cf. Figure 2).

#### **3.3** Variable importance

In order to assess the variable importance of the predictors, we calculated the increase in AIC when a predictor is withheld from the model specification. The left panel of Figure 9 clarifies that *speaker* and *word* have the greatest variable importance. The blue dots in this panel clarify that when a predictor and *word* are withheld jointly, the additional increase in AIC is roughly the same for all predictors, indicating that the effect of *word* cannot be traced back to the effects of other predictors.

The right panel of Figure 9 presents the concurvity scores for the predictors in the left panel. These scores, which range between 0 and 1, indicate to what extent the effect of a predictor is confounded with the effect of other predictors in the model. Concurvity scores are lowest for tonal context, speaker and word, which allows us to conclude that the effects of these predictors are mostly independent of the effects of the other predictors in the model. Conversely, concurvity scores are much higher for speech rate, utterance position, and bigram probabilities. This is perhaps unsurprising given that, for instance, speech rate tends to decrease as an utterance unfolds (r = -0.08, p < 0.0001), whereas bigram probability conditioned on the following word decreases with a word's position in the sentence (r = -0.29, p < 0.0001).



Figure 9: Variable importance (a) and concurvity (b) for selected terms in the GAMM fitted to the pitch contours of T2-T3 and T3-T3 words. Variable importance is evaluated with the increase in AIC when a predictor is withheld from the model specification (orange dots). In the left panel, the blue dots show the additional increase in AIC when a predictor is withheld together with word. Concurvity scores are calculated for the GAMM with all predictors included (summarized in Table 3).

## **4** Interpreting the effect of word

We have seen that *word* is an important predictor of how pitch contours are realized. This raises the question of what this effect reflects. In what follows, we first consider the possibility that the effect of *word* is actually a word frequency effect, as Yuan and Chen (2014) reported that lower-frequency words show stronger tone sandhi for T3-T3 words. We then consider the possibility that the effect of *word* is semantic in nature, given the results reported by Chuang et al. (2024).

## 4.1 A word frequency effect?

In order to clarify whether the effect of word can be traced back to an effect of frequency of use, we considered two word frequency measures: *spoken\_freq* (the frequency of word in the current corpus of spoken Taiwan Mandarin) and *written\_freq* (the frequency of word from in the written Sinica corpus).

As shown in Table 4, spoken frequency (including an interaction of frequency by normalized time) improves model fit by 5557.980 AIC units and written frequency (including an interaction of frequency by normalized time) improves model fit by 5712.524 AIC units. However, frequency is confounded with word type. For instance, there are 39 distinct written frequency values for 40 word types. This raises the question of whether the effect of word is actually an effect of frequency. Two observations argue against this possibility. First, adding word as a predictor to a model that already includes frequency as predictor leads to a substantial improvement in model fit (by 11904 and 11905 AIC units respectively). Second, a simpler model that includes word, but not word frequency, provides a fit that is just as good as a model with word and word frequency as predictors (see Table 4, last row). This allows us to conclude that word has an independent effect on tonal realizations that cannot be reduced to word frequency.

Table 4: The AIC scores of GAM models fitted with *word*, and with *spoken frequency* (word frequency in the Taiwan spoken corpus) or *written frequency* (frequency of use the much larger written Sinica Corpus of Taiwan Mandarin) replacing word as predictor, or added as additional predictor.

Model	AIC	AIC decrease
final GAMM with all other predictors, but without word	-58272.36	
all other predictors + spoken frequency	-63830.34	5557.980
all other predictors + written frequency	-63984.89	5712.524
all other predictors + spoken frequency + word	-70177.13	11904.768
all other predictors + written frequency + word	-70177.39	11905.028
all other predictors + word	-70177.17	11904.810

#### 4.2 Word or word sense?

Chuang et al. (2024) reported that replacing word by word sense improved GAM models fitted to the f0 contours of two-character words with the T2-T4 tone pattern. We therefore investigated whether word sense is also a superior predictor for the present dataset of words with the T3-T3 and T2-T3 tone patterns. More specifically, we used the same model specification as presented in section 3, but fitted two GAMM to the smaller dataset with 1144 tokens of 46 sense types. The first GAMM incorporated by-word factor smooths. In the second GAMM, these by-word factor smooths were replaced with by-sense factor smooths.

As shown in Table 5, replacing the by-word factor smooth with a by-sense factor smooth leads to a substantial further improvement in model fit by 676.72 AIC units. Furthermore, the concurvity score for the by-sense smooths (0.289) was slightly smaller than the corresponding score for the by-word

smooths, which allows us to conclude that replacing word by sense did not lead to overfitting. This result supports the hypothesis that tonal variation is more strongly tied to word sense than to word.

Table 5: The AIC scores of models with different predictor structures fitted to a smaller dataset.

Model	AIC
model with all other predictors + word	-41463.52
model with all other predictors + word sense	-42140.24

Figure 10 presents the partial effect tonal contours for different senses of two words: 有 (*mei2you3*, 'none') in tone pattern T2-T3 and 只有 (*zhi3you3*, 'only') in tone pattern T3-T3. Although the senses for 有 (left panel, from s1 to s5, are: 'there is not', 'not have', 'do not', 'be not as...as...', 'expressing questioning') are fairly similar, they show up with fairly distinct tonal contours: a rising contour for s1, a dipping contour for s5, and a rise-fall for s2. The contours for 只有 (right panel, 'from s1 to s4 are: 'only', 'exceptional', 'only if', and 'just') are more similar, with the strong fall for s4 standing out most.

The enhanced precision offered by sense as compared to word provides further evidence for the hypothesis offered by Chuang et al. (2024) that the fine details of Taiwan Mandarin pitch contours are functional in that they facilitate understanding what words mean given the phonetic signal. For other studies reporting a close relation between semantics and phonetic realization, see (Chuang et al., 2021; Gahl and Baayen, 2024; Schmitz, 2022; Saito, 2024).

The observation that words with the same tonal pattern show different tonal realization depending on their semantics dovetails well with usage-based approaches to speech production (Bybee, 2003; Hawkins, 2003; Pierrehumbert et al., 2002) as well as examplar-based approaches — see, for instance, Li (2016), who reported that neutralization of Fuzhou tone sandhi requires a hybrid phonological competence model encompassing both abstract categories and stored exemplars. For evidence based on computational modeling that meaning and pitch are intimately related and learnable, see Chuang et al. (2024).

Having presented the full GAM model for our data, we examine once more whether there is any evidence for incomplete neutralization of the T3-T3 pattern. As a first step, we compared three GAMs, one with separate contours for each combination of speaker gender and tone pattern, one with separate smooths for the two tone patterns but without an interaction with gender, and one with only a general smooth for time. The AIC scores for these three models were basically identical (-42140.24, -42141.47 and -42141.23), so we prefer the simplest model with only a general smooth for time that is the same across genders and tone patterns.

As a second step, we considered the possibility that incomplete neutralization is visible in our dataset when word or word sense are not included as predictors. When the factor smooth for word is removed from the model specification, a general smooth by tone pattern is supported by a lower AIC compared to a model that only includes a general smooth for time (difference in AIC: 119.09). When the factor smooth for sense is removed from the model specification, we observe the same: a general smooth by tone pattern is supported by a lower AIC compared to a model that only includes a general smooth for time (difference in AIC: 204.85). However, all models without word or word sense as predictors are substantially inferior to the models that include these predictors (AIC differences increase by two orders of magnitude). We conclude that there is no evidence in our data for incomplete neutralization in conversational Taiwan Mandarin, once word or word sense are in place as proper controls.



Figure 10: Examples of the partial effect tonal contours for different senses of the words 有 (*mei2you3*, 'not have' (left panel) and 只有 (*zhi3you3*, 'only', (right panel). The senses in the left panel, from s1 to s5, are: 'there is not', 'not have', 'do not', 'be not as...as...', 'expressing questioning'. The senses in the right panel (from s1 to s4) are: 'only', 'exceptional', 'only if', and 'just'. The vertical dashed lines indicate average syllable boundaries.

## **5** General discussion

Previous literature has reported that there is an incomplete neutralization process of Tone 3 sandhi in Beijing Mandarin (Xu, 1997). Xu (1997) showed for laboratory speech that T2-T3 and T3-T3 tones exhibit very similar contours, characterized by a initial slight fall, followed by a clear rise, and then a large fall. At the same time, the contour for T2-T3 was found to have a slightly higher pitch across most of the two syllables. Yuan and Chen (2014) reported for standard Mandarin connected speech (telephone conversations and news broadcasts) that the sandhi T3 in T3-T3 words differs with the T2 in T2-T3 in terms of the magnitude and time span of f0 rising. However, the difference between T2-T3 and T3-T3 was reported not to be statistically significant in Taiwan Mandarin laboratory speech (Peng, 2000).

We investigated the realization of Tone 3 sandhi in conversational speech recorded in Taipei. Above (in Figure 1), we presented a sample of pitch contours for bi-character words, and observed not only that the description given by Xu (1993) holds only for some tokens, but also that words can have very different actual pitch contours. The difference between T2-T3 and T3-T3 reported by Yuan and Chen (2014) is also not clearly visible in Figure 1. For example, the logarithm of the ratio of between the f0 at syllable offset and minimum f0 in their data of telephone conversation appears to have always been positive (see their Figures 1), which means that the f0 at the syllable offset is always greater than the minimum f0. But in our data on Taiwan Mandarin, there are tokens for which the logarithm of this ratio would be 0 (see the token LJS\_GY\_6870\_媒體in Figure 1 which has a fall in its first syllable).

We made use of the generalized additive model (Wood, 2017) to predict pitch as a function of (normalized) time. Unlike previous studies, we have taken into account a wide range of factors known to co-determine the realization of pitch (speech rate, position in the sentence, speaker gender, conditional bigram probabilities, word and tonal context). A further, new control variable that we took into account was word sense (Chuang et al., 2024). With these factors controlled for, for spontaneous conversational Taiwan Mandarin, the difference between T2-T3 and T3-T3 in Taiwan Mandarin is not statistically significant, though graphically we can observe some slight differences. Therefore, in line with previous research, we failed to find solid evidence for the incomplete neutralization of Tone 3 sandhi in informal Taiwan Mandarin.

This disparity with the study by Yuan and Chen (2014) can be attributed to several factors, such as differences in the register of the speech (telephone speech and news broadcasts as opposed to spontaneous face-to-face conversation), differences between the dialects of Mandarin sampled (Beijing Mandarin as opposed to Taiwan Mandarin, which is influenced by Southern Min), methodology (point measurements as opposed to modeling full f0 contours), and the absence of word or word sense as controls. It is of course possible that in Beijing Mandarin, the tone sandhi is indeed incomplete even when word or word sense are included as predictors. We leave this issue for future research.

In our GAMM analysis, word outperforms lexical frequency as a predictor of the f0 contour. Furthermore, when word-specific f0 components are replaced by sense-specific f0 components in a further analysis, model fit improves further.

In summary, our analyses indicate, first, that in conversational Taiwan Mandarin, Tone 3 preceding Tone 3 completely assimilates to Tone 2, and second, that f0 contours vary systematically with word sense. The effect of word sense is of similar magnitude as that of tonal context. Apparently, disyllabic words have their own f0 fingerprint in Taiwan Mandarin Chinese conversational speech, irrespective of whether the tone of the first character is T2 or T3.

The current study extends research on Tone 3 sandhi from careful speech to spontaneous conversations. Following Chuang et al. (2024), we have harnessed the power of the generalized additive model, which made it possible to model complete f0 trajectories as a function of (normalized) time, instead of point estimates gauging aspects of f0 contours (such as the magnitude, and the duration, of the f0 rise). One direction for future research is to investigate the realization of T2-T3 and T3-T3 tone patterns in spontaneous conversations in other dialects of Mandarin Chinese, including Beijing Mandarin. Another topic for further investigation is the observed word-specific or sense-specific pitch signatures that the GAMM reports for Taiwan Mandarin. Are these pitch signatures completely dialect specific, or do they generalize to other dialects? Given that dialects have features in common, but also differ, we expect that some pitch signatures will be shared, whereas others will be dialect-specific. A third area of investigation is the existence of word or sense-specific pitch signatures for all tone patterns, and not just the T2-T4 pattern studied by Chuang et al. (2024), and the T2-T3 and T3-T3 patterns scrutinized in the present study.

#### **Declaration of interest statement**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## References

- Boersma, P. and D. Weenink (2020). Praat: doing phonetics by computer [Computer program]. Version 6.0. 37, 2018.
- Box, G. E. P. and D. R. Cox (1964). An analysis of transformations (with discussion). *Journal of the Royal Statistical Society B* 26, 211–252.
- Brenner, D. (2013). The acoustics of Mandarin tones in careful and conversational speech. *The Journal* of the Acoustical Society of America 134(5\_Supplement), 4246–4246. Publisher: AIP Publishing.
- Bybee, J. (2003, February). Phonology and Language Use. Cambridge University Press.
- Chang, H.-S., C.-Y. Lee, X. Wang, S.-T. Young, C.-H. Li, and W.-C. Chu (2023, April). Emotional tones of voice affect the acoustics and perception of Mandarin tones. *PLOS ONE 18*(4), e0283635. Publisher: Public Library of Science.
- Chao, Y. R. (1968). A grammar of spoken Chinese. Univ of California Press.
- Chen, X., C. Zhang, Y. Chen, S. Politzer-Ahles, Y. Zeng, and J. Zhang (2022). Encoding categorylevel and context-specific phonological information at different stages: An EEG study of Mandarin third-tone sandhi word production. *Neuropsychologia* 175, 108367. Publisher: Elsevier.
- Cheng, C., J.-Y. Chen, and M. Gubian (2013). Are Mandarin sandhi tone 3 and tone 2 the same or different? The results of functional data analysis. In *Proceedings of the 27th Pacific Asia Conference on Language, Information, and Computation (PACLIC 27)*, pp. 296–301.
- Chuang, Y.-Y., M. J. Bell, Y.-H. Tseng, and R. H. Baayen (2024). Word-specific tonal realizations in mandarin. *Manuscript, University of Tübingen*.
- Chuang, Y.-Y., J. Fon, I. Papakyritsis, and H. Baayen (2021). Analyzing phonetic data with generalized additive mixed models. In *Manual of clinical phonetics*, pp. 108–138. Routledge.

- Chuang, Y.-Y., M. L. Vollmer, E. Shafaei-Bajestan, S. Gahl, P. Hendrix, and R. H. Baayen (2021, June). The processing of pseudoword form and meaning in production and comprehension: A computational modeling approach using linear discriminative learning. *Behavior Research Methods* 53(3), 945–976.
- Cui, P., J. Kuang, and Y. Wang (2020). The effect of focus and prosodic boundary on the two t3 sandhi in northeastern mandarin. *Jia* 12(53), 42.
- da Silva Miranda, L., C. G. da Silva, J. A. Moraes, and A. Rilliard (2020). Visual and auditory cues of assertions and questions in Brazilian Portuguese and Mexican Spanish: a comparative study. *Journal of Speech Sciences*, 73–92.
- Deng, D., F. Wang, and R. Wayland (2023). The pitch contour of the French discourse marker donc: A corpus-based study using generalized additive mixed modeling. *Journal of French Language Studies*, 1–33. Publisher: Cambridge University Press.
- Fon, J. (2004). A preliminary construction of Taiwan Southern Min spontaneous speech corpus. Technical report, Tech. Rep. NSC-92-2411-H-003-050, National Science Council, Taiwan.
- Fon, J. and W.-Y. Chiang (1999). What Does Chao Have to Say About Tones? —A Case Study of Taiwan Mandarin / 氏系与之及量化–以台地例. *Journal of Chinese Linguistics* 27(1), 13–37. Publisher: [Chinese University Press, Project on Linguistic Analysis].
- Gahl, S. (2008). Time and thyme are not homophones: The effect of lemma frequency on word durations in spontaneous speech. *Language* 84(3), 474–496. Publisher: Linguistic Society of America.
- Gahl, S. and R. H. Baayen (2022). Time and thyme again: Connecting spoken word duration to models of the mental lexicon. https://osf.io/kxpaj/.
- Gahl, S. and R. H. Baayen (2024). Time and thyme again: Connecting English spoken word duration to models of the mental lexicon. *Language*, page accepted.
- Hawkins, S. (2003). Roles and representations of systematic fine phonetic detail in speech understanding. *Journal of phonetics 31*(3-4), 373–405. Publisher: Elsevier.
- Hsieh, S.-K., Y.-H. Tseng, H.-Y. Chou, C.-W. Yang, and Y.-Y. Chang (2024, January). Resolving Regular Polysemy in Named Entities. arXiv:2401.09758 [cs].
- Huang, C.-R., S.-K. Hsieh, J.-F. Hong, Y.-Z. Chen, I.-L. Su, Y.-X. Chen, and S.-W. Huang (2010). Chinese wordnet: Design, implementation, and application of an infrastructure for cross-lingual knowledge processing. *Journal of Chinese information processing* 24(2), 14–23.
- Kaland, C., M. Swerts, and N. P. Himmelmann (2023, January). Red and blue bananas: Time-series f0 analysis of contrastively focused noun phrases in Papuan Malay and Dutch. *Journal of Phonetics 96*, 101200.
- Kratochvil, P. (1984). Phonetic tone sandhi in Beijing dialect stage speech. *Cahiers de Linguistique Asie Orientale 13*(2), 135–174. Company: Persée Portail des revues scientifiques en SHS Distributor: Persée Portail des revues scientifiques en SHS Institution: Persée Portail des revues scientifiques en SHS Label: Persée Portail des revues scientifiques en SHS Publisher: Centre de Recherches Linguistiques sur l'Asie Orientale EHESS.
- Kratochvil, P. (1987). The case of the third tone. the Chinese Language Society of Hong Kong (eds.), Wang Li Memorial Volumes, English Volume, 253–277.

- Li, Y. (2016). Complete and incomplete neutralisation in fuzhou tone sandhi. In *Proc. 5th International Symposium on Tonal Aspects of Languages (TAL 2016)*, pp. 116–120.
- Liang, L. and X. Meng (2011). A Sociophonetic Study on Tones of Chongqing Mandarin in Gender and Age Difference. In *International Congress of Phonetic Sciences (ICPhS 2023)*, pp. 1230–1233.
- Lohmann, A. (2018). Cut (n) and cut (v) are not homophones: Lemma frequency affects the duration of noun-verb conversion pairs. *Journal of Linguistics* 54(4), 753–777. Publisher: Cambridge University Press.
- Ma, W.-Y., Y.-M. Hsieh, C.-H. Yang, and K.-J. Chen (2001). 中文語料庫構建及管理系統設計(Design of Management System for Chinese Corpus Construction)[In Chinese]. In *Proceedings* of Research on Computational Linguistics Conference XIV, pp. 175–191.
- Myers, J. and J. Tsay (2003). Investigating the phonetics of Mandarin tone sandhi. *Taiwan Journal of Linguistics 1*(1), 29-68. Publisher: 政治大學語言學研究所暨英國語文學系.
- Peng, S.-H. (2000). Lexical versus 'phonological'representations of Mandarin sandhi tones. *Papers in laboratory phonology V: Acquisition and the lexicon 5*, 152. Publisher: Cambridge University Press Cambridge.
- Pierrehumbert, J., C. Gussenhoven, and N. Warner (2002). Word-specific phonetics. *Laboratory phonology* 7.
- Saito, M. (2024). Enhancement effects of frequency: An explanation from the perspective of Discriminative Learning. Doctoral dissertation, University of Tübingen.
- Schmitz, D. (2022). Production, perception, and comprehension of subphonemic detail: Word-Final/s/in English. Language Science Press.
- Shen, X. S. (1990). Tonal coarticulation in Mandarin. *Journal of Phonetics 18*(2), 281–295. Publisher: Elsevier.
- Shih, C. (1986). *The prosodic domain of tone sandhi in Chinese*. Doctoral dissertation, University of California at San Diego.
- Shih, C. (2000). A declination model of Mandarin Chinese. In *Intonation: Analysis, modelling and technology*, pp. 243–268. Springer.
- Stanford, J. N. (2016, January). Sociotonetics using connected speech: A study of Sui tone variation in free-speech style. Asia-Pacific Language Variation 2(1), 48–82. Publisher: John Benjamins.
- Team, R. C. (2020). R Core Team R: a language and environment for statistical computing. *Foundation for Statistical Computing*.
- Tian, Z., X. Dong, F. Gao, H. Wang, and C. Lin (2022, September). Mandarin Tone Sandhi Realization: Evidence from Large Speech Corpora. In *Interspeech 2022*, pp. 5273–5277. ISCA.
- Tomaschek, F., I. Plag, M. Ernestus, and R. H. Baayen (2021). Phonetic effects of morphology and context: Modeling the duration of word-final S in English with naïve discriminative learning. *Journal of Linguistics* 57(1), 123–161. Publisher: Cambridge University Press.
- Tucker, B. V. and M. Ernestus (2016, December). Why we need to investigate casual speech to truly understand language production, processing and the mental lexicon. *The Mental Lexicon* 11(3), 375–400.

- Wagner, P., J. Trouvain, and F. Zimmerer (2015). In defense of stylistic diversity in speech research. *Journal of Phonetics* 48, 1–12. Publisher: Elsevier.
- (2011). Warner. N. Reduction. In The Blackwell Companion to Phonol-1 - 26.John Wiley & Sons, Ltd. Section: 79 \_eprint: ogy, pp. https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781444335262.wbctp0079.
- Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics* 70, 86–116. Publisher: Elsevier.
- Wieling, M., F. Tomaschek, D. Arnold, M. Tiede, F. Bröker, S. Thiele, S. N. Wood, and R. H. Baayen (2016). Investigating dialectal differences using articulography. *Journal of Phonetics* 59, 122–143. Publisher: Elsevier.
- Wood, S. N. (2017). Generalized additive models: an introduction with R. CRC press.
- Wu, Y., Y. Chen, and L. Lamel (2023). Realization of low tone sequences in disyllabic words in a large mandarin speech corpus. In *International Congress of Phonetic Sciences (ICPhS 2023)*, pp. 1891–1895.
- Wu, Y., L. Lamel, and M. Adda-Decker (2021). Tone realization in Mandarin speech: a large corpus based study of disyllabic words. In 2021 12th International Symposium on Chinese Spoken Language Processing (ISCSLP), pp. 1–5. IEEE.
- Xu, Y. (1993). Contextual tonal variation in Mandarin Chinese. University of Connecticut.
- Xu, Y. (1997, January). Contextual tonal variations in Mandarin. Journal of Phonetics 25(1), 61-83.
- Xu, Y. and X. Sun (2002). Maximum speed of pitch change and how it may relate to speech. *The Journal of the Acoustical Society of America 111*(3), 1399–1413. Publisher: Acoustical Society of America.
- Yuan, J. and K. Church (2021, June). Speaking Rate and Tonal Realization in Mandarin Chinese: What Can We Learn From Large Speech Corpora? *ICASSP 2021 - 2021 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 6463–6467. Conference Name: ICASSP 2021 - 2021 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) ISBN: 9781728176055 Place: Toronto, ON, Canada Publisher: IEEE.
- Yuan, J. H. and Y. Chen (2014). 3rd tone sandhi in standard Chinese: A corpus approach. *Journal of Chinese Linguistics* 42(1), 218–237.
- Zee, E. (1980). A spectrographic investigation of Mandarin tone sandhi. UCLA working papers in phonetics 49(9), 98–116.
- Zhang, S., P. C. Ching, and F. Kong (2006). Acoustic analysis of emotional speech in Mandarin Chinese. In *International symposium on Chinese spoken language processing*, pp. 57–66. Citeseer.