World Academy of Science, Engineering and Technology
International Journal of Cognitive and Language Sciences
Vol:11, No:5, 2017

Statistical Modeling of Mandarin Tone Sandhi: Neutralization of Underlying Pitch Targets

Si Chen, Caroline Wiltshire, Bin Li

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000

Abstract**—**This study statistically models the surface f0 contour and the underlying pitch target of a well-studied third sandhi tone of Mandarin Chinese. Although the growth curve analysis on the surface f0 contours indicates non-neutralization of this sandhi tone (T3) and the base T2, their underlying pitch targets do show neutralization. These results in Mandarin are also consistent with the perception of native speakers, where they cannot distinguish the third T3 from the base T2, compensating contextual variation. It is possible to use the proposed statistical procedure of testing underlying pitch targets to verify tone sandhi processes in other tonal languages.

Keywords**—**Growth curve analysis, tone sandhi, underlying pitch targets.

I. Introduction

STATISTICAL modeling of the acoustic data is conducive to promoting our understanding of tone sandhi. The surface f0 contours are subject to more phonetic variation, and previous studies examining the surface contours report non-neutralization in the Mandarin third-tone sandhi rule [1] and tone sandhi rules in Tianjin Chinese [2]. We also obtain similar results after performing the growth curve analysis on the Mandarin third-tone sandhi rule. The surface f0 contours are statistically different between the sandhi T3 and the corresponding citation T2 it turns into as reported, suggesting non-neutralization on the surface. The statistical differences lie in the linear and quadratic term used to capture the surface contours. Although non-neutralization exists for the third sandhi tone on the surface, we are still able to obtain a neutralization result when the underlying pitch targets are modeled instead. The statistical model fitting procedure obtains the optimal statistical model for underlying pitch targets of tones, and tests whether the underlying target is linear or quadratic. Afterwards, the models can be used to test whether two underlying pitch targets are the same or not. The procedure applied to the well-studied third tone sandhi in Mandarin Chinese shows neutralization results of the third sandhi tone and T2 (35), consistent with the results of perceptual experiments [3].The statistical modeling on the underlying pitch targets correspond to the characteristics of a tone sandhi process involving stability, categorical shift and influence on the entire part of the tones. We may test whether the underlying pitch target has varied extensively from that of the original citation tone. If so, it indicates a categorical shift, and thus it is likely to be a phonological tone sandhi rule, involving a shift to a derived tone or another citation tone, which can also be statistically tested using the same procedure. However, if the underlying target does not show significant difference from its original citation form, then it is likely that the observed surface perturbation are simply due to phonetic variation, not distinctive enough to be a phonological tone sandhi.

Most researchers agree that the sandhi tone should be perceived differently from the base tone [4], thus leading to a requirement of statistical modeling more congruent to perceptual results. However, as mentioned in the introduction, the perceptual and acoustic results of the third tone sandhi rule are not consistent [4]. The results obtained in the current study showed inconsistency of perceptual results when modeling the surface tone, but more consistent results with perceptual experiments when modeling underlying pitch targets. When we separate the two modeling procedure, the non-neutralization of surface f0 contours and neutralization in the underlying pitch targets results obtained using growth curve analysis and nonlinear regression are similar to previous results in the literature. These methods might be able to apply to other less familiar tonal languages.

Mandarin Chinese has four tones, which can be described by Chao tone numbers as follows [5]. The numbers reflect the starting and ending point of tones on a 1 to 5 scale, where 1 indicates the lowest pitch of the speaker, and 5 the highest.

- 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”

Tone sandhi is the tonal alternation of a tone according to the phonological environment it occurs [4]. There is one famous tone sandhi rule in Mandarin as described in many studies [5]-[7]:

a. T3 (213) → T2 (35)/___ T3 (213) (third-tone sandhi).

Despite the descriptive rule, non-neutralization of the third sandhi tone and T2 has been reported when their surface f0 contours were examined. However, perceptual experiments on native speakers show that the third tone sandhi and T2 cannot be distinguished effectively. The following Subsection A and B summarize previous findings from the perspective of speech production and perception. The Subsection C illustrates the concept of underlying pitch targets.

Si Chen is with the Department of Chinese and Bilingual Studies, the Hong Kong Polytechnic University, Hong Kong, China (phone: (852) 3400-8061; email: qinxi3@gmail.com).

Caroline Wiltshire is with the Department of Linguistics, University of Florida, FL, U. S. (e-mail: wiltshir@ufl.edu).

Bin Li is with the Department of Linguistics and Translation, City University of Hong Kong, Hong Kong, China (e-mail: binli2@cityu.edu.hk).

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000

A. Non-Neutralization of Surface f0 Contours

Previous studies show that the third tone sandhi is acoustically different from T2. For example, Shen reports that the third sandhi tone is 6 Hz lower than T2 [8], and Xu also found this sandhi tone to be 3.2 Hz lower, reaching statistical significance [9]. Peng found a marginally significant difference in the mean value of the third sandhi and T2 in Taiwan Mandarin, where the overall f0 value of third tone sandhi is 2.33 Hz lower [3]. Peng explains that the reason for the sandhi tone to begin and end in a lower pitch might be due to the fact that the low onset value is maintained from its original tone (214) [3]. More recently, Yuan and Chen also found acoustic differences in a corpus of conversational speech [10]. Xu and Prom-on compared the synthesis accuracies from simulating three third tone sandhi hypotheses using a Chinese corpus: 1. There is no change in the underlying pitch target; 2. The third sandhi tone changes to the rising tone (T2); 3. The third sandhi tone changes to another tone. Their results show that the underlying pitch target of the sandhi low tone may have either changed to another category or the same as the rising tone [11].

B. Perceptual Studies

Multiple studies indicate that the third sandhi tone and T2 do show some differences acoustically. However, native speakers can hardly distinguish the two based on the acoustic differences as shown in perceptual experiments both by Beijing and Taiwan Mandarin listeners [3], [12], [13]. For example, in Mandarin “good rice” consists of two syllables /hau/ and /mi/ bearing two underlying T3, and “millimeter” consists of the identical segments /hau/ and /mi/, bearing T2 and T3 respectively. However, the T3+T3 undergoes tone sandhi, and native speakers cannot detect the differences between “good rice” and “millimeter” effectively [14]. Peng pointed out that it might be due to the general ability to compensate variations [3]. It is pointed out that although the four Mandarin tones may be affected substantially by the preceding tones, native mandarin speakers can compensate for the contextual variations [15], [16].

In general, the disyllable T2+T3 is easy to be confused with T3+T3. Phonetic details can affect perception of T2 and T3. It is shown that there is a trading relation between initial fall and timing of the turning point in identifying the T2 and T3, since undetectable initial fall of the falling-rising contour is perceived as T2, and detectable initial fall is perceived as T3. Later turning point is needed for shallower falling slope to be perceived as T3 due to detectable initial fall. Misidentification is due to violation of the correlation between initial fall and the timing of the turning point [17]. Both Mandarin and Dutch speakers show more confusion between the disyllable T2+T3 and underlying T3+T3, but Mandarin speakers demonstrate more pronounced misperception indicating a common functional basis suggested by cross-linguitic consistency as well as the fact that phonological knowledge can shape perception [14].

In sum, phonetic differences between T2 and the sandhi T3 are identified in previous studies. However, the perceptual experiments do agree that native speakers cannot distinguish between T2 and sandhi T3.

C. Underlying Pitch Targets

In this study, we examined surface contours as well as underlying pitch targets of the third sandhi tone. The models proposed to capture the underlying pitch targets are distinguished from those capturing surface f0 contours [18], [19]. The underlying pitch targets can include static and dynamic pitch targets, and the operation of the pitch targets adheres to pitch implementation rules. The statistical tests of the underlying pitch targets in this study are models of underlying pitch targets [18], [19].

We statistically test whether the underlying pitch target is linear or quadratic, and whether the underlying pitch target of a citation tone has changed significantly in tonal contexts or not, based on previous quantitative models. Two models have been proposed for the underlying pitch targets. One is proposed to estimate T(t), representing the underlying target as [20]:

$$T(t) = at + b$$
$$y(t) = \beta e^{-\lambda t} + \text{at} + \text{b} \quad (1)$$

where y(t) represents f0 values. The parameter λ represents the rate of approaching the target, the parameter a is the slope, and b is the intercept of the underlying target. Also, a third order critically damped system is proposed to estimate the underlying pitch target x(t) as [18]:

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

where f0(t) represents f0 values, and λ represents the rate of approaching the target. The initial f0 values, initial velocity and initial acceleration determine the three parameters c1, c2, and c3. The parameter m is the slope of the underlying pitch target, and the parameter b is the intercept of the pitch target.

Our analysis is based on these two models. Since it is mentioned that the underlying target might be curvilinear, and not necessarily linear, we statistically tested the degree of the underlying target in the model selection [21]. We used the R language [22] to conduct all the statistical analyses in this study.

II. Method

A. Stimuli

The stimuli included eight real disyllabic words with the tonal combination T3 + T3 (213 + 213) in Mandarin Chinese, and eight real disyllabic words with other tonal combinations as fillers, in order to disguise the purpose of this study. The participants were also recorded reading monosyllables bearing T2 in isolation, which have the exact consonants and vowels as the first tone in each disyllabic combination for comparison. The consonants and vowels bearing the first T3 in T3 + T3 (213 + 213) and T2 (35) in isolation were controlled in this

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000

study to avoid consonant perturbation and intrinsic f0 perturbation effects reported in the literature [23]-[25].

We followed the experimental design in previous studies in eliciting the Mandarin third tone sandhi [7], [26]. We recorded a Beijing native speaker reading each monosyllable of the eight 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. After extraction of all the recorded monosyllables, we normalized the peak intensity of each monosyllable.

B. Participants and Experimental Procedure

Thirteen participants were recruited, who were native speakers of Mandarin. They were in the age range of 21 - 35, and were born and have lived in Beijing for about 20 years before coming to Hong Kong. All participants were paid for participating in the experiment, and signed informed consent form in compliance with a protocol approved by the Human Subjects Ethics Sub-committee at the Hong Kong Polytechnic University. None of them reported history of speaking, hearing or language difficulty, or more than five years of formal musical training or any recent musical training within the past five years. All the participants wearing a MB Quart K800 C headset were recorded on a computer at the speech lab of the Hong Kong Polytechnic University using the software audacity with a sampling rate of 44.1kHz.

We presented each pair of the modified monosyllable using E-prime with a randomized order. Two monosyllables of one disyllabic word were presented in a row to participants, with a 800ms interval in between. Participants were instructed that after hearing the two monosyllables presented, they should put the two monosyllables together to form a disyllabic word in Mandarin. They were instructed to speak at a normal speaking rate, and can repeat themselves when necessary. All of them also practiced the procedure in a training session before the experiment.

C. F0 Extractions and Statistical Analysis

The recorded speech data were segmented manually for further acoustic analysis by Praat [27]. The Praat script Prosodypro [28], designed to extract continuous f0 contours and make other measurements, was used to obtain f0 values at 20 normalized time points in each segmented interval. We performed a logarithmic Z-score normalization on f0 values before the growth curve analysis and statistical modelling of the underlying pitch targets in order to cope with variation in f0 values from different genders [29], [30].

This study follows the idea of separating the models for surface tonal contours and underlying pitch targets [19], [20]. It is plausible that the surface contours of sandhi tones in disyllabic combinations (e.g. the first T3 in T3 + T3 (213 + 213) in Mandarin Chinese) and the reported tone it changes to, based on impressionistic data (i.e. T3 → T2) may demonstrate variation in the surface tonal contours. This variation in the surface corresponds to the more phonetic and gradient phenomena, showing non-neutralization on the surface contour, which is found in Mandarin [1], [3] and Tianjin Chinese [2]. However, the underlying pitch target of the sandhi tone (the first T3 in T3 + T3 (213 + 213), denoted as T33a hereafter, where the letter *a* stands for the first syllable in a tonal combination) may exhibit smaller variation, subject to no statistical differences, compared with the underlying pitch target of the tone in isolation (T2). Therefore, both the growth curve analysis to model the surface tonal contours and the statistical modelling procedure of the underlying pitch targets were applied to Mandarin Chinese speech data.

Specifically, the growth curve analysis [31] was used to test differences in the surface f0 contours because we are interested in whether sandhi tones are neutralized on the surface. In addition to surface contours, we also examined underlying pitch targets.

III. Results

A. Results for Surface Contours in Mandarin Chinese

We performed the growth curve analysis [31], [32] to compare the surface contour of T2 (35) in isolation and that of the first T3 in the combination T3 + T3 (213 + 213). Orthogonal polynomials were used in the model to ensure the linear and quadratic terms are uncorrelated. The fixed effect was the group effect of tones (T2 (35) in isolation or T3 in context), and the random effect was to model variation among the participants. We use orthogonal polynomials because they make linear and quadratic terms uncorrelated [32]. The problem of testing the statistical significance of two surface tonal contours amounts to testing the significance of the group effect of tones in our analysis. In order to do so, we fit a baseline model (m.base) without the group effect, and it includes orthogonal polynomial to model the f0 values across time points, and a random effect to allow individuals to vary on the intercept, slope and the quadratic term. The second model (m.0) includes the group effect on the intercept, and the third model (m.1) on the linear term, and the final model (m.2) on the quadratic term. Likelihood ratio tests between models (m.base, m.0, m.1 and m.2) are used to evaluate the significance of the intercept, slope and the quadratic term.

The result of the growth curve analysis shows the two tonal contours differ significantly in the slope ($\chi^2(1) = 114.71$, $p < 0.001$*) and quadratic ($\chi^2(1) = 7.55$, $p = 0.006$*) term, but not in the intercept ($\chi^2(1) = 0$, $p = 1$). Figure 1 represents the model fit to the data of T2 in isolation, and the first T3 in the combination T3 + T3 according to the growth curve analysis. Specifically, it plots the mean and error bar of the f0 data in each normalized time point, and the solid and dotted lines represent the fitted values of the growth curve models representing two tonal contours of T2 in isolation and the sandhi T3 in T3 + T3. From the figure and the statistical testing, it can be inferred that the surface contours of T2 and the sandhi T3 do not show complete neutralization on the surface, which is also reported in the literature mentioned in the introduction.

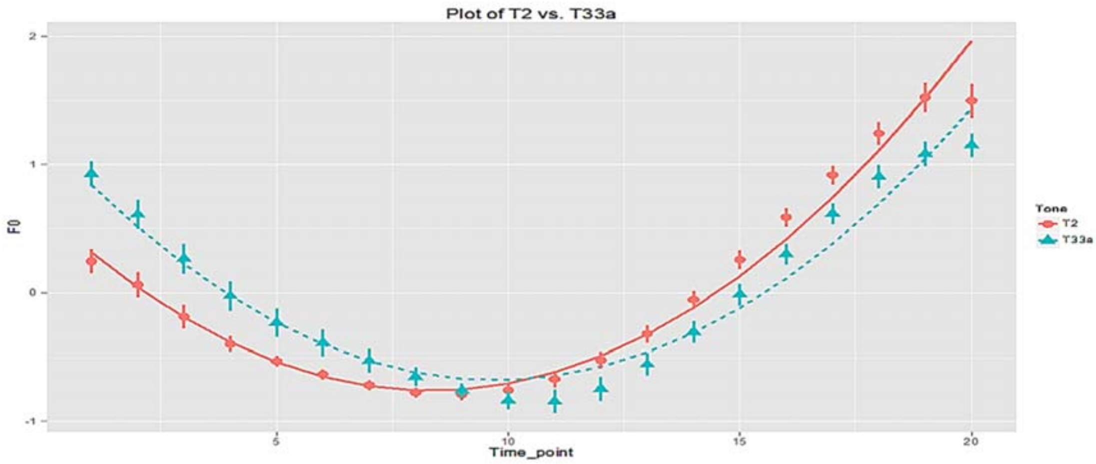

Fig. 1 *Growth curve analysis of T2 vs. T33a*

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000

B. Results for Testing Underlying Pitch Targets of Mandarin Chinese Sandhi Tones

This subsection describes the procedure of statistical modelling and testing of underlying pitch targets of two tones. It presents the testing results comparing the underlying pitch targets of the third sandhi tone and the citation T2 (35) in Mandarin Chinese.

We model the underlying pitch targets first, and then test whether a target changes to that of a citation tone reported in the literature. If the target has changed significantly, it is more likely that the tone has undergone a tone sandhi process. Moreover, we do not assume the linearity of the underlying pitch target, but performed statistical tests on whether a second polynomial degree is needed in addition to a linear term through model selection.

Since the four models listed (Eq. (3) - (6)) are non-linear models, we used non-linear regression. The four models are:

1. a simple model (sim_1) with polynomial degree = 1 for the underlying pitch target

$$y(t) = \beta e^{-\lambda t} + at + b \tag{3}$$

2. a more complex model (com_1) with polynomial degree = 1 for the underlying pitch target

$$y(t) = (c_1 + c_2 t + c_3 t^2) e^{-\lambda t} + at + b \tag{4}$$

3. a simple model (sim_2) with polynomial degree = 2 for the underlying pitch target

$$y(t) = \beta e^{-\lambda t} + dt^2 + at + b \tag{5}$$

4. a more complex model (com_2) with polynomial degree = 2 for the underlying pitch target

$$y(t) = (c_1 + c_2 t + c_3 t^2) e^{-\lambda t} + dt^2 + at + b \tag{6}$$

After obtaining the initial values and fitting the four models, we chose the best model with the minimum Akaike Information Criterion (AIC) value.

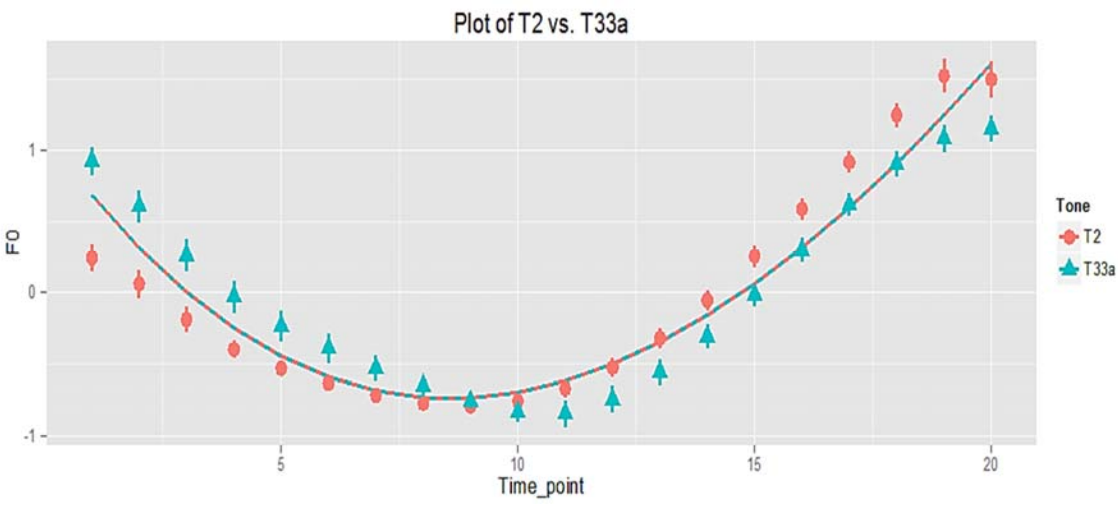

Fig 2 Regenerated surface contours based on underlying pitch targets of T2 vs. T33a

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000

Using this method, we fit a model for each tone uttered by each speaker. Then the coefficients of the underlying targets of two tones under examination (i.e. slope *a* and intercept *b* for T2 (35) and the first T3 in T3 + T3 (213 + 213)) are subject to a non-parametric test called Wilcoxon signed-rank test, which is used as an alternative of paired t-tests because the distribution of coefficients extracted from the fitted models may violate the distribution assumptions of a paired t-test. Using this method, we may test whether the underlying pitch target has varied from the original citation tone. In addition, we are able to test whether the underlying pitch target changes into that of other citation tones.

The results showed that the slope ($a = 0.83$, $p = 0.63$) and intercept ($b = -23.82$, $p = 0.63$) parameters of the third sandhi tone do not differ significantly from T2. Figure 2 plots the mean and error bar of the observed f0 data as well as the fitted values of the optimal model, which can be deemed as the surface tonal contours regenerated based on the fitted underlying pitch target. The underlying pitch targets of T2 and the first T3 in T3 + T3 do not differ significantly, showing that the tone sandhi rule in the traditional description do show neutralization in the underlying pitch target, which lends support to the fact that this rule is categorical and phonological.

The results of the underlying pitch targets are similar to the results obtained by synthesis [11], where both our results and their results demonstrate that T3 has undergone a phonological process, namely a tone sandhi rule. Our results show that the underlying pitch targets of the sandhi T3 are not statistically different from that of a citation T2, though the results obtained by Xu and Prom-on demonstrate two possibilities that T3 can either turn into a derived tone or it can turn into the citation T2 [11]. Our results might also be related to those reported in perceptual experiments, where native speakers cannot effectively differentiate the derived T3 in T3 + T3 (213 + 213) from the rising tone T2 (35) in the combinations of T2+T3 (35 + 213) [3]. It might be the case that native speakers cannot detect the differences of derived T3 and T2 on the surface because their underlying pitch targets are very similar with no statistical differences, although on the surface form, the derived T3 and T2 do not show complete neutralization.

IV. Discussion

Statistical modeling of the acoustic data is conducive to promoting our understanding of tone sandhi. The surface f0 contours are subject to more phonetic variation, and previous studies examining the surface contours report non-neutralization in the Mandarin third-tone sandhi rule [1] and tone sandhi rules in Tianjin Chinese [2]. We also obtain similar results after performing the growth curve analysis on the Mandarin third-tone sandhi rule. The surface f0 contours are statistically different between the sandhi T3 and the corresponding citation T2 it turns into as reported, suggesting non-neutralization on the surface. The statistical differences lie in the linear and quadratic term used to capture the surface contours.

Although non-neutralization exists for the third sandhi tone on the surface, we are still able to obtain a neutralization result when the underlying pitch targets are modeled instead. The statistical model fitting procedure obtains the optimal statistical model for underlying pitch targets of tones, and tests whether the underlying target is linear or quadratic. Afterwards, the models can be used to test whether two underlying pitch targets are the same or not. The procedure applied to the well-studied third tone sandhi in Mandarin Chinese shows neutralization results of the third sandhi tone and T2 (35), consistent with the results of perceptual experiments [3].

The statistical modeling on the underlying pitch targets correspond to the characteristics of a tone sandhi process involving stability, categorical shift and influence on the entire part of the tones. We may test whether the underlying pitch target has varied extensively from that of the original citation tone. If so, it indicates a categorical shift, and thus it is likely to be a phonological tone sandhi rule, involving a shift to a derived tone or another citation tone, which can also be statistically tested using the same procedure. However, if the underlying target does not show significant difference from its original citation form, then it is likely that the observed surface perturbation are simply due to phonetic variation, not distinctive enough to be a phonological tone sandhi.

Most researchers agree that the sandhi tone should be perceived differently from the base tone [4], thus leading to a requirement of statistical modeling more congruent to perceptual results. However, as mentioned in the introduction, the perceptual and acoustic results of the third tone sandhi rule are not consistent [4]. The results obtained in the current study showed inconsistency of perceptual results when modeling the surface tone, but more consistent results with perceptual experiments when modeling underlying pitch targets. When we separate the two modeling procedure, the non-neutralization of surface f0 contours and neutralization in the underlying pitch targets results obtained using growth curve analysis and nonlinear regression are similar to previous results in the literature. These methods might be able to apply to other less familiar tonal languages.

V. Conclusions

The growth curve analysis on the surface f0 contours show non-neutralization of tone sandhi pairs for Mandarin Chinese. The methods testing underlying pitch targets showed a desirable result confirming that the third tone sandhi rule is a more categorical and phonological process, consistent with results of perceptual experiments.

Acknowledgment

We are indebted to Dr. Nikolay Bliznyuk for helping with statistical modelling.

References

[1] E. Zee, "Tone and vowel quality," *Journal of Phonetics,* vol. 8, pp. 247–258, July 1980.

[2] J. Zhang, and J. Liu, "Tone sandhi and tonal coarticulation in Tianjin Chinese," *Phonetica,* vol. 68, no. 3, pp. 161-191, Nov. 2011.
[3] S. H. Peng, "Lexical versus 'phonological' representations of Mandarin sandhi tones", in *Papers in laboratory phonology V: Acquisition and the lexicon,* M. B. Broe, and J. Pierrehumbert Eds., Cambridge: Cambridge University Press, 2000, pp. 152-167.
[4] M. Chen, *Tone sandhi patterns across Chinese dialects,* UK: Cambridge University Press, 2000.
[5] Y. R. Chao, *Mandarin Primer,* Cambridge: Harvard University Press, 1948.
[6] C. C. Cheng, "English stresses and Chinese tones in Chinese sentences", *Phonetica,* vol. 18, no. 2, pp. 77-88, 1968.
[7] J. Zhang, and Y. W. Lai, "Testing the role of phonetic knowledge in Mandarin tone sandhi," *Phonology,* vol. 27, no. 1, pp. 153-201, May 2010.
[8] X. S. Shen, *"Tonal coarticulation in Mandarin",* Journal of Phonetics, vol. 18, no. 2, pp. 281-295, 1990.
[9] Y. Xu, "Contextual tonal variations in Mandarin," PhD thesis. University of Connecticut, 1993.
[10] J. H. Yuan, and Y. Chen, "3RD tone sandhi in Standard Chinese: A corpus approach," *Journal of Chinese Linguistics,* vol. 42, no. 1, pp. 218-234, 2014.
[11] Y. Xu, & S. Prom-On, "Toward invariant functional representations of variable surface fundamental frequency contours: Synthesizing speech melody via model-based stochastic learning," *Speech Communication,* vol. 57, pp. 181-208, Feb. 2014.
[12] W. S. Y. Wang, & K. P. Li, "Tone 3 in Pekinese," *Journal of Speech and Hearing Research*, vol. 10, no. 3, pp. 629-236, Sep. 1967.
[13] Y. C. Chang, & Y. C. Su, "La modification tonale du 3ème ton du mandarin parlé à Taiwan (Tone modification of the third tone in Mandarin spoken in Taiwan)," *Cahiers de Linguistique Asie Orientale,* vol. 23, no. 1, pp. 39-59, 1994.
[14] A. Chen, L. Liu, and R. Kager, "Cross-linguistic perception of Mandarin tone sandhi," *Language Sciences,* vol. 48, 62-69, Mar. 2015.
[15] Y. Xu, "Asymmetry in contextual tonal variation in Mandarin," *Advances in the study of Chinese language processing,* vol. 1, pp. 383-396, 1994.
[16] Y. Xu, "Contextual tonal variations in Mandarin," *Journal of Phonetics,* vol. 25, no. 1, pp. 61-83, Jan. 1997.
[17] X. S. Shen, & M. Lin, "A perceptual study of Mandarin tones 2 and 3," *Language and speech,* vol. 34, no. 2, pp. 145-156, April/June 1991.
[18] S. Prom-On, Y. Xu, & B. Thipakorn, "Modeling tone and intonation in Mandarin and English as a process of target approximation," *Journal of the Acoustical Society of America,* vol. 125, no. 1, pp. 405-424, 2009.
[19] Y. Xu, and Q. E. Wang, "Pitch targets and their realization: evidence from Mandarin Chinese," *Speech Communication,* vol. 33, no. 4, pp. 319-337, Mar. 2001.
[20] X. J. Sun, "Predicting underlying pitch targets for intonation modeling," *4th ISCA Tutorial and Research Workshop on Speech Synthesis*, 2001.
[21] Y. Xu, "Speech melody as articulatorily implemented communicative functions," *Speech Communication,* vol. 46, no. 3, pp. 220-251, July 2005.
[22] R Core Team, *R: A language and environment for statistical computing.* Vienna, Austria: Foundation for Statistical Computing, May 1, 2013. (http://www.R-project.org/)
[23] Y. Chen, "How does phonology guide phonetics in segment-f0 interaction?" *Journal of Phonetics,* vol. 39, no. 4, pp. 612-625, Oct. 2011.
[24] M. Halle, and K. N. Stevens, "A note on laryngeal features. Quarterly Progress Report," *MIT Research Lab of Electronics,* vol. 101, pp. 198-213, 1971.
[25] J. M. Hombert, J. J. Ohala, and W. G. Ewan, "Phonetic Explanations for the Development of Tones," *Language,* vol. 55, no. 1, pp. 37-58, Mar. 1979.
[26] C. C. Zhang, and G. Peng, "Productivity of Mandarin third tone sandhi: a wug test," In *Eastward flows the great river: Festschrift in honor of Prof. William S-Y. Wang on his 80th birthday*, G. Peng, and F. Shi Eds. Hong Kong: City University of Hong Kong Press, 2011, pp. 256-282.
[27] P. Boersma, and D. Weenink, Praat: doing phonetics by computer (Computer program), Version 5.4.17, retrieved 31 Aug 2015 from http://www.praat.org
[28] Y. Xu, "ProsodyPro — A tool for large-scale systematic prosody analysis," in *Tools and Resources for the Analysis of Speech Prosody (TRASP 2013)*, Aix-en- Provence, France, 2013, pp. 7-10.
[29] P. Rose, "Considerations in the normalization of the fundamental frequency of linguistic tone," *Speech communication,* vol. 6, no. 4, pp. 343-52, Dec. 1987.
[30] X. Zhu, "Shanghai Tonetics," PhD thesis. Australian National University, 1999.
[31] D. Mirman, J. A. Dixon, and J. S. Magnuson, "Statistical and computational models of the visual world paradigm: Growth curves and individual differences," *Journal of Memory and Language,* vol. 59, no. 4, pp. 475-494, Nov. 2008.
[32] D. Mirman, *Growth Curve Analysis and Visualization Using R,* London: Chapman and Hall/CRC, 2016.

International Science Index, Cognitive and Language Sciences Vol:11, No:5, 2017 waset.org/Publication/10007000