A quantitative analysis of tone sandhi in Standard Mandarin and Nanjing Mandarin based on surface pitch contours and underlying pitch targets

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Abstract Two statistical modelling methods are first used to quantify the third tone sandhi in Standard Mandarin in which the first falling-rising T3 becomes a rising T2 in the T3 + T3 disyllabic context. Growth curve analysis suggests non-neutralization of the surface f0 contours of the sandhi tone and its corresponding citation tone (T2), whereas a quantitative f0 target approximation model reveals neutralization of their underlying pitch targets, congruent with the stable and categorical tone shift properties of tone sandhi processes. The same statistical procedure is successfully extended to examine tone sandhi rules in Nanjing Mandarin. Our analysis leads to a proposal to change tonal values based on the Chao's number system of some Nanjing Mandarin monosyllabic tones. The transformation method from acoustic data to Chao's number applies well to our data and proves superior to those previously described in the literature.

Keywords: tone sandhi, growth curve analysis, linear systems, underlying pitch target, Standard Mandarin, Nanjing Mandarin

1. Introduction

The phonological and categorical nature of tone sandhi has been studied for decades based on impressionistic data, acoustic data, and perceptual experiments (e.g., Chao 1948; Shen 1992; Peng 2000). Unlike the phonetic and gradient phenomenon of tonal coarticulation in which the acoustic realization of tones exhibits either a carryover (progressive) or anticipatory (regressive) effect of the preceding or the following tones, (e.g., Gandour, Potisuk, Dechongkit, & Ponglorpisit 1992a, 1992b; Gandour, Potisuk, & Dechongkit 1994; Xu 1993, 1997; Brunelle 2009; Zhang & Liu 2011; Chen, Wiltshire, & Li 2018;), tone sandhi is a phonological and categorical process exhibiting contextually determined tone alternations at the juncture of words or morphemes. In addition, while tonal coarticulation has been attested in many languages (Gandour et al. 1994; Potisuk, Gandour, & Harper 1997; Xu 1997; Wong 2006; Brunelle 2009; Chang & Hsieh 2012; Li & Chen 2016;), tone sandhi has mainly been reported in tonal languages spoken in China and mainland Southeast Asian (Chen 2000; Zhang 2014). A similar phenomenon of tonal variation has been reported in African languages (e.g., Hyman 2007; Chen 2012;). Typologically, tone sandhi involves local tone substitution of non-final tones as in Standard Mandarin, default tone insertion as in a Southern Wu dialect (e.g., Wuyi dialect) and tone extension of the tone on the initial syllable onto non-initial syllables as in Northern Wu dialects in China (Chen 2009; Zhang 2007, 2014). Chen (2012) pointed out that tonal coarticulatory effects were characterized more often as phonological processes in African languages than in Asian languages. For example, a similar phenomenon of carryover assimilation in Asian languages is sometimes characterized as a phonological process in African languages (Laniran & Clements 2003; Hyman 2007), where in partial spreading, a High tone can spread onto the second syllable with a Low tone, known as High tone spreading, (or a Low tone onto the second syllable with a High tone, known as Low tone spreading) to form a phonologically distinct new contour tone.

Characteristics of tone sandhi, as well as quantitative and qualitative methods for its identification, have been proposed in previous work (e.g., Chen 2000; Shih & Sproat 1992; Shen 1992; Yang 2015; Zhang & Liu 2011). The proposed qualitative methods, however, suffered from their lack of generalizability to other tonal languages and the proposed quantitative methods suffered from their statistical shortcomings as evaluated by statisticians. For instance, Zhang and Liu (2011) concluded that tone sandhi can be easily differentiated from tonal coarticulation in Tianjin Chinese, because "tone sandhi in Tianjin is right-dominant, and regressive tonal coarticulation in Tianjin, like in other languages, is of small magnitude" (p. 184). According to Zhang and Liu, tone sandhi processes in Tianjin are largely characterized as phonologically dissimilatory, with properties that are distinct from regressive tonal coarticulation processes. They illustrated this point with an example of the Tianjin tone sandhi rule T1 + T1 → T2 + T1 (41 + 41 → 34 + 41 in Chao's tone numbers (Chao 1948), where 1 stands for the lowest pitch point in a tonal space, and 5 stands for the highest. This tone sandhi process raises the low offset of the first T1 and is, therefore, inconsistent with the property of tonal coarticulation process in which High targets are more affected than Low targets. However, not all tone sandhi processes can be differentiated from tonal coarticulation in this manner, i.e., some tone sandhi processes may share properties with tonal coarticulation, such as in Nanjing Mandarin. Specifically, based on impressionistic data (Liu 1995; Sun, 2003), the tone sandhi rules in Nanjing Mandarin affected both Low (T3→T2/_T1(11→24/_41)) and High tones (T5→ derived T/_T5 (5→3/_5)).

There exist quantitative methods that aim to model sandhi tones and reveal tone sandhi processes. However, a number of these methods have some limitations, for example by measuring and comparing the overall mean f0 values, which provide information about the entire f0 contour (e.g., Peng, 2000), or by using repeated measures ANOVA (e.g., Zhang & Liu 2011) to test differences between curves, which has been criticized for failing to model individual deviation in terms of the slope or trend parameters over time (Gibbons, Hedeker, & DuToit 2010).

The current study tested quantitative methods that may be used to model the sandhi tones and reveal tone sandhi processes. Specifically, we tested a more recent method, growth curve analysis, which allows subject-specific variation to be modelled in terms of slope in addition to intercept (Mirman, Dixon, & Magnuson, 2008; Mirman, 2014). This method has been employed in more recent studies to examine tonal variations (Li & Chen 2016; Zhang & Meng 2016). In addition, we evaluated a similar statistical procedure to that used by Chen, Zhang, McCollum and Wayland

(2017) based on the model proposed by Xu and Wang (2001), which directly calculates and statistically compares underlying pitch targets and has been shown to statistically distinguish between phonetic and phonologized effects. The current study aims to compare the two quantitative methods in capturing the well-studied third tone sandhi in Standard Mandarin and use the same procedure to examine Nanjing Chinese to offer a comprehensive acoustic and statistical analysis of tones and tone sandhi in Nanjing Mandarin.

1.1 Characteristics of tone sandhi

Chen (2012) argues for various types of tonal variation including traditionally known phonetic tonal coarticulation and categorical tonal alternation, though the question of "to what extent should tonal contextual variation be accounted for in terms of phonological processes, and to what extent as phonetic variation" (p. 114) remains. Conventionally, variations in surface acoustic realization of lexical tones (i.e., f0) can be induced by tone sandhi or tonal coarticulation; the former refers to a phonological process that results in a categorical tone shift while the latter is characterized as a phonetic effect of the preceding and following tones that result in 'phonetic perturbation' or 'allophonic change' of an underlying tone (Xu 1993).

Shen (1992) proposed two principles to differentiate between tone sandhi and tonal coarticulation; (1) Tone sandhi is related to language-specific morphological and phonological conditions, whereas tonal coarticulation is subject to language-independent biomechanical restrictions; and, (2) Tone sandhi can be either assimilatory or dissimilatory, whereas tonal coarticulation must be assimilatory. However, these two criteria were criticized by Chen (2000), because tonal coarticulation can also be sensitive to morphosyntactic structure, and it can be both assimilatory and dissimilatory (Chen & Xu 2006; Chen, Wiltshire, & Li 2018; Wong 2006; Xu 1997).

More recently, Li and Chen (2016) argue that since it is difficult to establish the boundary between tone sandhi and tonal coarticulation, the f0 variation should be observed objectively before any conclusions can be drawn. They examined tone sandhi rules in Tianjin Chinese and found non-neutralization of the surface f0 contours of sandhi tones and those of the reported target outputs in the literature. Therefore, they concluded that neutralization on the surface may not distinguish the tone sandhi process from tonal coarticulation. Instead, they argued that the lexical tonal contour should remain distinct if it is affected by phonetic coarticulation, whereas the tonal contour should undergo major changes and become unpredictable from the canonical form if it is affected by a tone sandhi process. On this basis, they proposed that T1T1, T41 and T33 in Tianjin Chinese have undergone tone sandhi processes. They further pointed out that the observed raising effects of T3 and T1 should be differentiated. First, T3 is involved in a sandhi process in T3T3 across Chinese dialects, which was proposed as early as 16th century. Second, the sandhi T3 in T3T3 is considered as a near-merger to the rising T2. In contrast, T1 in T1T1 and T4 in T4T1 bear no similarity to any lexical tones in the tone system of Tianjin Chinese. In addition, differences in the tonal variation were observed between T4T1 and T1T1 and T2T1 and T3T1. Li and Chen further proposed that since T4 and T1 are falling tones, the observed raising effects were enhanced and phonologized, whereas T2 and T3 are rising tones with little room to be raised further, which is more of a coarticulatory effect. Based on these proposals, we may summarize that a tone sandhi process should involve a categorical shift, which deviates significantly from the original tonal contour and becomes similar to a lexical tone in the tone system or to a non-existing derived tone.

Another property of tone sandhi is perceptual distinction. It has been proposed that tone sandhi and tonal coarticulation are not essentially different except that ‘tone sandhi processes are perceptible to the unaided ears’ (Chen 2000; Shen 1992; Yang 2015). Yang (2015) also argues that listeners perceive differences between sandhi tones and the base tone. Moreover, despite acoustic differences on the surface f0 contours, native listeners cannot distinguish between a sandhi tone and the tone it turns into. For example, for the third tone sandhi rule in Standard Mandarin, where T3 becomes T2 before another T3 (T3→T2/_T3 (213→35/_213)), perceptual experiments indicate that native speakers cannot distinguish the sandhi tone (the first syllable of the combination T3 + T3 (213 + 213)) from the rising tone T2 (35) in the combinations of T2 + T3 (Peng 2000), despite their differences in surface f0 contours (Peng 2000; Shen 1992; Xu 1993; Zee 1980). However, perceptual experiments showed that listeners were not insensitive to tonal coarticulation in all cases, and they did sometimes compensate for the variations (Xu 1993). He found that the tone identification rate by native listeners might drop below chance if the original context was not presented for tones originally occurring in conflicting contexts where adjacent tonal values disagreed with them. In addition, there might be individual differences in the perception of tonal coarticulation and tone sandhi by native speakers. Further perceptual experiments are called for to examine the claim that the essential differences between tone sandhi and tonal coarticulation lies in the fact that 'tone sandhi processes are perceptible to the unaided ears'.

In sum, a tone sandhi process (1) involves a categorical shift from the ideal form of the original tone to another citation tone or to a derived allotone significantly different from any citation tone, (2) results in a lack of perceptual distinction among native listeners between the sandhi tone and the tone it changes into despite surface acoustic difference. On the basis of the first property, this study proposes to model the third tone sandhi process in Standard Mandarin using two statistical methods: growth curve analysis and underlying pitch target approximation, comparing surface pitch contours and model-derived pitch targets of the sandhi tone and its corresponding citation tone. We proceed to apply the procedure to a less-studied Chinese dialect Nanjing Mandarin.

1.2 Underlying pitch targets

One of the quantitative methods that this study aims to test is based on the notion of underlying pitch targets (Xu & Wang 2001). Underlying pitch targets are defined as 'the smallest articulatorially operable units associated with linguistically functional pitch units such as tone and pitch accent' (Xu & Wang 2001:321). Surface f0 contours are considered to be the implementation of underlying pitch targets and are, therefore, subject to contextual variations (Xu & Wang 2001; Xu, Lee, Prom-on, & Liu 2015). The proposed concept of underlying pitch targets is articulatory, which differs from the more abstract conventional underlying forms of linguistic representation in the literature. Based on this conceptual framework, Prom-On, Xu and Thipakorn (2009) offer a quantitative target approximation model, modelling functionally specified and articulatorially obligatory properties separately. They assert that communicative functions are linked to the parameters of underlying pitch targets. Moreover, Chen et al.

(2017) show that this model can distinguish gradient, phonetic perturbation from categorical, phonologized changes. Differences in underlying pitch targets often indicate different lexical tones, but differences found only in the surface f0 contours can be due to phonetic variation. The current study employs a similar procedure to test whether the underlying pitch target of a tone changes significantly to that of another tone during a tone sandhi process, and whether this method can help us identify tone sandhi processes in under-studied languages. More details of modelling underlying pitch targets are provided in Section 2.4.2.

The structure of the current paper is as follows. Section 2 tests two statistical approaches on Standard Mandarin. Section 3 further applies the two methods on Nanjing Mandarin and offers a comprehensive description of Nanjing Mandarin tones. Section 4 and 5 offer discussions of tone sandhi modelling and transcriptions of tones based on statistical modelling.

2. Tone sandhi in Standard Mandarin

2.1 Background of Standard Mandarin

Standard Mandarin has four tones, which can be transcribed using Chao's tone numbers (Chao 1948) as follows.

Tone 1 (T1) /ma/ high-level (55) 'mother'

Tone 2 (T2) /ma/ high-rising (35) 'hemp'

Tone 3 (T3) /ma/ low-dipping (213) 'horse'

Tone 4 (T4) /ma/ high-falling (51) 'to scold'

The third tone sandhi rule is described as T3 (213) → T2 (35)/___ T3 (213) (e.g., Chao 1948, 1968; Cheng 1968). Previous studies consider this third tone sandhi rule to be phonological, because it involves language-specific tonal changes and is not solely due to tonal coarticulation affecting the beginning and/or end of a tone (Xu 1997; Zhang & Lai, 2010). However, the sandhi T3 and the citation T2 (35) are found to be acoustically different in many studies. The sandhi T3 is reported to have a lower mean f0 than

T2 (35) in Standard Mandarin spoken on the mainland and Taiwan (Zee 1980; Shen 1992; Xu 1993; Peng 2000;). Based on a corpus study, Yuan and Chen (2014) also noted the difference between the sandhi T3 and T2 (35) in the magnitude of f0 rise and the percentage of f0 rise duration. Xu and Prom-on (2014) propose three possibilities concerning the result of the tone sandhi rule: (1) T3 remains unchanged; (2) T3 changes to another derivational tone; or (3) T3 changes to T2. After comparing the accuracies of synthesis obtained from the simulation of these three hypotheses, the first possibility is proven to be unlikely. The second and third possibilities are both likely, with the former being slightly favored by their results.

2.2 Stimuli

The stimuli used in this study included eight T3 + T3 (213+213) disyllabic words and eight T2+T3 disyllabic words, along with sixteen fillers with other tonal combinations in Standard Mandarin. The consonants and vowels were controlled to be similar to avoid consonant perturbation and intrinsic f0 perturbation effects (Chen 2011; Halle & Stevens 1971; Hombert, Ohala, & Ewan 1979; Tang 2008).

Following the experimental design of Zhang and Lai (2010) and Zhang and Peng (2013), we first recorded a Beijing native speaker reading each monosyllable of the target and filler disyllabic words with a MB Quart K800 C headset on a computer, using the software Audacity with a sampling rate of 44.1kHz at the speech lab of the Hong Kong Polytechnic University. Then, all recorded monosyllables were extracted and normalized for peak intensity before being presented to participants to elicit production of tone sandhi.

2.3 Participants and experimental procedure

The monosyllables were presented in pairs to thirteen native speakers of Standard Mandarin, who were between 21 to 35 years of age, were born in Beijing and had lived there for about 20 years before coming to Hong Kong. None of them reported any history of speaking, hearing or language difficulty. All participants were recorded at the speech lab of the Hong Kong Polytechnic University using the same equipment and software as described above.

Using E-prime, pairs of monosyllables of the target disyllabic words were presented to each speaker in a random fashion, with an Inter-Stimulus Interval (ISI) of 800ms. After hearing both monosyllables, participants were instructed to put them together to form a disyllabic word in Standard Mandarin. They were also instructed to speak at a normal speaking rate, and could repeat themselves when necessary. All participants practiced the procedure in a training session before the experiment.

2.4 F0 extractions and statistical analysis

The recorded disyllables were manually extracted for further acoustic analysis by Praat (Boersma & Weenink 2015). The Praat script Prosodypro (Xu 2013) was used to obtain f0 values at 20 normalized time points in each segmented interval. We focus on comparing pitch contours while controlling for the effects from duration. To normalize variation in f0 values across gender, a logarithmic Z-score was performed on the measured f0 values before statistical modelling (Rose 1987; Zhu 1999). As mentioned earlier, two quantitative models, growth curve analysis and the underlying target approximation were compared in this study (Xu & Wang 2001; Prom-On et al. 2009; Xu & Prom-on 2014; Chen et al. 2017). Specifically, the growth curve analysis was used to compare surface f0 contours of the sandhi tone (T3) and the tone it turns into (T2) whereas the pitch target approximation procedure was used to model their underlying pitch targets. These two models are described in more detail below.

2.4.1 Surface f0 contours: growth curve analysis. Growth curve analysis (Mirman et al. 2008; Mirman 2014: 51-55) was used to test differences in the surface f0 contours because we were interested in whether sandhi tones were neutralized with the tones they reportedly turned into on the surface. Growth curve analysis is also known as “multilevel regression”, “hierarchical linear modelling" and "mixed-effects model" (Raudenbush & Bryk 2002; Mirman 2014: 22), which models both fixed and random effects (Mirman 2014: 61).

We started with a simple model as follows (Mirman et al. 2008),

$$Y_{ij} = (\gamma_{00} + \zeta_{0i}) + (\gamma_{10} + \zeta_{1i}) * Time_{ij} + \varepsilon_{ij} \qquad (1)$$

where i stands for the i^{th} f0 contour and j is the j^{th} time point of extracted f0 value, γ_{00} is the population mean of the intercept, ζ_{0i} models variability of individual's intercept, γ_{10} is the population mean of the slope, ζ_{1i} models variability of individual's slope and ε_{ij} are the error terms. Orthogonal polynomials were used to avoid any correlation of the linear and quadratic terms (Mirman 2014: 52). We then optimized the initial model for each pair of surface f0 contours. Specifically, the quadratic terms as the fixed effect and the random effect modelling variation were included if they were significant as indicated by likelihood ratio tests. We proceeded to test each pair of surface f0 contours by comparing a model treating them as the same with a model treating them as different using a likelihood ratio test. A result of significant difference in the model comparison indicates a difference between the members of each pair of the surface f0 contours.

2.4.2 Underlying pitch targets. To compare the underlying pitch targets of the sandhi tone and the tone it becomes, we employed a similar statistical procedure employed by Chen et al. (2017), which is based on the quantitative target approximation model (qTA) proposed by Prom-on et al. (2009).

In qTA, a pitch target is the underlying goal of the local tonal shape resulting from the combined force of the laryngeal muscles that control the tension of the vocal folds. The underlying pitch target can be represented as a simple linear function: x(t) = mt+b, where t is the scope of time, m is the slope and b is the height of the pitch target. The slope of a static pitch target (e.g., high, mid, low) equals to zero while that of a dynamic target is either positive (e.g., rising) or negative (e.g., falling).

According to Prom-On et al. (2009), control of vocal fold tension reflects two antagonistic forces (the activation of the cricothyroid and thyroarytenoid muscles), and should be modeled as a second order linear system at least. Interestingly, the fourth and higher order linear systems do not show further improvement in the model fitting, and a critically damped linear system is proven to be mathematically simpler and more efficient than an overdamped system.

In this study, following the results from Prom-on et al. (2009) and the procedures described in Chen et al. (2017), we used a critically damped linear system. Since the fourth and higher order linear systems are not more optimal than the second or third order linear systems (Prom-on et al. 2009), we only considered the second and third order linear systems. Two models listed below allowed us to choose between the second and third order linear systems, determined by statistical model selection. Specifically, the optimized model was chosen from the following two models:

1) The second order linear system with linear underlying targets $at + b$;

$$f_0(t) = \beta e^{-\lambda t} + at + b \quad (2)$$

where $f_0(t)$ stands for f0 values, λ represents the rate of approaching the underlying pitch target, a is the slope of the underlying target, and b is the intercept of it.

2) The third order linear system with linear underlying targets $at + b$;

$$f_0(t) = (c_1 + c_2 t + c_3 t^2)e^{-\lambda t} + at + b \quad (3)$$

$$c_1 = f_0(0) - b \quad (4)$$

$$c_2 = f'_0(0) + c_1\lambda - m \quad (5)$$

$$c_2 = (f''_0(0) + 2c_2\lambda - 2c_1\lambda^2)/2 \quad (6)$$

where $f_0(t)$ stands for f0 values, λ represents the rate of approximating the underlying pitch target, a is the slope of underlying pitch target, b is the intercept of it, c1, c2 and c3 are transient coefficients determined by the initial f0 values, initial velocity and initial acceleration.

Of the two models, the model with the least Akaike's Information Criterion (AIC) was chosen as the optimal one since the least AIC indicates the best fit (Kim & Timm 2006). For each tone, in order to fit the four models to find the optimal one, and to calculate the coefficients of underlying pitch targets from f0 values extracted from our speech production data, we made use of nonlinear regression. In fitting nonlinear regression models, initial estimates of parameters are required, and the models should be iteratively solved (Huet, Bouvier, Poursat, & Jolivet 2006). The nonlinear regression can improve the fit by adjusting the initial parameters until the model converges, indicating that the improvement is small enough to be neglected. We plotted functions in the proposed four models to find reasonable initial estimates. The parameters were adjusted so that the shape of the contour is closer to the curve going through the mean f0 values. By choosing the optimal model fitting, we will be able to estimate the parameters *a* and *b* based on the optimal model, which stand for the slope and intercept of the underlying pitch targets. In this way, we extract all the underlying pitch targets.

In addition, Chen et al. (2017) propose that in order to statistically test a pair of underlying pitch targets, the optimized model for the two target tones uttered by each speaker should be fitted first. After obtaining all parameters from the model fit for each speaker and each tone, including the slope a and the intercept b, a non-parametric Wilcoxon signed rank test was used to test whether the obtained coefficients of the underlying targets of the two tones under examination were statistically significant. Using this method, we tested whether the underlying pitch target changed into that of another tone. We used the R language (R Core Team 2018) to conduct all the statistical analyses.

2.5 Results for Standard Mandarin

In the presentation of the results hereafter, the sandhi T3 in the combination T3 + T3 (213 + 213) is denoted as T33a, where the letter a stands for its being the first syllable in the disyllabic word, while T23a stands for the first tone in the T2 + T3 (34 +213) combination. The result of the growth curve analysis is shown in Table 1, where tonal contours are characterized by the quadratic term, slope and intercept. The two surface f0 contours T33a and T23a differed significantly in slope ($\chi^2(1) = 0.39$, $p = 0.53$), but not in the intercept or quadratic term. Figure 1 plots the fitted values of the model against the observed data.

Table 1 and Figure 1 demonstrate that the surface contours of T2 in T2+T3 and the sandhi T3 in T3 +T3 were not completely neutralising.

Table 1. Results of the growth curve analysis in Standard Mandarin

Tone Sandhi Pair	Quadratic term		Slope		Intercept	
	$\chi^2(1)$	P-value (S or D)	$\chi^2(1)$	*P*-value (S or D)	$\chi^2(1)$	P-value (S or D)
T23a vs. T33a	0.39	$p = 0.53$ (S)	53.25	$p < 0.001$* (D)	0	$p = 1$ (S)

Same: S; Different: D

In addition, we modeled their underlying pitch targets. Recall that we first fit the second and third order linear system models and chose the optimal one based on AIC. Table 2 lists the optimal model chosen for T2 in the tonal combination T2 + T3 (T23a) and the first T3 in T3 + T3 (T33a). After choosing the optimal model, we proceeded to test the parameters of underlying pitch targets.

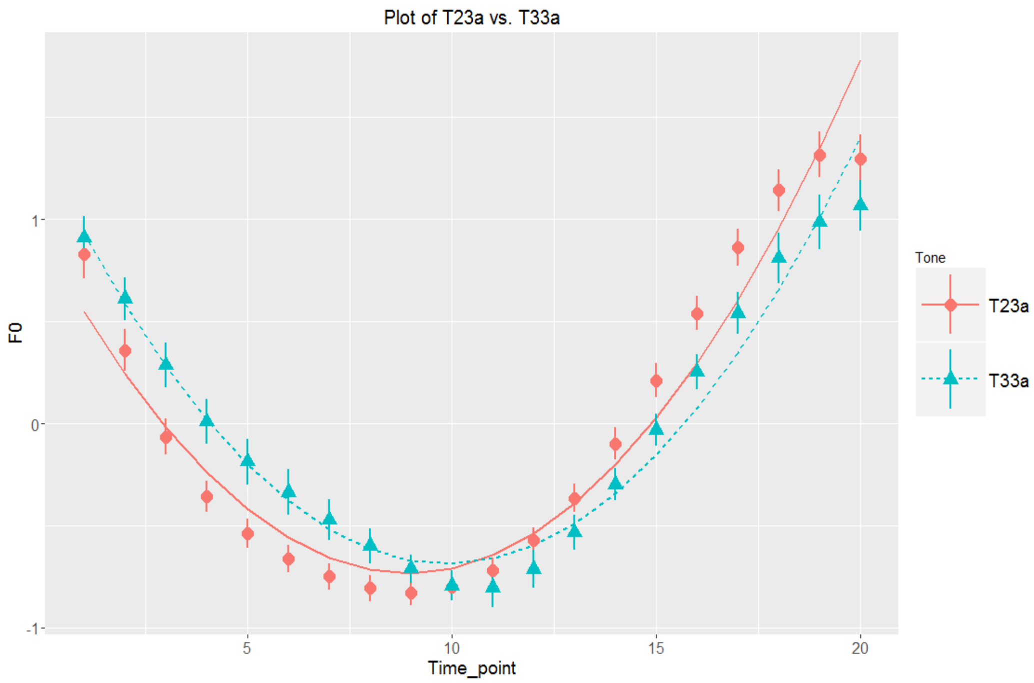

Fig. 1. Growth curve analysis of T23a vs. T33a in Standard Mandarin; The mean and error bar of observed f0 at each time point are plotted; The solid and dotted lines represent the fitted values of the growth curve models.

Table 3 shows the results of testing whether the two underlying pitch targets of T23a and T33a are the same because the slope and intercept terms did not differ significantly. From Table 3, the coefficients of underlying targets did not differ significantly, suggesting that the tone sandhi rule in the traditional description did show neutralization in the underlying pitch target. Figure 2 plots the surface tonal contour regenerated based on the fitted underlying pitch targets and the quadratic underlying pitch targets against observed data.

Table 4 lists the estimated coefficients for linear underlying pitch targets of T23a and T33a. Table 5 shows the results of testing whether the two underlying pitch targets of T23a and T33a are the same. Table 5 presents that the coefficients of underlying targets did not differ significantly, suggesting that neutralization was also obtained when modeled by a linear underlying pitch target. Figure 3 plots the surface tonal contour regenerated based on the fitted underlying pitch targets and the linear underlying pitch targets against observed data. Both our results and those of Xu and Prom-on (2014) demonstrated that T3 has undergone a categorical and phonological tone sandhi process. The results of neutralization in the underlying pitch targets were obtained for both linear and quadratic underlying pitch targets.

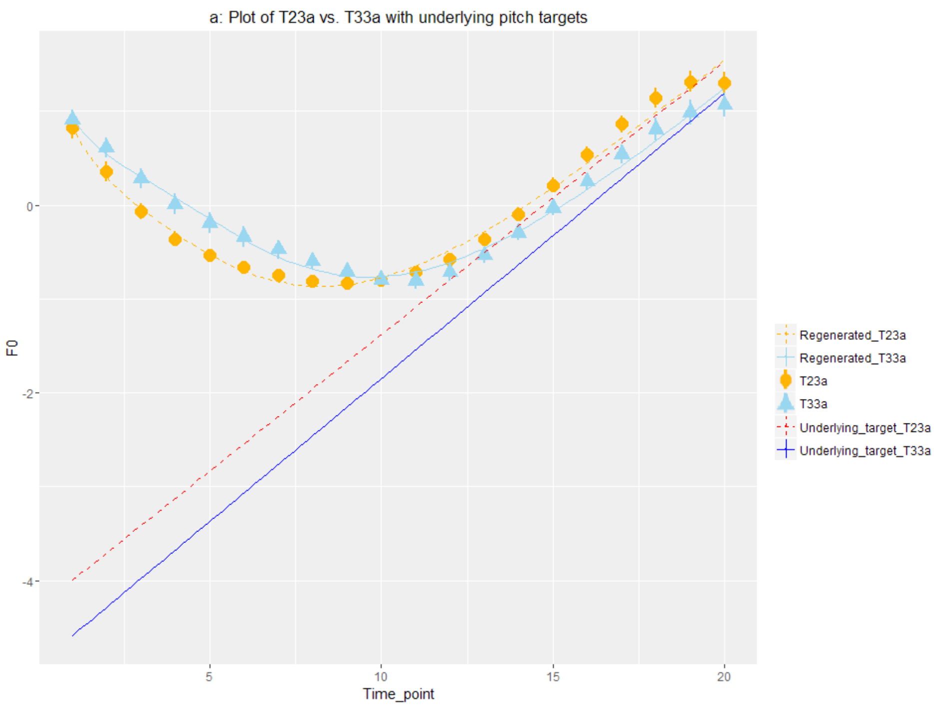

Fig. 2. Plot of regenerated surface contour of T23a and T33a with the linear underlying pitch targets and mean and error bars of observed f0 (log z-score) at each time point

Table 2. The relatively optimal models chosen for T23a and T33a with a linear underlying pitch target

Tone	Model Selected	c1	c2	c3	λ	a	b
T23a	Third order	6.42	0.82	0.62	0.48	0.29	-4.29
T33a	Third order	6.84	1.02	0.63	0.43	0.30	-4.89

Table 3. Results of testing linear underlying pitch targets in Standard Mandarin

Tone Sandhi Pair	Same or Different *a*	*Same or Different b*
T23a vs. T33a	Same *T23a: mean(sd) = -0.33(0.14),* *T33a: mean(sd) = -0.33(0.16),* V= 40, p = 0.46	Same *T23a: mean(sd) = -5.11(2.50),* *T33a: mean(sd) = -5.46(2.96),* V = 76, p = 0.15

2.6 A comparison of statistical methods

Our results showed that the underlying pitch target of the sandhi T3 was not statistically different from that of T2 despite non-neutralization on the surface f0 contours. We thus argue that the procedure of testing underlying pitch targets in addition to surface f0 contours may better help identify tone sandhi processes.

Underlying pitch targets are more stable than the surface f0 contours. For example, Xu (2005) found that extensive variability on the surface of Standard Mandarin tones may be due to contextual variation, but they asymptotically converged to more constant linear underlying pitch targets. As mentioned in the introduction, we should model functionally specified and articulatorially obligatory properties separately (Prom-on et al. 2009). Therefore, statistically testing the parameters of underlying pitch targets means that we are testing communicative functions such as lexical tones, modelled as the driving force of the linear system, rather than articulatory implementation (Xu 2005; Prom-On et. al. 2009). Therefore, the underlying pitch target approximation captures a more stable state of tone sandhi because it compensates for variation on the surface. Since the procedure involves fitting one model for a sandhi tone and another one for the citation tone it turns into, and then extracted the parameters of the two models from each speaker for comparison, it better captures a more stable state of tone sandhi rather than the more variable and idiosyncratic styles of individual speakers.

Moreover, if tone sandhi is a categorical shift from the original tone, then when we model the tone as the driving force of a linear system, the driving force should also change in this process. Therefore, in a tone sandhi process, the underlying pitch target of a sandhi tone is likely to show significant deviation from that of the original one. Sometimes the underlying pitch target of the sandhi tone may even become neutralized to that of another base tone. In the case of the Standard Mandarin third tone sandhi rule T3 (213) → T2 (35)/___ T3 (213), the underlying pitch target of the first T3 in T3 + T3 exhibits deviation from the original T3 and neutralizes with that of T2. With the significant deviation of the underlying pitch target in a sandhi tone from the original one, the surface tonal contour may in turn demonstrate dramatic changes from that of the original tone. Li and Chen (2016) also points out that if a tone sandhi process is involved, then the tonal contour should undergo dramatic deviation from its canonical form.

In sum, statistical modelling of the acoustic data can deepen our understanding of tone sandhi processes. We evaluated quantitative methods and demonstrated that statistically testing underlying pitch targets in addition to surface f0 contours may help reveal the categorical nature of tone sandhi.

3. Tone sandhi rules in Nanjing Mandarin

The proposed procedure of statistically modelling and testing underlying pitch targets in addition to surface f0 contours may serve as a tool in identifying phonological tone sandhi processes quantitatively, as attested in Standard Mandarin. Therefore, we applied this procedure to examine both surface f0 contours and the underlying pitch targets of reported tone sandhi rules in the under-studied Nanjing Mandarin. In addition, we offered a transcription of Nanjing Mandarin based on statistical modelling and updated the descriptions of Nanjing Mandarin tone sandhi.

3.1 Background of Nanjing Mandarin

The city of Nanjing in Jiangsu province is located along the east coast of China and in the Yangtze Delta, with eleven districts and a population of over 5.3 million (Xu, Liu, Zhang, An, Yu, & Chen 2007). Nanjing Mandarin and Standard Mandarin (Xu 2006) are mainly spoken in Nanjing. Nanjing Mandarin used to be classified as one of the Wu dialects, but it is now considered to belong to Jianghuai Mandarin (Jin 2010).

Tone values are often transcribed with some discrepancies among scholars based on impressionistic data, and phonological analyses can vary due to different transcription (Zhang & Liu 2011). Although tone values for Nanjing Mandarin are transcribed differently among researchers, the general consensus is that there are five basic tones and five or six tone sandhi rules (Liu 1995, 1997; Song 2006; Sun 2003). Sun (2003) and Liu (1995, 1997) report the basic tones with the following values: T1 (31/41), T2 (24/13), T3 (22/212/11), T4 (44), T5 (5/55) with some examples listed in Table 4.

Table 4. Nanjing tones

Tone	Syllable	Transcription	Meaning
T1	/fu/	31/41	*'skin'*

T2	/fu/	24/13	*'hold'*
T3	/fu/	22/212/11	*'rotten'*
T4	/fu/	44	*'negative'*
T5	/fu/	5/55	*'fortune'*

Liu (2011) notes that the values of certain tones are still debatable: (1) whether T3 is a contour or a level tone with different transcriptions, such as 212, 22 and 11; and (2) whether T1 can be described as 31 or 41 and (3) whether T2 has the tone value 13 or 24.

Moreover, there are also some discrepancies concerning tone sandhi rules among scholars. Table 5 provides a comparison of tone sandhi rules reported by Liu (1995) and Sun (2003). Liu (1995) has one more sandhi rule for the tonal combination T4 + T5 (22/212/11 + 5/55) than those proposed by Sun (2003). Also, Liu (1995) argues that the first T3 in T3 + T3 becomes T2, but Sun (2003) states that it becomes T1 instead. In the tonal combination T5 + T5, Liu (1995) argues that the first T5 turns into a derived tone, but Sun (2003) argues that it turns into T4.

Table 5. A comparison of Liu's and Sun's sandhi rules

Liu (1995)	Sun (2003)
T1→T4/_T1 (41→44/_41)	T1→T4/_T1 (31→44/_31)
T2→T3/_T5 (24→11/_5)	T2→T3/_T5(13→22/_5)
T3→T2/_T1 (11→24/_41)	T3→T2/_T1(22→13/_31)
T3→T2/_T3 (11→24/_11)	T3→T1/_T3(22→31/_22)
T4→T1/_T5 (44→41/_5)	None
T5→3/_T5 (5→3/_5)	T5→T4/_T5 (5→44/_5)

3.2 Participants and stimuli

A total of 12 native speakers of Nanjing Mandarin (six females and six males) participated in this study. Participants were between 35 and 65 years old and had lived in Nanjing for most of their lives. Literature on Nanjing Mandarin (Liu 1995; Song 2006; Chen & Wiltshire 2013) documents differences across age groups, so we chose a specific age group for the current study. The age range contains only participants considered to speak a relatively new version of the dialect, compared with speakers of more than 75 years of age who speak an older version as noted by Liu (1995). All our participants were recorded in a quiet room during the course of fieldwork using a Marantz PMD 660 digital recorder with a Shure SM2 head-mounted microphone, and the recordings were transferred to a PC with a sampling rate of 44.1kHz.

The speech materials selected in this study consisted of 660 monosyllabic tones (11 monosyllables * five tones * 12 participants) and 360 disyllabic tones (five disyllabic words * six combinations * 12 participants). Real words were used because the application of tone sandhi rules on nonsense words may be different from the application on real words (Zhang & Lai 2010). Most disyllables were chosen from the Dictionary of the Nanjing Dialect (Liu 1995) with consultations from native speakers of Nanjing Mandarin. All the words were recorded at a normal speaking rate, and the speakers were instructed to adhere to the same intonation pattern they would use for declarative sentences.

3.3 F0 extractions and statistical analysis

The target words were first segmented manually, using Praat (Boersma & Weenink 2012), and a Praat script was run to extract f0 within each individual segment. In each interval, time-normalized f0 values were extracted with 20 time points, and the analysis window size was 25.6ms. We first performed a logarithmic Z-score normalization on f0 values (Rose 1987; Zhu 1999), and modelled the surface tonal contours and the underlying pitch targets. We focus on comparing pitch contours while controlling for the effects from duration.

In addition, we offered a description of tonal values based on the collected acoustic data. We applied a method of transformation from f0 values to Chao’s tone numbers based on statistical modelling (Chen accepted). Different methods have been proposed to transform from acoustic values to Chao’s tone numbers (Shi 1990; Zhu, Shi, & Wei 2012). Shi (1990) proposes a formula to first take the log of the onset, middle point and the offset of f0 contours, and normalize it with respect to the maximum and minimum values of a particular speaker. The one to five in Chao's tone numbers are then assigned to normalized values in the interval zero-one, one-two, two-three, three-four and four-five respectively. Zhu et al. (2012) further incorporates phonation types in analysing the tone system of Yuliang Miao.

The method we use in this study is based on the modelling of underlying pitch targets. We first calculated four sample quantiles (20%, 40%, 60%, and 80%) for all the fitted values of monosyllabic tones to obtain cut-off values corresponding to each sample quantile. Using these sample quantiles, we may cut the acoustic tonal space evenly, and perform a transformation. For example, if a fitted value f0 falls in the range of the sample quantiles 0% - 20%, then this value is transformed to the integer 1 according to Chao's tone numbers.

3.4 Results of testing surface contours of Nanjing Mandarin sandhi tones

The plotted observed data in Figure 3 suggest that the polynomial model with the first or second degree should suffice for growth curve analysis. From Figure 3, the shape of these pairs is fairly close, especially the slopes, except for the pair T33a and T1, exhibiting different signs of the slopes. However, most pairs do show small yet distinct acoustic differences on the surface contours visually. Statistical tests showed that all the pairs of tone sandhi reported in the literature were non-neutralized in the surface tonal contours. There were significant acoustic differences between each pair as reported in Table 6. All the pairs of sandhi tones and citation tones in the same phonological environment reported in Table 5 were tested. The differences mainly lie in the intercept and the slope terms. All the underlined tones are sandhi tones in Table 6. From Table 6, the following pairs differed in the intercept term only: T41a vs. T11a ($\chi^2(1)$ = 206.41, p < 0.001) and T44a vs. T55a ($\chi^2(1)$ = 92.11, p < 0.001). In addition, the following pairs differed both in the slope and the intercept terms: T35a vs. T25a (slope: $\chi^2(1)$ = 30.90, p < 0.001; intercept: $\chi^2(1)$ = 48.56, p < 0.001), T21a vs. T31a (slope: $\chi^2(1)$ = 88.10, p < 0.001; intercept: $\chi^2(1)$ = 458.85, p < 0.001), T13a vs. T33a (slope: $\chi^2(1)$ = 188.52, p < 0.001; intercept: $\chi^2(1)$ = 234.6, p < 0.001), T23a vs. T33a (slope: $\chi^2(1)$ = 8.39, p = 0.004; intercept: $\chi^2(1)$ = 142.1, p < 0.001), T15a vs. T45a (slope: $\chi^2(1)$ = 103.32, p < 0.001; intercept: $\chi^2(1)$ = 90.59, p < 0.001). Note that we chose the first T4 in the disyllabic context T4 + T4 (T44a) to compare with the first T5 in T5 + T5 (T55a) instead of T4 in T4 + T5 (T45a), because it is reported that T4 changes into T1 in T4 + T5 (Liu, 1995). The reason for choosing T4 + T4 is that the disyllabic context is relatively similar to T4 + T5, where T4 precedes a high and level tone T4, the most similar tone to T5.

From our results, one tone sandhi pair T4→T1/_T5 is reported by Liu (1995), but not by Sun (2003). The surface tonal contour for the sandhi T4 in T4 + T5 did deviate from T4 in isolation, but the existence of this tone sandhi is still questionable, since tonal coarticulation may also have affected the surface tonal contours. Therefore, we further tested whether neutralization may have occurred in the underlying pitch targets.

3.5 Underlying pitch targets of Nanjing Mandarin monosyllabic tones

We further examined underlying pitch targets of Nanjing Mandarin monosyllabic tones in order to offer a description of them. Table 7 presents the selected model and the estimated parameters for each monosyllabic tone. Plugging in the estimated coefficients in Table 7 for each model of tones, we can plot the fitted tonal contours and the mean tonal contours from the original data for comparison as in Figure 4.

Table 6. Results of the growth curve analysis in Nanjing Mandarin

Tone Sandhi Pair	Quadratic term		Slope		Intercept	
	$\chi^2(1)$	*P*-value (S or D)	$\chi^2(1)$	*P*-value (S or D)	$\chi^2(1)$	*P*-value (S or D)
T41a vs. T11a	0.12	*p* = 0.73 (S)	1.10	*p* = 0.29 (S)	206.41	*p* < 0.001* (D)
T35a vs. T25a	2.73	*p* = 0.10 (S)	30.90	*p* < 0.001* (D)	48.56	*p* < 0.001* (D)
T21a vs. T31a	0.53	*p* = 0.47 (S)	88.10	*p* < 0.001* (D)	458.85	*p* < 0.001* (D)
T13a vs. T33a	3.26	*p* = 0.07 (S)	188.52	*p* < 0.001* (D)	234.6	*p* < 0.001* (D)
T23a vs. T33a	2.46	*P* = 0.12 (S)	8.39	*p* = 0.004*(D)	142.10	*p* < 0.001* (D)

T15a vs. T45a	0.41	$p = 0.52$ (S)	103.32	$p < 0.001$* (D)	90.59	$p < 0.001$* (D)
T44a vs. T55a	0.41	$p = 0.52$ (S)	1.61	$p = 0.20$ (S)	92.11	$p < 0.001$* (D)

Same: S; Different: D

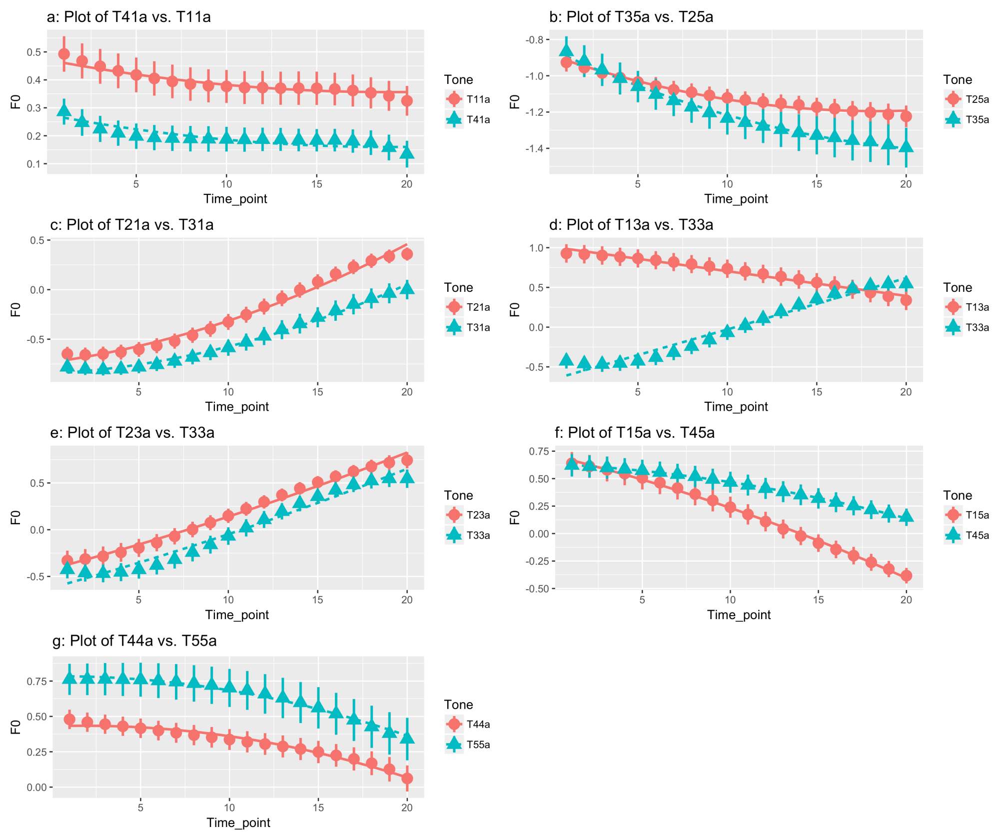

Fig. 3. Growth curve analysis in Nanjing Mandarin: the mean and error bar of the f0 data in each normalized time point are plotted, and the solid and dotted lines represent the fitted values of the growth curve models representing two tonal contours (a: T41a vs. T11a; b: T35a vs. T25a; c: T21a vs. T31a; d: T13a vs. T33a; e: T23a vs. T33a; f: T15a vs. T45a; g: T44a vs. T55a)

It can be seen that these two contours are very close to each other, and the contours plotted from the fitted models are smooth. This suggests that a sensible model has been chosen, and the surface contour given by the model is very close to the aggregated f0 data after normalization.

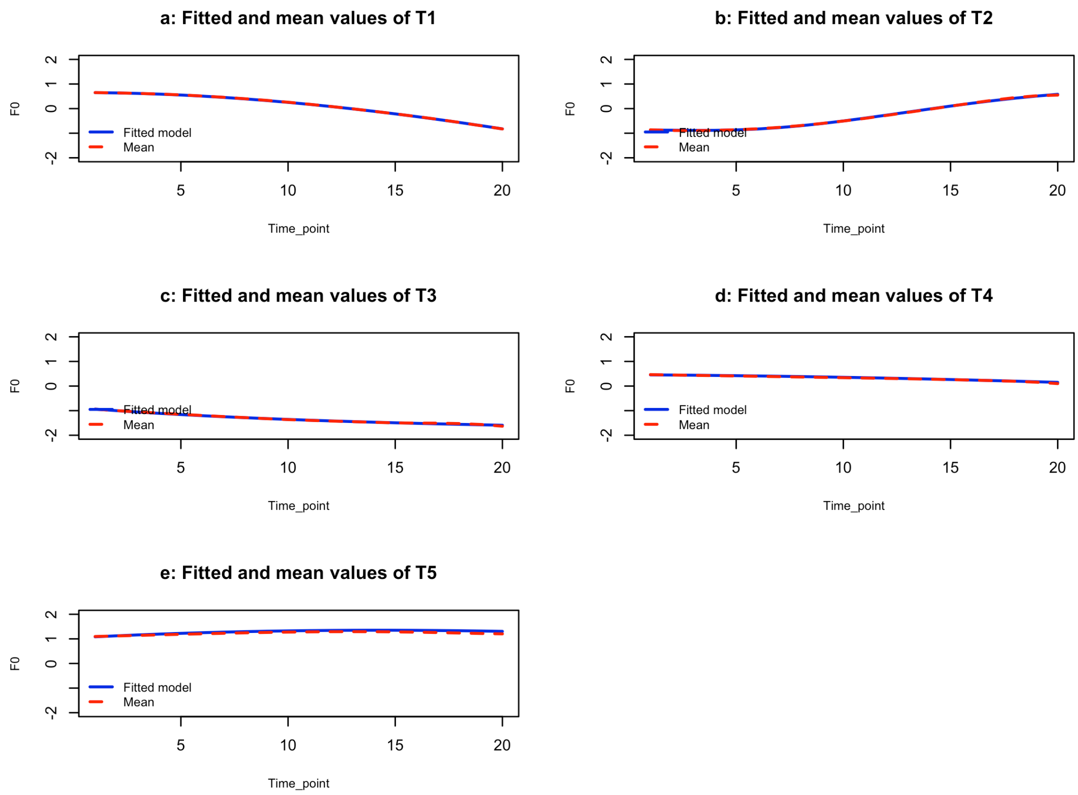

Fig. 4. Fitted and mean values of Nanjing Mandarin T1-T5: the dotted lines plot the averaged values from the original observed data, and the solid line is the fitted values from the optimal model for each tone.

Table 7. Models chosen for each tone and estimated coefficients

Tone	Model Selected	*c1*	*c2*	*c3*	*β*	*λ*	*a*	*b*
1	Second order	NA	NA	NA	-7.80	0.035	-0.27	8.45
2	Third order	-11.85	-1.30	-0.09	NA	0.14	-0.27	10.96
3	Second order	NA	NA	NA	0.71	0.09	-0.0065	-1.58
4	Second order	NA	NA	NA	-5.21	0.015	-0.083	5.67
5	Second order	NA	NA	NA	- 9.30	0.02	-0.14	10.34

After choosing the optimal model for each tone, we proceed to calculate fitted values in order to offer a description of tonal values in Chao's scale based on acoustic data. The beginning and ending points of the fitted values based on the optimal model of each tone are given in Table 8. The four sample quantiles (20%, 40%, 60%, and 80%) for all the fitted values of five monosyllabic tones were then calculated. The cut-off values corresponding to each sample quantile is as follows: 20%: -0.90; 40%: -0.02; 60%: 0.39; 80%: 0.97. The transformation criteria for Chao's five points and the transformed integers are also listed in Table 8. For example, if the fitted f0 is 0.65, which falls in the range 0.39 (60%)-0.97 (80%), then this value is transformed to the integer four according to Chao's scale.

Table 8. Beginning and ending points of fitted tone values

Tone	Beginning normalized f0 (Chao's scale)	Ending normalized f0 (Chao's scale)	Transformation criteria in Chao's scale	Reported tone values in the literature	Proposed Tone values
1	0.65 (4)	-0.82 (2)	1 (< -0.90 (20%))	31/41	42
2	-0.85 (2)	0.94 (4)	2 (-0.90 (20%)--0.02 (40%))	24/13	24
3	-0.94 (1)	-1.59 (1)	3 (-0.02 (40%)-0.39 (60%))	22/212/11	11
4	0.45 (4)	0.15 (3)	4 (0.39 (60%)-0.97 (80%))	44	43
5	1.08 (5)	1.31 (5)	5 (> 0.97 (80%))	5/55	55

Compared to our analysis, the traditional description of monosyllabic tones is reasonable in most cases. Recall that the tone values for each monosyllabic tone is reported as follows: T1 (31/41), T2 (24/13), T3 (22/212/11), T4 (44), T5 (5/55) (Liu 1995, 1997; Sun 2003). We agree with the traditional description that T1 has a falling slope and T2 a rising one, but the transcription 42 for T1 and 24 for T2 seem to be more appropriate according to the transformation based on statistical models. Also, there are two relatively level tones T3 and T4 with a shallow falling slope. The transcription 11 for T3 corresponds well to our data. T3 has a linear underlying target, and the acoustic analysis and the plot show no obvious turning point for this tone, which suggests a representation using the reported 212 of a contour tone may not be appropriate. The transcription of T4 (44) does not reflect the shallow falling slope, where the offset can be better transcribed with 3, resulting in T4 (43). The traditional transcription for T5 (5) for a short tone is reasonable from our model fitting and transformation, since both the onset and offset correspond to the integer 5.

3.6 Results of testing underlying pitch targets of Nanjing Mandarin sandhi tones

The same procedure of testing underlying pitch targets in Standard Mandarin was applied to Nanjing Mandarin. We first determined the optimal model for each pair of sandhi tone and the reported tone it turns into, appearing in the same or similar disyllabic contexts. Then, we fit the chosen optimal model and obtained coefficients from each speaker to compare the coefficients of underlying pitch targets. Table 9 presents the means and standard deviations of estimated coefficients for each sandhi tone and the reported citation tone it turns into. Table 9 also lists whether the coefficients of underlying pitch targets are statistically different. The results showed that most of the underlying pitch targets of the sandhi tones did become neutralized with the reported citation tone. Recall that the sandhi T1 in the combination T1 + T1 is denoted as T11a, where the letter a stands for its being the first syllable in the disyllabic word. From Table 9, since the slope and intercept did not exhibit significant differences, the underlying pitch target of sandhi T1 neutralizes with that of T4 before another T1. Similarly, other underlying pitch targets of sandhi tones also neutralize with that of citation tones listed in Table 9. All the sandhi tones are underlined in Table 9. Note that the underlying pitch target of the first T3 in T3 + T3 did not neutralize with that of the reported citation T1 (Sun 2003), but it neutralized with that of T2 (Liu 1995). Moreover, the modelling of acoustic data lends support to Sun (2003)'s proposal of the rule T5 → T4/_T5, where the underlying pitch target of T55a neutralized with T45a, not supporting Liu (1995)'s description of a derivational tone with the tone value transcribed as "3".

Table 9. Results of testing underlying pitch targets in Nanjing Mandarin

Tone Sandhi Pair	Model	Slope a	S or D Slope *a*	Intercept *b*	S or D Intercept *b*
T41a vs. T<u>1</u>1a	Second	T41a: *mean(sd)=*	$V = 5, p = 0.16$ (S)	T41b: *mean(sd)=0.34(0.54);*	$V = 16, p = 0.31$ (S)

		-0.000053 (0.011); T11a: mean(sd)= -0.015 (0.029)		*T11b: mean(sd)= -0.12(0.84)*	
T35a vs. T25a	Second	T35a: mean(sd) = 0.00082(0.03) T25a: mean(sd) = -0.0066(0.04)	$V = 22, p = 0.64$ (S)	T35b: mean(sd) = -1.2(0.33) T25b: mean(sd) = -1.12(0.61)	$V = 6, p = 0.81$ (S)
T21a vs. T31a	Second	T21a: mean(sd) = 0.079(0.023) T31a: mean(sd) = 0.081(0.027)	$V = 25, p = 0.82$ (S)	T21b: mean(sd) = -1.14(0.35) T31b: mean(sd) = -1.65(0.80)	$V = 7, p = 0.074$ (S)
T13a vs. T33a	Second	T13a: mean(sd) = -0.06(0.038) T33a: mean(sd) = 0.078(0.047)	$V = 45, p = 0.0039$ (D)	T13b: mean(sd) = 3.77(3.03) T33b: mean(sd) = -0.84(0.67)	$V = 1, p = 0.016$ (D)
T23a vs. T33a	Second	T23a: mean(sd) = 0.080 (0.012) T33a: mean(sd) =0.089 (0.038)	$V = 21, p = 0.74$ (S)	T23b: mean(sd) = -0.82 (0.20) T33b: mean(sd) = -1.03	$V = 10, p = 0.58$ (S)

				(0.44)	
T15a vs. T45a	Second	T15a: mean(sd) = -0.047 (0.049) T45a: mean(sd) = -0.041 (0.043)	$V = 24, p = 0.91$ (S)	T15b: mean(sd) = 0.97(0.56) T45b: mean(sd) = 2.31(4.89)	$V = 16, p = 0.81$ (S)
T44a vs. T55a	Second	T44a: mean(sd) = -0.22 (0.19) T55a: mean(sd) = -0.29 (0.24)	$V = 16, p = 0.077$ (S)	T44b: mean(sd) = 33.41 (35.43) T55b: mean(sd) =47.15 (40.75)	$V = 51, p = 0.38$ (S)

S: Same; D: Different

Figure 5 plots the mean and error bars of the observed data as well as the fitted values of the model, which can be regarded as the surface tonal contours regenerated based on the fitted underlying pitch target. In sum, based on the modelling of acoustic data consisting of monosyllabic tones and tone sandhi, we propose the following tone sandhi rules with the transcription: T1→T4/_T1 (42→43/_42); T2→T3/_T5 (24→11/_5); T3→T2/_T1 (11→24/_42); T3→T2/_T3 (11→24/_11); T4→T1/_T5 (43→42/_5); T5→T4/_T5 (5→43/_5).

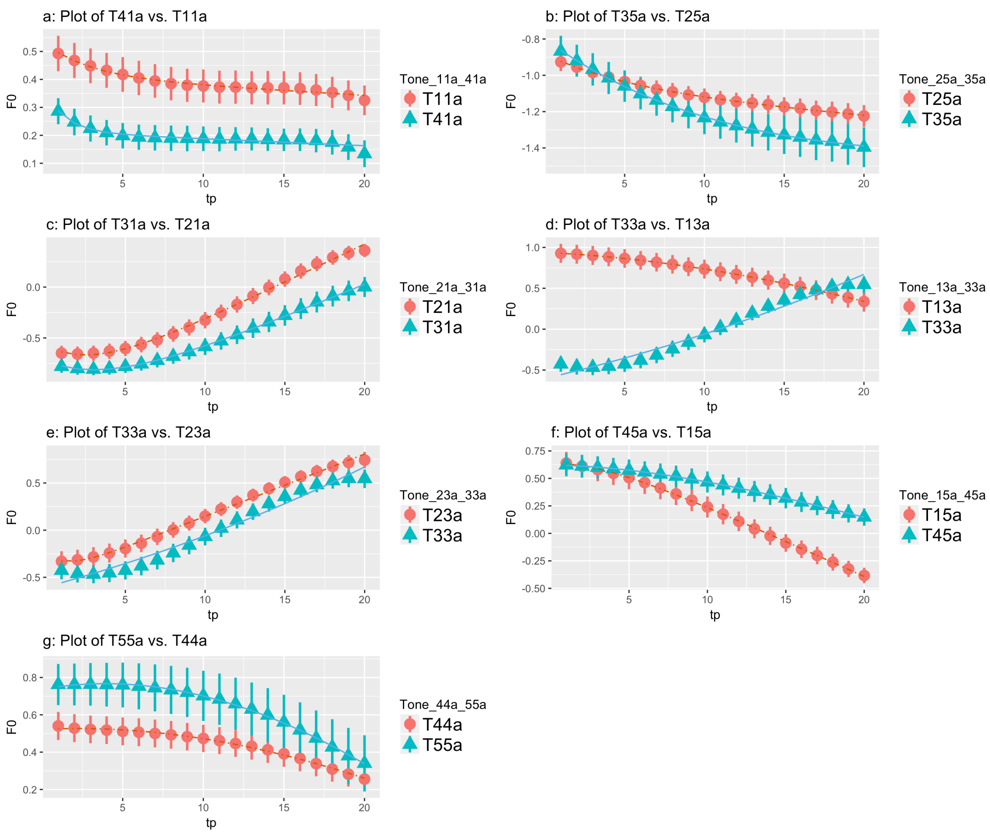

Fig. 5. Fitted underlying pitch target models in Nanjing Mandarin (a: T41a vs. T11a; b: T35a vs. T25a; c: T21a vs. T31a; d: T13a vs. T33a; e: T23a vs. T33a; f: T15a vs. T45a; g: T44a vs. T55a)

4. Discussion

Statistical modelling of the acoustic data can deepen our understanding of tone sandhi process. We evaluated quantitative methods and demonstrated that statistically testing underlying pitch targets revealed the categorical nature of tone sandhi. Moreover, acoustic studies involving statistical testing and modelling of both surface f0 contours and underlying pitch targets can provide a quantitative basis for a more precise transcription of tones.

4.1 Transcriptions of Nanjing Mandarin monosyllabic tones

In addition to examining tone sandhi, this study also offered an updated transcription of monosyllabic tones of Nanjing Mandarin to provide a more comprehensive picture of Nanjing Mandarin.

Transcriptions in Chao's scale were previously proposed for monosyllabic tones in Nanjing Mandarin based on impressionistic data in the literature. This study proposes transcriptions of Nanjing Mandarin monosyllabic tones to represent the onset and offset of each tone, which corresponded well with the plots of tones and statistical models of acoustic data.

The tonal shapes, including tones with a rising or a falling slope, correspond fairly well to traditional descriptions, though the specific integers chosen for Chao's transcription based on acoustic data in this study exhibit some variation from traditional descriptions. After examining the slope and intercept values for the underlying pitch target as well as the plots for regenerated f0 contours and mean f0 contours, a transcription of each monosyllabic tone that we propose based on statistical analysis of acoustic data is as follows: T1 (42), T2 (24), T3 (11), T4 (43), T5 (5). The transformation to Chao's tone numbers based on statistical modelling has some advantages (Chen, accepted): (1) Statistical modelling may help determine whether a tone should be represented as a straight or circumflex tone; (2) Statistical modelling helps predict tonal contours of the entire speech community based on samples of speech production; (3) The transformation is based on underlying pitch targets, conforming to articulatory mechanisms (Xu & Prom-on 2014), whereas previous transformation methods rely extensively on the raw data or some transformation of it without statistical modelling.

4.2 Modelling tone sandhi

As discussed earlier, tone sandhi cannot be easily distinguished qualitatively and quantitatively from tonal coarticulation in some languages or dialects like Nanjing Mandarin, since some tone sandhi rules share properties of tonal coarticulation. Therefore, we examined whether quantitative methods may help us in the task of identifying tone sandhi. The growth curve analysis on the Standard Mandarin and Nanjing Mandarin tone sandhi rules reveal that the surface f0 contours of the sandhi tone and the corresponding citation tone it turns into are statistically different, and thus not neutralizing. The phenomenon of non-neutralization on the surface f0 contours by statistical testing for the proposed impressionistic sandhi tones was also found in many studies including Standard Mandarin (Zee 1980;

Shen 1992; Xu 1993; Peng 2000; Yuan & Chen 2014) and Tianjin Chinese (Zhang & Liu 2011; Li & Chen 2016) using different statistical techniques. For Standard Mandarin, the sandhi T3 and the citation T2 (35) are reported to have different mean f0 values (Zee 1980; Shen 1992; Xu 1993; Peng 2000) or magnitude of f0 rise and duration (Yuan & Chen 2014). For Tianjin Chinese, Zhang and Liu (2011) found that except for the tone sandhi rule T1 + T1 → T2 + T1, all other impressionistic sandhi rules (T3 + T3 → T2 + T3; T4 + T1 → T2 + T1; T4 + T4 → T1 + T4) were acoustically non-neutralizing using Repeated Measures ANOVA. Li and Chen (2016) further tested impressionistic Tianjin Chinese tone sandhi rules for tones in a disyllabic combination T1T1a vs. T2T1a, T1T1a vs. T3T1a, T4T1a vs. T2T1a, and T3T3a vs. T2T3a using the growth curve analysis and also found non-neutralization on the f0 contours. Thus, using growth curve analysis in both Tianjin Chinese (Li & Chen 2016) and Nanjing Mandarin in our study, the statistical difference may lie in the intercept or the linear terms used to capture the surface contours. These results indicate that growth curve analysis is able to capture variability in the surface f0 contours, and is sensitive to phonetic perturbation.

The procedure of testing underlying pitch targets has proven to be useful in identifying phonological tone sandhi processes because, in this procedure, statistical significance is obtained only when there is a consistent and significant difference between the two underlying pitch targets in question, consistent with the proposed two characteristics of a tone sandhi process, namely stability and a categorical shift.

Consequently, this procedure can be extended to help examine tone sandhi phenomena in other under-studied languages. If the underlying pitch target has varied extensively from that of the original citation tone in the same or similar disyllabic context, then a categorical shift has likely occurred, and thus tone sandhi rather than tonal coarticulation is responsible for the observed variation. On the other hand, if the underlying pitch target is not significantly different from that of the original citation tone, then the observed surface perturbation is likely due to contextual coarticulation or perturbation on the surface. In this study, we examined tone sandhi rules in Nanjing Mandarin, especially those where discrepancies were found in the literature. Our modelling of the acoustic data confirmed Sun (2003)'s proposal of T5→T4/_T5 rule, which was differently described in Liu (1995), and Liu (1995)'s proposal T4→T1/_T5, which was not described in Sun (2003). Liu (1995)'s proposal of the rule T3→T2/_T3, explained differently by Sun (2003), was also supported by our statistical testing.

Note that our study mainly focuses on the statistical modeling of acoustic data, and we did not test if there is a direct link between significant differences in acoustic data and significance differences in perception for Standard Mandarin and Nanjing Mandarin. Based on perceptual studies in Standard Mandarin (Peng 2000), such a link is likely to be reaffirmed. For future studies, it is worth investigating if such a link exists cross-linguistically.

In conclusion, the methods chosen to test significant changes in underlying pitch targets may better help us identify tone sandhi processes. Based on statistical modelling of underlying pitch targets, we confirm some of the results reported based on impressionistic data, and propose the following tone sandhi rules with transcription in the parenthesis in Table 10. A numerical approach can function as a useful tool, and thus helps validate and modify research results based on impressionistic data.

Table 10 A comparison of tone sandhi rules proposed in the literature and in the current study

Liu (1995)	Sun (2003)	Newly proposed tone sandhi rules
T1→T4/_T1 (41→44/_41)	T1→T4/_T1 (31→44/_31)	T1→T4/_T1 (42→43/_42)
T2→T3/_T5 (24→11/_5)	T2→T3/_T5(13→22/_5)	T2→T3/_T5 (24→11/_5)
T3→T2/_T1 (11→24/_41)	T3→T2/_T1(22→13/_31)	T3→T2/_T1 (11→24/_42)
T3→T2/_T3 (11→24/_11)	T3→T1/_T3(22→31/_22)	T3→T2/_T3 (11→24/_11)
T4→T1/_T5 (44→41/_5)	None	T4→T1/_T5 (43→42/_5)
T5→derived T/_T5 (5→3/_5)	T5→T4/_T5 (5→44/_5)	T5→T4/_T5 (5→43/_5)

5. Conclusions

The current study is the first study to evaluate current quantitative methods to model tone sandhi rules. It was found that growth curve analysis captures fine differences of surface f0 contours suggesting non-neutralization on the surface f0 contours of sandhi tone and its corresponding citation tone. On the other hand, the pitch target approximating method suggested neutralization of underlying pitch targets of the two tones, revealing that the third tone sandhi rule in Standard Mandarin is a stable, categorical and phonological process. When the same approach was applied to Nanjing Mandarin, the underlying pitch targets of reported sandhi tones also showed neutralization with reported base tones in most cases, but the surface f0 contours of each pair are not neutralized. Our results provided acoustic evidence for the debate over the existence of some tone sandhi rules in Nanjing Mandarin based on impressionistic data. Finally, transcription modification of some monosyllabic Nanjing Mandarin tones were recommended based on transformation of the results of the statistical modelling on the acoustic data.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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APPENDIX

Standard Mandarin disyllabic word list

T2+T3	T3+T3
凡响 [fæn ɕaŋ] "ordinary tones"	反响 [fæn ɕaŋ] "reverberation"
携手 [ɕee ʂəu] "hand in hand"	写手 [ɕee ʂəu] "writer"
埋土 [mai tʰʷuu] "bury … under soil"	买土 [mai tʰʷuu] "buy soil"
仁者 [ʐən ʈʂɤɤ] "a benevolent man"	忍者 [ʐən ʈʂɤɤ] "ninja"
神美 [ʂən məi] "aesthetic spirit"	审美 [ʂən məi] "aesthetic appreciation"
梅酒 [məi tɕəu] "plum wine"	美酒 [məi tɕəu] "good wine"
油水 [jəu ʂwəi] "grease"	有水 [jəu ʂwəi] "have water"
唯美 [wəi məi] "aestheticism"	伟美 [wəi məi] "magnificent"

Nanjing Mandarin monosyllabic word list

T1	T2	T3	T4	T5
妈 [mɑ] "mother"	麻 [mɑ] "hemp"	马 [mɑ] "horse"	骂 [mɑ] "scold"	抹 [mɑ] "wipe"
诗 [ʂʅ] "poem"	时 [ʂʅ] "time"	使 [ʂʅ] "use"	试 [ʂʅ] "try"	石 [ʂʅ] "stone"
披 [pʰi] "batch"	皮 [pʰi] "skin"	痞 [pʰi] "ruffian"	屁 [pʰi] "fart"	劈 [pʰi] "hack"
梯[tʰi] "ladder"	提[tʰi] "carry"	体[tʰi] "body"	替[tʰi] "substitute"	踢[tʰi] "kick"
肤[fu] "skin"	扶[fu] "hold"	腐[fu] "rotten"	负[fu] "negative"	福[fu] "blessing"
呼[xu] "call"	胡[xu] "Hu (family name)"	虎[xu] "tiger"	护 [xu] "protect"	忽 [xu] "sudden"
期[tɕʰi] "term"	奇[tɕʰi] "strange"	起 [tɕʰi] "from"	气 [tɕʰi] "gas"	七 [tɕʰi] "seven"
痴 [tʂʰʅ] "silly"	迟 [tʂʰʅ] "late"	耻 [tʂʰʅ] "humiliation"	翅 [tʂʰʅ] "wings"	吃 [tʂʰʅ] "eat"

铺 [pʰu] "pave"	葡 [pʰu] "Portuguese"	浦 [pʰu] "river side"	铺 [pʰu] "shop"	扑 [pʰu] "throw oneself on"
初 [tsʰu] "beginning"	锄 [tsʰu] "hoe"	楚 [tsʰu] "clear"	醋 [tsʰu] "vinegar"	促 [tsʰu] "urgent"
摸 [mo] "stroke"	蘑 [mo] "mushroom"	抹 [mo] "smear"	磨 [mo] "rub"	末 [mo] "end"

Nanjing Mandarin disyllabic word list:

First↓ Second →	T1	T2	T3	T4	T5
T1	T1 T1 花生 [xuɑ sən] "peanut" 天空 [tʰien kʰoŋ] "sky" 猪肝 [tʂu kɑŋ] "pork liver" 司机 [sɿ tɕi] "driver" 相思 [ɕiɑŋ sɿ] "miss"	T1 T2 梳头 [su tʰəɯ] "comb one's hair" 清除 [tɕʰin tsʰu] "eliminate" 升旗 [sən tɕʰi] "raise a flag" 专题 [tʂuɑn tʰi] "subject" 分离	T1 T3 观点 [kuɑn tʰien] "opinion" 清楚 [tɕʰin tsʰu] "clear" 思想 [sɿ ɕiɑŋ] "thought" 生理 [sən li] "physiology" 收礼	T1 T4 关店 [kuɑn tʰien] "close the store" 相似 [ɕiɑŋ sɿ] "similar" 多谢 [to sie] "many thanks" 生气 [sən tɕʰi] "angry" 初四 [tsʰu sɿ] ""	T1 T5 公立 [koŋ li] "public" 综合 [zoŋ xo] "comprehensive" 收集 [səɯ tɕi] "collect" 高级 [kɔo tɕi] "advanced" 锅贴

		[fən li] "separate"	[səɯ li] "receive a gift" *拘捕* [tɕy pʰu] "arrest"	"the 4th day of the lunar new year"	[ko tʰie] "fried dumplings"
T2	T2 T1 *厨师* [tsʰu sɿ] "chef" *胡椒* [xu tɕiɔo] "pepper" *流星* [liəɯ sin] "meteor" *平菇* [pʰin ku] "oyster mushroom" *回锅* [xuəi ko] "cook again"	T2 T2 *烦神* [fɑn sən] "bother" *神奇* [sən tɕʰi] "miraculous" *厨房* [tsʰu fɑŋ] "kitchen" *流行* [liəɯ ɕin] "popular" *旗袍* [tɕʰi pʰɔo] "cheongsam"	T2 T3 *胡搅* [xu tɕiɔo] "make trouble" *河水* [xo suəi] "river" *骑马* [tɕʰi mɑ] "ride a horse" *民主* [min tʂu] "democracy" *长短* [tsʰɑŋ tuɑn] "length"	T2 T4 *文化* [un xuɑ] "culture" *强调* [tɕʰiɑŋ tiɔo] "emphasize" *无趣* [u tɕʰy] "uninteresting" *陪唱* [pʰəi tsʰɑŋ] "accompany singing" *城市* [tsʰən ʂʅ] "city"	T2 T5 *其实* [tɕʰi ʂʅ] "actually" *除法* [tʂʰu fɑ] "division" *诚实* [tʂʰən ʂʅ] "honest" *残疾* [tsʰɑŋ tɕi] "disabled" *民族* [min tsu] "ethnicity"

					回国 [xuəi ko] "return to one's country"
T3	T3 T1 审批 [sən pʰi] "examine and approve" 手机 [səɯ tɕi] "mobile phone" 小偷 [ɕiɔo tʰəɯ] "theif" 火星 [xo sin] "Mars" 苦思 [kʰu sɿ] "think hard"	T3 T2 体裁 [tʰi tsʰae] "genre" 小头 [ɕiɔo tʰəɯ] "small head" 几年 [tɕi lien] "several years" 粉红 [fən xoŋ] "pink" 整齐 [tsən tɕʰi] "tidy"	T3 T3 起跑 [tɕʰi pʰɔo] "start of a race" 打赌 [tɑ tu] "bet" 保险 [pɔo ɕien] "insurance" 手里 [səɯ li] "in the hand" 俘虏 [fu lu] "capture"	T3 T4 主干 [tʂu kɑŋ] "main body" 死相 [sɿ ɕiɑŋ] "disgusting face" 打架 [tɑ ɕiɑ] "fight" 火气 [ko tɕʰi] "internal heat" 打闹 [tɑ lɔo] "roughhousing"	T3 T5 省力 [sən li] "labor-saving" 组织 [zu tʂʅ] "organization" 简历 [tɕien li] "curriculum vitae" 妥协 [tʰo ɕie] "compromise" 处罚 [tʂʰu fɑ] "punishment"
T4	T4 T1 化身 [xuɑ sən] "transform" 大家	T4 T2 话题 [xuɑ tʰi] "topic" 灌肠	T4 T3 治理 [tʂʅ li] "governace" 大脑	T4 T4 四季 [sɿ tɕi] "four seasons" 胜利	T4 T5 智力 [tʂʅ li] "intelligence" 祝福

	[tɑ ɕiɑ] "everybody" *上街* [sɑŋ tɕie] "go shopping" *误区* [u tɕʰy] "misunderstanding" *唱歌* [tsʰɑŋ ko] "singing"	[kuɑn tʂʰɑŋ] "enema" *化肥* [xuɑ fəi] "fertilizer" *富婆* [fu pʰo] "rich woman" *路盲* [lu mɑŋ] "poor sense of direction"	[tɑ lɔo] "brain" *上海* [sɑŋ xae] "Shanghai" *禁赌* [tɕin tu] "ban gambling" *敬礼* [tɕin li] "salute"	[sən li] "victory" *气泡* [tɕʰi pʰɔo] "bubble" *问话* [un xuɑ] "ask a question" *气势* [tɕʰi ʂʅ] "vigor"	[tʂu fu] "wish" *附录* [fu lu] "appendix" *奋力* [fən li] "spare no effort" *禁毒* [tɕin tu] "drug prevention"
T5	T5 T1 *激光* [tɕi kuɑŋ] "laser" *木花* [mu xuɑ] "wood flowers" *滑梯* [xuɑ tʰi] "slide" *读书* [tu ʂu] "read a book" *活该*	T5 T2 *脱鞋* [tʰo ɕie] "take off one's shoes" *力行* [li ɕin] to "make an effort" *脱毛* [tʰo mɔo] "hair removal" *活埋* [xo mae] "bury alive"	T5 T3 *合理* [xo li] "reasonable" *发表* [fɑ piɔo] "publish" *客体* [kʰə tʰi] "object" *毒死* [tu sɿ]	T5 T4 *熟透* [ʂu tʰəɯ] "well-done" *出事* [tsu ʂʅ] "have an accident" *活性* [xo ɕin] "activity" *局部* [tɕy pu] "partial"	T5 T5 *出发* [tsu fɑ] "departure" *国籍* [ko tɕi] "nationality" *屋脊* [u tɕi] "ridge" *格局* [kə tɕy] "layout"

	[xo kae] "serves someone right"	*秃头* [t^{h}u t^{h}əɯ] "bald"	"kill with poison" *极小* [tɕi ɕiɔo] "extremely small"	*国际* [ko tɕi] "international"	*蜡烛* [lɑ tʂu] "candle"