Interspeech 2025
17-21 August 2025, Rotterdam, The Netherlands

On Apical Vowels in Eastern Zhenjiang Mandarin

Xuying Wang[1], *Fang Hu*[2]

[1]Nanjing Polytechnic Institute, Nanjing, China
[2]Institute of Linguistics, Chinese Academy of Social Sciences, China
Wangxuying1994@163.com, hufang@hotmail.com

Abstract

There is generally no distributional constraint for the apical vowels in Eastern Zhenjiang Mandarin, and the apical vowels contrast with the high front vowels when preceded by an initial consonant [p pʰ m t tʰ n l tɕ tɕʰ ɕ] or occurring in an onset-less syllable. This paper analyzes acoustic characteristics and lingual articulation in the production of the apical vowels [ɿ ʮ] in Eastern Zhenjiang Mandarin. The results show that although accompanied by frication noise, the apical vowels [ɿ ʮ] have their own spectral properties that are distinctive to the high front vowel [i y]. The ultrasound data reveal that both the anterior and posterior parts of the tongue are involved in the production of [ɿ ʮ].

Index Terms: apical vowel, acoustics, articulation, Eastern Zhenjiang Mandarin

1. Introduction

Apical vowels are common in Chinese dialects, but are seldom reported in the World's other languages [1]. Apical vowels are thus of particular importance to the understanding of Chinese vowel phonology [2]. There is, however, controversy regarding the phonetics and phonology of apical vowel. Some scholars define apical vowels as vowels [3] [4] [5] [6], whereas others treat them as consonants [7] [8] [9] [10] [11] [12]. Apical vowels synchronically cooccur with sibilants in the majority of Chinese dialects, and diachronically they are developed from high front vowels [13] [14] [15] [16] [17]. Therefore, apical vowels and high front vowels are in a complementary distribution and could be treated as allophones in most cases.

What is less documented is that apical vowels do have wide distributions in a few Chinese dialects, particularly in Jianghuai Mandarin dialects and neighboring Wu dialects such as Hefei [18], Jixi [19], Gubai (Gaochun) [20], Fanchang [21], Wuhu [22], Yanchi [23], etc. Eastern Zhenjiang dialect is an exemplar of this dialect group, and there is generally no distributional constraint for the apical vowels. Zhenjiang is a city in southern Jiangsu Province, and Eastern Zhenjiang consists of Yaoqiao, Dalu, and Dinggang Towns, with a population of around 90,000 as of 2019. Eastern Zhenjiang speaks a variety of Jianghuai Mandarin. Eastern Zhenjiang Madarin has 22 initial consonants [p pʰ m f ; t tʰ n l; ts tsʰ s; tʂ tʂʰ ʂ ʐ; tɕ tɕʰ ɕ; k kʰ x ŋ], 50 finals including the two syllabic consonants [ɿ ʮ i u a ɛ ɔ e; əl; ɔu ui ia iɛ iɔ iu ua ue uɛ uo ʮɛ; æ̃ ũ ũ iæ̃ uæ̃ iũ; in ən aŋ oŋ iən iaŋ ioŋ uən uaŋ ʮən; iʔ uʔ aʔ ɔʔ əʔ iaʔ iɔʔ iəʔ iuʔ uaʔ uoʔ uəʔ; m̩ ŋ], and 5 tones [53 23 312 44 4].

There are two apical vowels: [ɿ ʮ] in Eastern Zhenjiang Mandarin. The unrounded apical vowel [ɿ] can be preceded by an initial consonant [p pʰ m t tʰ n l ts tsʰ s tɕ tɕʰ ɕ] or occur in an onset-less syllable, and the corresponding high front vowel [i] can be preceded by [p pʰ m t tʰ n l tɕ tɕʰ ɕ], or occur in an onset-less syllable. In other words, the unrounded apical vowel [ɿ] has a wider distribution than the corresponding high front vowel [i], and when being preceded by [p pʰ m t tʰ n l tɕ tɕʰ ɕ] or in an onset-less syllable, they contrast with each other. The other apical vowel, the rounded [ʮ] has much narrower distribution than [ɿ] and can be preceded by [n l ts tsʰ s] or occur in an onset-less syllable.

This paper examines acoustics and articulation in the production of the apical vowels in Eastern Zhenjiang Mandarin. First, formant data of the apical vowels are presented and examined in the vowel system. Second, the acoustic data are examined to evaluate whether the production of apical vowel is featured with frication. Third, the articulation of apical vowel is compared with the corresponding vowels or consonants to check whether the production of apical vowel is more vowel-like or consonant-like.

2. Methodology

2.1. Speakers and test materials

Seven speakers, 3 male and 4 female, provided the speech data during the author's fieldwork trip at Eastern Zhenjiang. All of them were born and raised up in Eastern Zhenjiang, and the local dialect is their daily language. Their ages ranged from 25 to 40 years old at the time of recording.

Table 1: *Target vowels and the monosyllabic test words.*

V	C	test words
i	p pʰ m t tʰ n l tɕ tɕʰ ɕ k kʰ Ø	扁偏棉点舔年脸钱浅显沟口严
ɿ	p pʰ m t tʰ n l ts tsʰ s tɕ tɕʰ ɕ Ø	比匹米抵题呢璃籽词时几棋洗已
ʮ	n l ts tsʰ s Ø	女吕主娶苏雨
u	p pʰ f t tʰ n l k kʰ Ø	补谱腐赌土努炉古苦吴
e	p pʰ m f t tʰ l ts tsʰ s	杯坯梅非抖投楼走丑手
ɛ	m k kʰ p pʰ t tʰ n l ŋ	买改开摆排呆胎奶来碍
ɔ	p pʰ m t tʰ n l ts tsʰ s k kʰ x ŋ Ø	饱抛毛刀陶闹老找草少搞考好咬袄
a	p t tʰ n l tsʰ s	把打他拿拉查洒

Test words containing all monophthongs were used as the test material. Table 1 shows target vowels (V), the preceding

10.21437/Interspeech.2025-282

initial consonants (C), and the monosyllabic test words in Chinese characters, which are all CV syllables. The symbol [∅] represents for an onset-less syllable, the so-called zero-initial in Chinese phonology. Test words were placed in a carrier sentence [_, ŋɔ23 pa23 _ tɔʔ5 pa23 ni23 t^{h}in312] "_, I read _ for you". Five repetitions were recorded.

2.2. Equipment and Recording

Recordings were conducted in a quiet room. The Echo B ultrasound recording system from Articulate Instruments was employed to record lingual articulatory data. Mid-sagittal ultrasound videos were recorded into the Telemed Echo Blaster 128 through a probe (C3.5/20/128). The probe was placed under the chin of the speaker, who kept their hands still. And the video data parameters were set to frequency 3 MHz, field 93.35°, and depth 120 mm.

Audio and ultrasonic articulatory data were simultaneously recorded into a laptop by using the software of Articulate Assistant Advanced (AAA Version 220.5.1). A SHURE SM8 microphone and a USB Sound device Focusrite Scarlett Solo were used for the audio recordings. And the sampling rate for audio recording is 22,050 Hz, 16-bit.

2.3. Data analysis

Acoustic data were annotated and analyzed in PRAAT 6.2.12 [24]. First, the lowest three formants were extracted from the middle point of the target vowel. Second, the harmonic-to-noise ratios (HNR) were calculated for the apical vowels, high vowels and sibilants [ɿ ɥ i u ɕ s]. Third, spectral parameters such as Centre of Gravity (COG), Standard Deviations (SD), Skewnewss, and Kurtosis were calculated for [ɿ ɥ i u ɕ s]. The data was fitted by using the linear model (lm) and further tested by using the post-hoc tests.

In line with acoustic annotations, ultrasonic videos were annotated on a frame-by-frame basis in the Articulate Assistant Advanced software (AAA Version 220.5.1). The tongue curve was annotated based on the boundary of the tongue surface image presented in the video. The polar data were used for plotting tongue contours. When plotting the articulatory pictures, the mid-point of frictions and vowels was selected. A modified version of the smoothing spline technique (SSANOVA) was employed in the analysis of tongue contours [25] by using the gss package of R [26].

The Cartesian coordinates data were used for quantifying lingual data. They were transferred into the defined polar coordinate system in a way as described in [27]. Following [28], six parameters were calculated for quantifying lingual articulation: blade anteriority, blade angle, dorsum height, dorsum frontness, root advancement, and root convexity. Blade anteriority was measured as the most anterior point on the tongue trace. Blade angle was measured as the angle between the last two points on each tongue trace. Dorsum height was measured as the vertical distance from the origin to the highest point on the tongue dorsum. Dorsum frontness was measured as the angle in radians from the origin to the most distant point of the tongue trace. Root advancement was measured as the x-value of the lowest and most posterior point on each tongue trace. Root convexity was measured as the distance between the highest point and the last point on the root of the tongue contour. All parameters were normalized for the comparison.

3. Results

3.1. Formants

Figure 1 plotted the eight vowels [ɿ ʮ i u e ɛ ɔ a] of Eastern Zhenjiang Mandarin in a two-dimensional acoustic space defined by the lowest two formants (F2 against F1) in Herz with the origin of the axes to the top right of the plot. Additionally, the grayscale is used for representing the third formant (F3). Each 95% confidence ellipse is based on measured data points and the final numbers for each vowel are: [i] 426, [ɿ] 483, [ʮ] 326, [u] 361, [e] 227, [ɛ] 59, [ɔ] 491, [a] 227. The F1/F2 vowel plane establishes a good correlation with linguistic vowel features such as height and backness, namely F1 with vowel height and F2 with vowel backness. And F3 helps further differentiate the two apical vowels. As can be seen from the figure, there are three levels of vowel height: [i ɿ ʮ u] are high, [e ɛ ɔ] are mid, and [a] is low. [e ɛ] are merging. Only a few speakers have [ɛ] on a limited number of test words so that there are only 59 samples for [ɛ]. And the ellipses for [e ɛ] heavily overlap with each other. There are three levels of vowel backness: [i e ɛ] are front, [u ɔ] are back, and [ɿ ʮ a] are central.

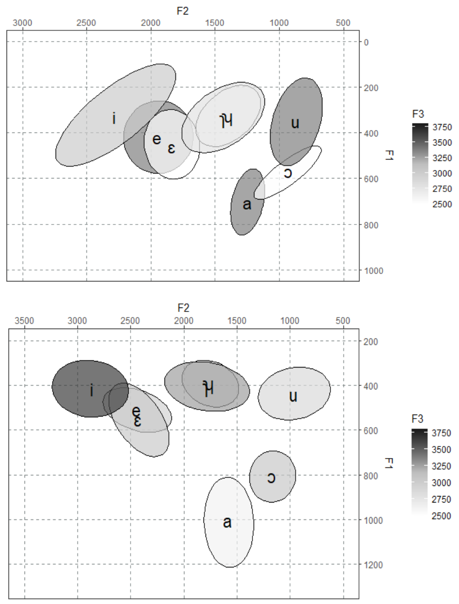

Figure 1: *Vowel ellipses of Eastern Zhenjiang Mandarin: male (upper) and female (lower) speakers.*

The formant data of [i ɿ ɥ] are shown in Table 2. It can be observed from both Table 2 and Figure 1 that the ellipses for the two apical vowels overlap with each other, and they mainly differ in F3, namely the rounded [ʮ] has an F3 value significantly lower than its unrounded counterpart [ɿ]. Since Eastern Zhenjiang Mandarin doesn't have a contrast between the rounded [y ʮ], this paper focuses on the difference between the unrounded contrasting pair [i ɿ]. [i ɿ] have similar F1 in both male and female speakers. And the linear model (lm) yielded significant difference for F2 and F3: $t(413)=47.41$, $p<0.0001$ for F2 in male speakers; $t(492)=64.16$, $p<0.0001$ for F2 in female speakers; $t(413)=12.31$, $p<0.0001$ for F3 in male speakers; $t(492)=14.99$, $p<0.0001$ for F3 in female speakers. In summary, formant data suggest that the apical vowels in Eastern Zhenjiang Mandarin are central high vowels (c.f.: [29] for a review on apical vowels in other dialects).

Table 2: *The lowest three formants for [i ɿ ʮ].*

			Mean（Hz）	SD（Hz）	Samples
i	male	F1	333	99	
		F2	2281	211	197
		F3	3011	182	
	female	F1	418	61	
		F2	2863	190	229
		F3	3644	278	
ɿ	male	F1	336	67	
		F2	1441	147	218
		F3	2771	212	
	female	F1	403	51	
		F2	1791	181	265
		F3	3260	290	
ʮ	male	F1	325	58	
		F2	1406	109	149
		F3	2541	156	
	female	F1	391	49	
		F2	1766	149	177
		F3	2829	279	

3.2. Frication

The production of apical vowels is often accompanied by turbulent noise or frication [6] [14] [30], which is an essential feature to treat apical vowels as consonants [31]. However, there is also research suggesting that the frication is redundant in the production of fricative and apical vowels [32]. This paper employes the harmonic-to-noise ratio (HNR) as an indicator of friction. And a lower value of HNR indicates a stronger degree of frication. Figure 2 summarizes mean HNRs for the apical vowels as compared with the corresponding high vowels and sibilants respectively. I can be observed from the figure that the apical vowels [ɿ ʮ] have a relatively smaller HNR than the corresponding high vowels [i u] do. But the difference between the rounded pair [u ʮ] is not significant. Interestingly, there is a clear difference in HNR between apical vowels and the two sibilants [s ɕ]. Both [s] and [ɕ] have significantly lower HNR than [ɿ] or [ʮ] does. That is, apical vowels [ɿ ʮ] are more vowel-like than consonant-like in terms of the accompanying frication.

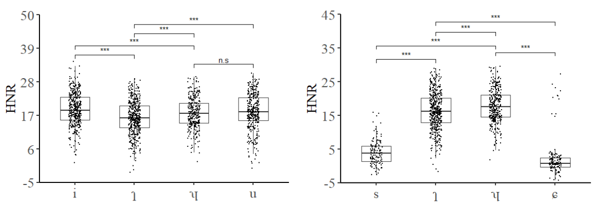

Figure 2: *Mean HNR of [i ʮ ɿ u] (left) and [s ʮ ɿ ɕ] (right).*

3.3. Spectral parameters

It has been shown so far that apical vowels have formant structures as vowels do and are produced with lesser frication than the corresponding sibilants. Another argument for treating apical vowels as consonants is that apical vowels could be viewed as a continuation of the preceding sibilant [7] [8] [9] [31]. This section addresses this issue by examining the four spectral parameters of apical vowels and the corresponding high vowels and sibilants. As can be seen from Table 3, apical vowels [ɿ ʮ] share commonality with the corresponding vowels [i u], but differ apparently from the sibilants [ɕ s]. In short, the vowels [i u ɿ ʮ] show concentrated low-frequency energy, whereas the sibilants [ɕ s] show dispersed high-frequency energy. Statistical results for the [s ɿ] pair show that they exhibit significant differences in terms of all the four parameters, namely COG (t(585)=-38.10, p<0.0001), SD (t(585)=-31.73, p<0.0001), skewness (t(585)=19.54, p<0.0001), and kurtosis (t(585)=9.51, p<0.0001). The results suggest that [ɿ] is not typically sibilant-like, and therefore should not be treated as a continuation of [s].

Table 3: *Spectral parameters of [i ɿ ʮ u ɕ s].*

		COG（Hz）	SD（Hz）	Skewness	Kurtosis
i	Mean	377	569	10.82	200
	SD	192	344	6.56	217
ɿ	Mean	489	889	8.60	126
	SD	267	550	4.95	153
ʮ	Mean	381	552	11.40	249
	SD	151	381	5.80	255
u	Mean	337	329	11.56	299
	SD	83	170	4.58	220
ɕ	Mean	4889	2629	0.11	2
	SD	1481	689	1.33	16
s	Mean	4899	3210	0.02	3
	SD	2337	961	1.71	13

3.4. Lingual articulation

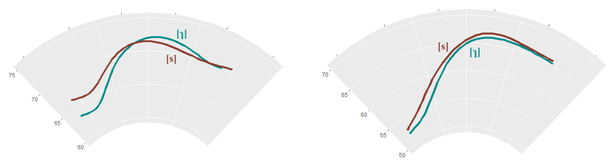

Figure 3: *SSANOVA comparisons for [ɿ] and [s]: male (left) and female (right) speakers.*

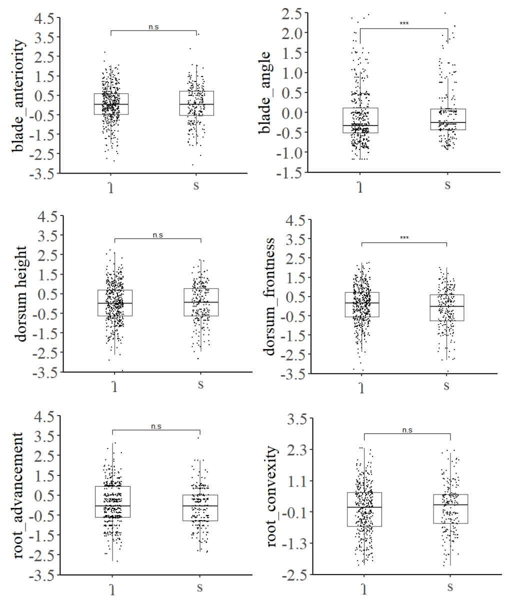

Figure 4: *Blade anteriority, blade angle, dorsum height, dorsum frontness, root advancement, and root convexity for [ɿ] and [s].*

Acoustic data have shown that apical vowels are vowel-like rather than consonant-like. This section explores lingual articulation of apical vowels and the corresponding high vowels and sibilants. The discussion will focus on the unrounded apical vowel [ɿ], since the two apical vowels [ɿ] and [ʮ] have similar lingual articulation. SSANOVA comparisons are used to present the tongue contours for the [s ɿ] pair in Figure 3 and for the vowels [[i ɿ u] in Figure 5. In the figures, the speakers are facing right, so the right part of the tongue contour represents the tongue blade, the middle part represents the tongue dorsum, and the left part represents the tongue root. The six parameters are further calculated to quantify these comparisons [28].

It can be seen from Figure 3 that the apical vowel [ɿ] has a comparable but somehow different tongue contour from the sibilant [s]. In male speakers, both anterior and posterior parts of the tongue exhibit certain differences; in female speakers, the tongue contour for [ɿ] is generally lower than that for [s]. Figure 4 further presents quantitative comparisons between the apical vowel [ɿ] and the sibilant [s] across six parameters. The results indicate that [ɿ] and [s] differ significantly in blade angle and dorsum frontness, but not in blade anteriority, dorsum height, root advancement, or root convexity. It appears that the production of the apical vowel [ɿ] involves both the anterior and posterior parts of the tongue. Compared to the sibilant [s], the production of the apical vowel [ɿ] requires a lower blade angel and a more advanced tongue dorsum.

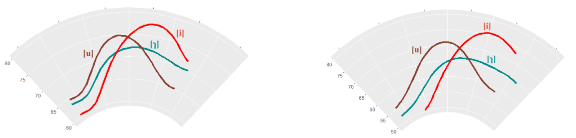

Figure 5: *SSANOVA comparisons for [i], [ɿ], [u]: male (left) and female (right) speakers.*

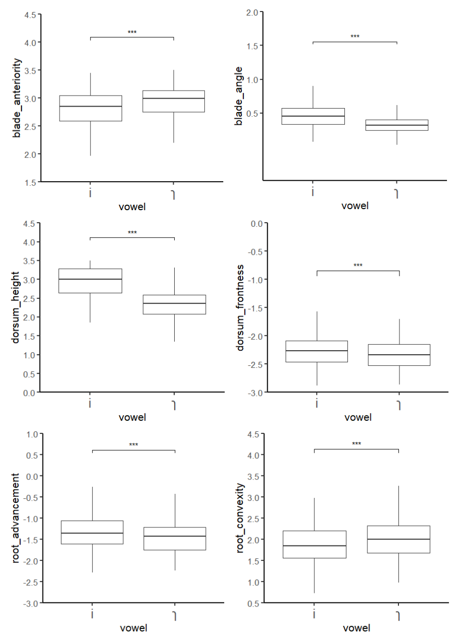

Figure 6: *Blade anteriority, blade angle, dorsum height, dorsum frontness, root advancement, and root convexity for [ɿ] and [i].*

It can be observed from Figure 5 that the apical vowel [ɿ] has a lingual configuration that is intermediate between the front high vowel [i] and the back high vowel [u]. And the tongue contour for [ɿ] is apparently lower than that for [i] and [u]. As shown in Figure 6, quantitative comparisons revealed significant differences between the apical vowel [ɿ] and its corresponding high front vowel [i] across all six parameters. Compared to [i], [ɿ] has a tongue blade that is significantly more advanced and lowered, a tongue dorsum that is significantly lower and more retracted, and a tongue root that is more retracted and humped. It appears that the production of [ɿ] requires independent control of the anterior and posterior part of the tongue: the tongue blade needs to be lowered and advanced, while the posterior part of the tongue needs to be retracted and bunched.

4. Discussion and Conclusion

This paper presented acoustic and articulatory data for the apical vowels in Eastern Zhenjiang Mandarin, one of a small group of dialects that has no constraint on the cooccurrence of the apical vowel with a homorganic sibilant. In Eastern Zhenjiang Mandarin, the production of apical vowels is sometimes accompanied by noise. However, this is not essential to the apical vowels and cannot serve as evidence to argue that the apical vowels are fricatives [32]. On the contrary, the apical vowels have their own formant structures, and spectral analyses show that the apical vowel [ɿ] is not a continuation of the initial sibilant [s]. The fact that the apical vowels are central high vowels in the acoustic F1/F2 vowel plane is consistent with results from other Chinese dialects [29].

The acoustic characteristics of apical vowels can be well explained in terms of articulation. Ultrasound data reveal that both the anterior and posterior parts of the tongue are involved in the production of the apical vowel: the tongue blade is lowered and advanced, while the posterior part of the tongue is retracted and bunched. The results are generally consistent with recent ultrasound-based studies of apical vowels [10] [33] [34], as well as with previous X-ray studies [35] [36] [37] and electromagnetic articulography (EMA) studies [38] [39]. In summary, apical vowels are featured by double articulation, with the tongue blade and tongue dorsum functioning as two relatively independent articulators simultaneously.

In conclusion, both the acoustic and articulatory data presented in this paper indicate that apical vowels have typical vowel characteristics [40]. Syllabic consonants often have strict phonotactic constraints and, as a result, typically exhibit narrow distributions [41]. One might argue that apical vowels cooccur with sibilants in the majority of Chinese dialects. But that is not the case for Eastern Zhenjiang Mandarin. Diachronically, the apicalization is a common phonological process for high vowels in Chinese dialects [32]. Nevertheless, at the current stage, there is no evidence—phonetic or phonological—to suggest that these high vowels are changing into consonants. Instead, they remain vowels, albeit apical and sometimes fricative.

5. References

[1] Fabienne E Westerberg, *An auditory, acoustic, articulatory and sociophonetic study of Swedish Viby-i*, University of Glasgow, pp. 24-27, 2016.

[2] Fang Hu, "The Descriptive Tradition in Chinese Phonetics," In *the Oxford Research Encyclopedia of Linguistics*. Oxford University Press. doi: 10.1093/acrefore/9780199384655.013.900, pp. 21-25, 2024.

[3] Bernhard Karlgren, *Études sur la Phonologie Chinoise*, Archives d'Études Orientales (Vol. 15), Leiden and Stockholm: Norsedebt, 1915-1926.

[4] Chin-Chuan Cheng, *A Synchronic Phonology of Mandarin Chinese.* Hague: Mouto, pp. 13, 1973.

[5] J. M. Howie, *Acoustical Studies of Mandarin Vowels and Tones*, Cambridge etc.: Cambridge University Press, 1976.

[6] Peter Ladefoged and Ian Maddieson, "Vowels of the world's languages," *Journal of Phonetics*, vol. 18, pp. 93-122, 1990.

[7] Richard Wiese, "Underspecification and the description of Chinese vowels," *Linguistic Models*, vol. 20, pp. 219-250, 1997.

[8] San Duanmu, *The Phonology of Standard Chinese*, New York: Oxford University Press, 2007.

[9] Hua Lin, *A Grammar of Mandarin Chinese*, Munich, Germany: Lincom Europa, 2001.

[10] S.-I. Lee-Kim, "Revisiting Mandarin 'apical vowels': An articulatory and acoustic study," *Journal of the International Phonetic Association*, vol. 44, no. 3, pp. 261-282, 2014.

[11] J. Wiedenhof, *A Grammar of Mandarin*, Amsterdam: John Benjamins, 2015.

[12] Bowei Shao, *The apical vowel in Jixi-Hui Chinese: phonology and phonetics*, Ph. D. dissertation, Université de la Sorbonne nouvelle-Paris III, 2020.

[13] Wei Wu, "On the fronting of -i and -y syllables in the Hefei dialect," *Yuwen Yanjiu*, no. 3, pp. 58-60+21, 1995.

[14] Rujie Shi, "On the frication of high vowels in Chinese dialects," *Yuyan Yanjiu*, no. 1, pp. 100-109, 1998.

[15] Xiaonong Zhu, "Further developments of Chinese high vowels," *Studies of the Chinese Language*, no. 5, pp. 440-451, 2004.

[16] Rinxin Zhao, "Sound of [i]>[ɿ] in Chinese dialects," *Studies of the Chinese Language*, no. 1, pp. 46-54+96, 2007.

[17] Fanfeng Tian and Yinggu Xie, 安徽方言舌尖化再探 "Revisiting apicalization in the dialects in Anhui province," *Dialect*, no. 2, pp. 165-175, 2022.

[18] Jinling Li, *The Audio Documents of the Hefei Dialect*, Shanghai: Shanghai Educational Press, 1997.

[19] Rinxin Zhao, *The Dictionary of the Jixi Dialect*, Nanjing: Jiangsu Educational Press, 2003.

[20] Liuwen Xie, "The homophony syllabary of the Gubai dialect in the Gaochun District of Jiangsu Province," *Dialect*, no. 3, pp. 272-286, 2016.

[21] Guofu Zhao, "The Homophony syllabary of the Fanchang dialect in Anhui province," *Dialect*, no. 1, pp. 94-109, 2020.

[22] Muzi Li, *A Study on the Wuhu (Qingshui) Dialect*, M. A. Thesis, Anhui Normal University, pp. 24-27, 2008.

[23] Ming Shen and Jingai Huang, "The homophony syllabary of the Yanchi dialect in Xuancheng of Anhui province," *Dialect*, no.1, pp. 58-69, 2015.

[24] Paul Boersma, "Praat, a system for doing phonetics by computer," *Glot International*, 5:9/10, pp. 341-345, 2001.

[25] Lisa Davidson, "Comparing tongue shapes from ultrasound imaging using smoothing spline analysis of variance," *The Journal of the Acoustical Society of America*, vol. 120, 407–415, 2006.

[26] Chong Gu, "Smoothing spline ANOVA models: R package gss," *Journal of Statistical Software*, vol. 58, 1-25, 2014.

[27] Jeff Mielke, "An ultrasound study of Canadian French rhotic vowels with polar smoothing spline comparisons," *The Journal of the Acoustical Society of America*, vol. 137, no. 5, 2858-2869, 2015.

[28] Qandeel Hussain and Jeff Mielke, "An acoustic and articulatory study of rhotic and rhotic-nasal vowels of Kalasha," *Journal of Phonetics*, vol. 87, 101028, 2021.

[29] Fang Hu, *The Vowel: A General Introduction with Reference to Chinese Data*, Beijing: Foreign Language Teaching and Research Press, pp. 173-179, 2020.

[30] Bo Wu, "A typology of the apical vowel [ɿ] in Chinese dialects," *Bulletin of Linguistic Studies*, vol. 10, no. 1, pp. 113-122+328, 2013.

[31] Bowei Shao and Ridouane Rachid, "On the Nature of Apical Vowel in Jixi-Hui Chinese: Acoustic and Articulatory Data," *Journal of the International Phonetic Association*, vol. 53, no. 1, pp.1-26, 2023.

[32] Fang Hu and Feng Ling, "Fricative vowels as an intermediate stage of vowel apicalization,"*Language and Linguistics,* vol. 20, no. 1, pp. 1-14, 2019.

[33] Sean Foley, "The coarticulatory behavior of Standard Mandarin apcial vowels," In *Proceedings of the 20th International Congress of Phonetic Sciences*, by Radek Skarnitzl & Jan Volin, pp. 1027-1031, Prague: Guarant International, 2023.

[34] Huifang Kong, Shengyi Wu, Mingxing Li, and Xiangrong Shen, "The articulatory properties of apical vowels in Hefei Mandarin," *Journal of the International Phonetic Association*, vol. 54, no. 1, pp. 165-188, 2024.

[35] Dianfu Zhou and Zongji Wu, *The Chart of Mandarin Pronunciations*, Beijing: The Commercial Press, 1963.

[36] Huaiqiao Bao, "A physiological interpretation of classification of monophthongs in Pǔtōnghuà," *Studies of the Chinese Language*, no. 2, pp. 117-127, 1984.

[37] Peter Ladefoged and Zongji Wu. "Places of articulation: An investigation of Pekingese fricatives and affricates," *Journal of Phonetics*, vol. 12, pp. 267–278, 1984.

[38] Fang Hu, "An acoustic and articulatory analysis of vowels in Ningbo Chinese," In *Proceedings of the 15th International Congress of Phonetic Sciences*, pp. 3017-3020, Barcelona, Spain: Universitat Autonoma de Barcelona, 2003.

[39] Fang Hu, *A Phonetic Study of the Vowels in Ningbo Chinese*, Beijing: China Social Sciences Press, 2014.

[40] Roman Jakobson, C. Gunnar M. Fant, and Morris Halle, *Preliminaries to Speech Analysis: The Distinctive Features and Their Correlates*. Cambridge: MIT Press, 1951.

[41] Marianne Pouplier and Štefan Beňuš, "On the phonetic status of syllabic consonants: Evidence from Slovak," *Laboratory phonology*, vol. 2, no. 2, pp. 243-273, 2011.