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Variation in the articulation of Russian stressed vowels and the mechanics of palatalization in consonants

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A 3D/4D ultrasound study of Russian stressed vowels in the context of 'soft' (phonetically palatalized or palatal) versus 'hard' consonants reveals that vowels in these two contexts differ systematically in terms of the position of the tongue root while the tongue dorsum is less consistently modified depending on the speaker, vowel or consonant context. This paper proposes that the observed vowel allophony, as well as the softness contrast in Russian consonants, and the contrast between /i/ and /ɨ/, are all defined in terms of the feature [ATR].

Keywords: palatalization; [ATR]; Russian; Russian vowels; ultrasound speech research

1 Introduction

This article reports on the results of a 3D/4D ultrasound study of Russian stressed vowels and documents the variation in the realization of the vowels triggered by the context of palatalized (soft) as opposed to non-palatalized (hard) consonants.[1] We argue that vowels in the soft-hard consonant contexts differ systematically in the position of the tongue root and less systematically in terms of the fronting or raising of the tongue dorsum. Given the assumption that abstract phonological features in a stable phonological system have well defined phonetic correlates, the articulatory findings motivate [+ATR] as a common feature for all Russian vowels in the context of soft consonants, and as the softness feature in consonants. While our analysis is couched within the feature geometry framework (Clements 1985; Halle 1995; Clements & Hume 1995), the basic point of the paper is to acknowledge the role of the tongue root in secondary palatalization processes. This insight refers to physical facts and is largely independent of the theoretical framework we choose to adopt.

1.1 Russian vowel allophony

Russian vowels accommodate to the adjacent consonants. Hamilton (1980: 28ff), Swan (2011: 40ff), Jones & Ward (1969: 33, 41–44, 193), and Timberlake (2004: 39) all report that soft-consonant-context (SCC) vowels are fronted, raised, or both fronted and raised in comparison to the hard-consonant-context (HCC) vowels. These differences are clearly visible, for example, on X-ray images in Koneczna & Zawadowski

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[1] Following the Slavic linguistic tradition, we use in this article the terms 'soft' and 'hard' in reference to palatalized and non-palatalized consonants, respectively. Unlike the articulatorily oriented terms 'palatalized', 'velarized', 'plain', etc., the terms 'soft' and 'hard' refer primarily to the phonological contrast rather than a particular phonetic interpretation.

(1956). Koneczna & Zawadowski (1956) also repeatedly observed that the tongue root is fronted and the pharynx is enlarged in SCC vowels.

These differences between SCC and HCC vowels are described to be slightly different across different vowels in terms of the degree of fronting/raising, but it is in all cases tacitly assumed that the fronting/raising reflects an assimilation triggered by the soft consonant.

According to Hamilton (1980: 28ff), /a/ is fronted and /o, u/ are raised and fronted between soft consonants, /e/ is fronted before soft consonants, and /i/ is retracted to /ɨ/ after hard consonants. The context that triggers assimilation can therefore be a preceding consonant, a following consonant, or a bilateral context, depending on the vowel. Timberlake (2004: 39) offers a slightly different generalization:

> Before a following palatalized consonant, all vowels are fronted and/or raised, in the last third of the vowel and especially in the final transition. After a soft consonant, vowels are fronted and/or raised in the first third. Between soft consonants, vowels are fronted and raised in both transitions and, in an additive fashion, in the middle of the vowel as well.

Koneczna & Zawadowski (1956) report based on an x-ray study that the position of the triggering consonant (before or after the vowel) has a minimal effect, with the exceptions that /a/ is more strongly affected by a following consonant (p. 18), and /o/ is more strongly affected by a preceding consonant (p. 23). The vowel phonemes of Russian, as assumed in this paper, are /a/ (low), /i/, /ɨ/, /e/ (front), and /u/, /o/ (back). The patterning of vowels and their allophones is shown in Table 1. We assume that the vowel /ɨ/ is a separate phoneme in Russian (e.g., Shcherba 1950), rather than a derived allophone of /i/ (e.g., Avanesov 1956, Padgett 2001). This assumption does not affect our findings, although it is consistent with our proposed phonological analysis of palatalization in Russian (see Section 4).

Table 1: Phonotactic constraints in Russian, distribution of vowels depending on consonantal context[2]

HCC vowels	SCC vowels
Phonemic	
ɨ	i
Allophonic[3]	
u	ʉ
ɛ	e
o	ɵ
a	a̧

We assume that the mechanism governing the distribution of vowels in the soft- and hard-consonant contexts is the same across all vowels. This is based both on phonetic and phonological (phonotactic) grounds. In the earlier literature, similar phonetic effects have been observed for all vowels and the same consonantal triggers apply in both the phonemic and the allophonic cases.

The current study evaluates the phonetic effect of consonant palatalization on the adjacent vowel, assuming that the vowels in Russian assimilate to the consonants by spreading of the palatalization feature. We will argue in this paper that the articulatory difference between the corresponding vowel pairs – SCC

[2] Different symbols are used to refer to the 'fronted' vowel variants. So, for example, Bolla (1981) uses "ẹ" to mark the 'fronted' version of /e/ in the bilateral soft context, and [ü] to indicate the bilateral SCC vowel /u/, "æ" for the 'fronted' version of /a/, and a diacritic "+" to the left or right of the symbol to indicate the unilateral context. Hamilton (1980) uses [e] for SCC and [ɛ] for the HCC vowel, but [æ] for the 'fronted' version of /a/, and non-IPA [ü, ö] for the fronted versions of /u/ and /o/, respectively. The symbols used in Table 1 are the IPA interpretation of Hamilton (1981) with the caveat that each of the versions still displays variation, sometimes diverging from the prototypical intended IPA value.

[3] No claim is made as to which allophone is major/basic, vowels displaying allophonic variation are assumed not to be specified for the feature in which they differ.

vowels versus HCC vowels – can be best described along a single phonetic dimension, namely, the advancement of the tongue root in the context of soft consonants as opposed to the retraction of the tongue root in hard-consonant contexts. This motivates [+ATR] as a common feature for all Russian vowels in the context of soft consonants, and as the softness feature in consonants. Importantly, we do not propose to generally substitute [-back] with [+ATR]. Vowels utilize both [+/-back] and [+/-ATR]. As for consonants, [+/-back] (or a counterpart in a different feature theory) seems not necessary to express secondary palatalization but might be used to mark major place distinctions. This point will be developed in Section 4.

1.2 Inherent 'soft' and 'hard' sounds

While in this paper we concentrate on vowels, we have to mention some dynamic effects that vowels trigger in preceding consonants. As discussed in the previous section, hard consonants have to be followed by HCC vowels and soft consonants have to be followed by SCC vowels. If a hard consonant is followed by /i, e/ through the concatenation of morphemes, vowels /i/ and /e/ induce palatalization of the preceding underlying hard consonant, e.g., руки Nom.Pl. 'hands' ([ruk^j+i], cf. [ruk+a], Nom.Sg.), лете Preposit.Sg. 'summer' ([l^{j}et^j+e], cf. [l^{j}et+o] Nom.Sg). Phonetically there is no difference between presumably underlyingly palatalized consonants (e.g., теперь [t^{j}ep^{j}er^j] 'now') and consonants palatalized by a phonological rule (e.g., лете [l^{j}et^j+e]). Inherently hard consonants /š, ž, ts/ are an exception to palatalization. Unlike other consonants, /š, ž, ts/ do not undergo palatalization and instead trigger an adjustment of the following vowel: HCC [ɨ] substitutes SCC [i] (e.g., фашист [faš+ɨst] 'fascist', cf. альтруист [al^{j}tru+ist] 'altruist'), and /e/ is always rendered as the HCC [ɛ]. This is summarized in Table 2. As it will be argued in Section 3, lack of palatalization is realized the same in the inherently hard (those that do not undergo palatalization) and the neutral hard (those that undergo palatalization) consonants. We will discuss possible accounts of these interactions in Section 4.

Table 2: Functional categories of segments

(a) Consonants (examples)

Soft: combine with SCC vowels	Hard: combine with HCC vowels	
p^j / t^j / ɕ	Neutral/underspecified/may undergo palatalization by palatalizing vowel	Inherent/phonologically active/may not undergo palatalization
	p / t	ts /tš

(b) Vowels (whole inventory)

Palatalizing	Non-palatalizing	
i / e*	Neutral, accommodating	Inherently non-palatalizing
	u / o / a	ɨ**

* Accommodating to the preceding inherently hard consonants.

** Unlike commonly assumed, /ɨ/ is treated as phonologically [-back] with the relative retraction of the dorsum in relation to /i/ due to the dependence of the dorsum on the position of the tongue root.

1.3 On the palatalization feature

Palatalization as a process is usually seen as an articulatory assimilation (cf., e.g., Hyman 1975; Bhat 1978; Hume 1992) with the tongue fronting and raising during the articulation of a consonant in the context of (usually) front and (most often) high vowels. In Russian, palatalized (or soft) consonants sometimes result from synchronic phonological palatalization processes, and sometimes they encode a phonemic softness distinction in the context of both front and back vowels, where no synchronic alternations are attested. Chomsky & Halle (1968) proposed to express secondary palatalization in consonants by the vocalic features [-back][+high] (with the original notation in SPE using [-low] instead of [+high], cf. Chomsky & Halle 1968: 305). [-back][+high] can be interpreted as fronting and raising of the tongue dorsum. In Feature Geometric approaches (Sagey 1986; Halle 1995), the Dorsal node is potentially added to the list of palatalization features, since [-back] and [+high] are executed by the Dorsal articulator. Halle's (1995) model, however, has been unable to explain palatalization processes resulting in the change of the major place of articulation (not to mention common affrication).[4]

A whole new way of thinking about palatalization started with the work of Hume (1992) and Clements & Hume (1995). Hume (1992) analyzed primary place palatalization (or coronalization) in terms of the Coronal node, arguing that Coronal defines the location of the constriction rather than the active articulator. Mester & Ito (1989) represent palatalization in terms of the Coronal node specified for [-anterior]. Coronal – with or without [-anterior] – has a function equivalent to the feature [-back] in the more traditional approaches. The two-layer model of the Place node of Clements & Hume (1995) provided a formal device to segregate features of vowels and consonants, in spite of using a common set of features for both categories. This model brought under one umbrella all palatalization processes, including those resulting in changes to the primary place of articulation, as well as secondary palatalization. A number of loose ends remained though, including the phonetic motivation for C-Place versus V-Place, the common emergence of [-anterior] specification in primary place palatalization, the mechanism for affrication as an effect of palatalization,[5] and the potentially unconstrained mechanism of feature promotion, which strictly speaking goes against the fundamental principles of feature geometry. Ni Chiosain (1994) combined the insights of the two approaches, adopting as a configuration representing secondary palatalization a V-Place node of the Clements-Hume model with the dependent [-back] of the SPE/Halle (1995) approach. While this solution accounts for independent spreading of the primary and secondary articulation (like in Irish), it is an abstract account. With an ambiguous feature [back] attaching to either C-Place or V-Place, it rests upon the abstract distinction between C-Place and V-Place.

Cavar (2004) introduced [ATR] ([Advanced Tongue Root]) as a secondary palatalization feature in Polish. The obvious correlate of [ATR] is a relative advancement of the tongue root. Instead of [+/-ATR], Lindau (1978) proposed the feature Expanded, referring to the joint effect of the expansion of the pharyngeal cavity and tongue root position and remarking that "[t]he articulatory correlate […] involves the tongue root and the larynx, working together to accomplish variation of pharyngeal size." We assume that [+/-ATR] and Expanded refer to the same dimension of contrast.[6] While the original proposal in Cavar (2004) was primarily based on theoretical system-internal arguments, recent instrumental phonetic studies of Polish (Lulich & Cavar 2019, Cavar et al. 2020), Russian (Matsui & Kochetov 2018), and Irish (Bennett et al. 2018) lend support. [ATR] is a relative newcomer to phonological theory, probably due to the relative

[4] Halle (2005) attempts to resolve the problem of the palatalization resulting in change of the primary articulation in the articulator-based model by assuming that front vowels are both Dorsal and Coronal. The implication of this account is that the tongue blade moves to produce palatalization involving a change of the primary articulation (Clements & Hume 1995 avoided such a statement and instead referred to the place of the constriction rather than the active articulator). The adoption of the solution washes out the definition of the nodes in Halle's model – what are the correlates of the nodes and can they sometimes be articulatory and sometimes auditory? Further, Halle takes the fact that palatalization processes with the change of the primary articulator usually go through a stage of secondary articulation to be evidence for the double specification of front vowels. Yet, it is not necessary that the two specifications must be Dorsal and Coronal (as in Halle 2005), cf. Section 4. Further, the representation of a front vowel as Dorsal and Coronal in the 'bottle brush' structure can only treat both nodes the same way, consequently, the curious asymmetry of the phonological progression, always over the secondary palatalization to perhaps finish as a primary palatalization, still cannot be accounted for.

[5] See, for example, Guion (1998) and Kim (2001) for arguments that affrication in the context of palatalization is an auditory enhancement mechanism.

[6] See Beltzung et al. (2015) for a thorough review of the literature on [ATR].

inaccessibility of the tongue root for direct inspection. The term appeared first in Stewart (1967). [ATR] was originally used as a distinctive feature for vowels, but recent studies show an effect of tongue root position in consonants, too (Matsui & Kochetov 2018; Cavar et al. 2020; and others, e.g., see also references in Beltzung et al. 2015).

An underlying assumption in much of literature on features is that abstract phonological features typically have specific phonetic correlates (Jakobson & Halle 1956; Chomsky & Halle 1968; Ladefoged 1972; Stevens 1972, 1989, 2002; Halle 1983[Stevens & Keyser 2010; Lulich 2010). A consistent presence of a feature's phonetic correlate may imply the phonological specification of that feature. On the other hand, the mapping from features to phonetic correlates is usually many-to-many, so that unambiguous conclusions about phonological feature specifications based on phonetic data may be problematic. Nevertheless, we believe that consistent phonetic contrasts, *interpreted within the context of the language-specific phonology*, can be used as part of an argument for the specification of particular phonological features (cf. Lulich & Cavar 2019). In this paper, we use ultrasound to examine the articulatory phonetics of Russian SCC and HCC vowels. When interpreted within the context of palatalization in Russian phonology, we propose that the phonetic data supports an analysis in which the palatalization feature is [ATR]. Because the features [-back] and [+high] have also been posited as palatalizing features, we examine tongue dorsum fronting and raising, as separate factors and a combined effect, as well as tongue root advancement, in HCC and SCC vowels.

1.4 Earlier instrumental studies

Some earlier instrumental studies used x-rays to image the tongue position in the articulation of Russian vowels and consonants (Koneczna & Zawadowski 1956; Skalozub 1963; Avanesov 1984; Bolla 1981). They represented the state-of-the-art of their time. However, by modern standards, they all investigated a small number of subjects in a limited number of consonant contexts. Newer studies include an EPG project by Barry (1992), where the magnitude of the palatalization gesture in palatalized consonant clusters was investigated. Further, an EMA study was conducted by Kochetov (2006) and MRI studies of sustained Russian palatalized consonants and vowels by Kedrova et al. (2008). No prior studies have systematically investigated vowel allophony in SCC vs. HCC consonant contexts with more than 3 subjects.

Few recent studies have investigated Russian sounds using 2D ultrasound imaging. These include Proctor (2011), who looked at the articulation of liquid consonants (/l, l^j, r, r^j/) in intervocalic position and observed the advancement of the tongue dorsum in palatalized consonants and a uvular-pharyngeal gesture of the dorsum in the hard liquids. Litvin (2014) reports that non-palatalized consonants in Russian are always produced with a secondary articulation, and are either uvularized or velarized. She concludes that phonologically both types of articulation serve the same function, to enhance the contrast with palatalized consonants. Based on the laryngeal ultrasound pilot data from one speaker, she concludes also that Russian non-palatalized consonants are not pharyngealized in the sense of the Laryngeal Articulator Model of Esling (2005). Pharyngealization is defined in Esling (2005: 26) as the retraction of the tongue and raising of the larynx, and Litvin (2014) did not observe the latter. Matsui & Kochetov (2018) set out to examine the effect of voicing on the tongue root in Russian, finding instead an effect of tongue root advancement in palatalized consonants. Finally, the study by Roon & Whalen (2019) looked at the articulation of non-palatalized labial consonants and established a strong effect of the hard consonant on adjacent vowels.

In contrast to the current project, previous studies do not focus on the variation in vowels. The modern 3D/4D ultrasound technology provides high quality images and allows us to look beyond the well-described tongue dorsum, as well as see some elements of the internal anatomy of the tongue (e.g., tendon of the genioglossus). In comparison to earlier studies, we have expanded the number of speakers and included all places of articulation in all (high-frequency) vocalic contexts.

2 Method

2.1 Participants and materials

Nine native speakers of Russian (6 women, 3 men) participated in this study. The participants completed a language background questionnaire before being recorded. The questionnaire results are included in Table 4. All participants spoke a variety of Standard Russian (which tends to be spoken in urban centers), and thus dialect differences are not really expected.

The participants read word lists containing 50 nonce words (non-randomized, no fillers, though only a subset of the data – 32 nonce words – were analyzed systematically in this paper). The list was read three times by 8 participants, and two times by one participant (a male), yielding a total of 832 tokens (32 x 3 x 8 + 32 x 2 x 1).

This study focuses on stressed vowels (of an initial syllable) in disyllabic nonce words, in bilateral 'soft' and 'hard' consonant contexts. All words were of the shape $C_iV_jC_iV_j$ with identical consonants throughout each word, drawing from the set {p, pʲ, t, tʲ, k, kʲ, š, ɕ},[7] where /š/ is a hard, non-palatalized posterior fricative and /ɕ/ is a soft posterior sound. Both vowels in each word were also phonemically identical, drawing from the vowel set {i, ɨ, u, e, o, a}. We chose to investigate nonce words with a bilaterally symmetric consonant context in order to maximize the coarticulatory effects of the consonants on the vowels, although similar effects are expected in unilateral, asymmetric contexts as well (Timberlake 2004).

The Russian phonemes /i, e/ palatalize the consonants /p, t, k/ (cf. Bolla 1981: 61; Litvin 2014: 20). This is obligatory for /i/. Sequences of non-palatalized consonants followed by phoneme /e/ (realized as the lax allophone [ɛ]) occur only in (usually recent) borrowings. The vowel /ɨ/ does not normally occur after soft consonants or after /k/. Therefore, we did not evaluate contrastive pairs of nonce words of the form PEPE, TETE, KEKE and KIKI, where P, T, and K refer to plain or palatalized sounds, and E and I refer to the phonemes /e/ and /i, ɨ/, respectively. The consonants /š, ɕ/ are inherently hard/soft (respectively) but are subject to the same phonotactic constraints as other consonants, that is, they combine with the HCC/SCC vowels, respectively. The complete list of nonce words that were recorded are presented in Table 3.

Table 3: List of nonce words. Consonants P, T, K, and SH refer to the pairs /p, pʲ/, /t, tʲ/, /k, kʲ/, and /š, ɕ/, respectively. Vowels I, E, A, O, U refer to the vowels /i, ɨ/, /e/, /a/, /o/, and /u/, respectively.

	I	E	A	O	U
P	pʲipʲi pɨpɨ		pʲapʲa papa	pʲopʲo popo	pʲupʲu pupu
T	tʲitʲi tɨtɨ		tʲatʲa tata	tʲotʲo toto	tʲutʲu tutu
K			kʲakʲa kaka	kʲokʲo koko	kʲukʲu kuku
SH	ɕiɕi šɨšɨ	ɕeɕe šeše	ɕaɕa šaša	ɕoɕo šošo	ɕuɕu šušu

[7] Kochetov (2017) uses symbols [ʂ, ʃʲ] corresponding to [š, ɕ] in this article. Also, Yanushevskaya & Bunčić (2015) use [ʃʲ] for the soft posterior. The hard, non-palatalized posteriors are in the phonological literature often referred to as retroflex sounds (e.g., Hamann 2003), however they lack entirely the curling back of the tip of the tongue, which is the most prominent characteristic for retroflexes. Like other hard consonants in Russian, they often show, according to different accounts, velarization, uvularization, or pharyngealization (cf. Knyazev 2002; Kasatkin 2007; Kodzasov & Krivnova 2001; Bolla 1981; Litvin 2014). Since a detailed discussion of the phonetics of Russian consonants is outside of the scope of the paper, we prefer to use a more neutral Slavic symbol [š] which is defined in terms of the softness opposition rather than by reference to phonetic characteristics. We also find [ɕ] more theory-neutral than [ʃʲ], where the latter implies a double articulation.

2.2 Data collection

Recordings were made with both an ultrasound machine (to image lingual articulation) and a microphone (for acoustics). In this study, the acoustic recordings were used only to identify target ultrasound frames for further articulatory analysis. The acoustic recordings were made with a SHURE KSM32 microphone placed approximately 1 meter in front of the participant, with a sampling rate of 48kHz and 16bit quantization.

Ultrasound recordings were made with a Philips EPIQ 7G machine (core software version 1.5.8; Lulich & Pearson 2019) using a Philips xMatrix x6-1 digital 3D/4D ultrasound transducer (Lulich et al. 2018). The transducer was secured under the chin using an Articulate Instruments ultrasound stabilization headset (Scobbie et al. 2008). Fully uncompressed DICOM ultrasound files were transferred from the ultrasound machine to a Windows 10 computer for analysis. The DICOM files were analyzed with a custom MATLAB toolbox called "WASL",[8] following Charles & Lulich (2018, 2019), Patel et al. (2019), Lulich & Cavar (2019), and Cavar et al. (2020).

While 2D ultrasound has been widely used in phonetics research for many years (e.g., Gick 2002, Davidson 2002, Miller & Finch 2011, Proctor 2011, Zharkova 2013, Mielke 2015, Boyce et al. 2016, Al-Tairi et al. 2017, Strycharczuk & Scobbie 2017, Turton 2017, Ahn 2018, Bennett et al. 2018, Tabain & Beare 2018), 3D/4D ultrasound is a relatively new technology that was originally used in speech and swallowing research by Chi-Fishman et al. (2000), Bressmann et al. (2007), and Bressmann (2010). Modern 3D/4D ultrasound equipment, described by Lulich et al. (2018) and Lulich & Pearson (2019), has recently been used to study liquid sound articulation in American English (Berkson et al. 2017), South Korean (Hwang et al. 2019a; Hwang et al. 2019b), and Brazilian Portuguese (Charles & Lulich 2018, 2019), as well as tongue dorsum and tongue root articulation in Arabic (Mokh et al, 2020) and Polish (Cavar et al. 2017; Lulich et al. 2017; Lulich & Cavar 2019; Cavar et al. 2020).

The designation "3D/4D" refers to the type of ultrasound technology, in which the transducer surface contains a two-dimensional array of piezoelectric elements. This contrasts with 2D and 3D ultrasound technology, both of which make use of a one-dimensional line of (typically 128) piezoelectric elements. As described by Lulich et al. (2018), the Philips xMatrix x6-1 digital 3D/4D transducer contains a two-dimensional array of 9,212 piezoelectric elements. The large number of elements arranged in a two-dimensional array enables the imaging of volumes (rather than planar sectors), and results in superior focusing and spatial resolution throughout most of the imaged volume. The array also enables beamforming and steering to proceed very quickly, allowing volumes to be imaged at high frame rates (this contrasts with mechanical 3D transducers). The "4D" in "3D/4D" refers to this fast volumetric imaging capability, while the "3D" refers simply to volumetric imaging.

In this study, 3D/4D ultrasound was used to record lingual articulations with the inherent benefits of superior focusing and spatial resolution. An additional benefit of volumetric imaging (as proposed by Lulich et al. 2018) is the ability to use information in parasagittal, coronal, and transverse images to help interpret midsagittal images, which are the focus of this study. The pixel sizes in the anterior-posterior, medial-lateral, and superior-inferior directions, as well as the recording frame rates for each participant are given in Table 4. The average frame rate was approximately 20 fps, corresponding to a frame duration of approximately 50ms. While this is a slower frame rate than in many 2D ultrasound studies (standard 30 fps), it is fast enough for the study of vowels and other sounds with relatively slow-moving articulations (Wrench & Scobbie 2011; Lulich et al. 2018). In the present study, two or three frames representing the steady-state middle portion of the target vowel were obtained in most cases.

[8] WASL is available for download at https://spliu.sitehost.iu.edu/software/software.html.

Table 4: Pixel size (rounded) in millimeters per pixel (field size, rounded, in cm) in the anterior-posterior (AP), medial-lateral (ML), and superior-inferior (SI) directions, as well as frame rates (fps) and gender for each participant.

Participant	Gender	Age (yrs)	AP	ML	SI	Frame rate	Origin	Presumed Dialect Group
1	F	29	.69 (8.6)	.71 (4.4)	.36 (7.2)	20.32	Nikolayev (Ukraine)	Southern
2	M	27	.67 (10.1)	.90 (4.4)	.41 (8.3)	22.21	Vladimir (Central Russia)	Central
3	F	48	.78 (9.3)	.81 (5.0)	.40 (8.3)	21.52	St. Petersburg (North Russia)	Northern
4	F	32	.78 (9.3)	.81 (5.0)	.40 (8.3)	21.52	Maykop (Southern Russia)	Southern
5	M	72	.86 (10.3)	.90 (5.5)	.45 (9.2)	21.52	Moscow (Central Russia)	Central
6	F	61	.77 (9.8)	.88 (6.1)	.39 (8.3)	16.63	Ufa (Bashkortostan, Russian Federation)	Central
7	M	26	.87 (10.8)	.97 (6.8)	.44 (9.3)	16.63	Moscow (Central Russia)	Central
8	F	38	.78 (11.2)	.80 (5.0)	.40 (8.3)	17.42	Brest (Byelarus)	Southern
9	F	48	.83 (9.3)	.79 (5.3)	.39 (8.2)	20.32	Ukraine	Southern

2.3 Data visualization and analysis

To visualize the results, we have used the Threshold and Overlay (TaO) method as described in Lulich & Cavar (2019). In TaO images, pixels with low intensity are filtered out so that only pixels with ultrasound echo intensity greater than some threshold value remain. One thresholded image is overlaid on another, and both are assigned different color schemes. Such TaO images allow for the direct comparison of articulations from a given speaker within a recording session. An example of a TaO image and its two corresponding raw ultrasound images is illustrated in Figure 1. Further images in Section 3.3 were created by manually tracing the surface of the tongue and overlaying the tracings.

In evaluation of the articulation, we have taken the following effects into consideration, illustrated in Figure 1:

- Tongue root advancement (henceforth referred to by the abbreviation "TRA"), visible in the midsagittal plane, was quantified as the Euclidean distance between the tongue root in the SCC vs. HCC allophones of vowels. TRA was measured along a line parallel to the tendon of the genioglossus (TnG)[9] (metric A in the right panel of Figure 1). If the line pointed to a part of the tongue root that was obscured by the hyoid shadow, the nearest visible part of the surface of the tongue root was measured (cf. Lulich & Cavar 2019).
- Tongue dorsum fronting (abbreviated "TDx"), visible in the midsagittal plane, was quantified as the distance in the horizontal plane between the points of maximal constriction for the two

[9] In our experience (working with our particular ultrasound system) the TnG is almost always visible and identifiable, including in the TaO figures included in the manuscript. We were unable to confidently identify the TnG in fewer than 3.6% of tokens in this study (3.6% includes also the data that was not analyzed because of the problems with the files as opposed to the quality of the image). Variability in TnG location (due to translation) is small because of the use of a transducer stabilization headset, and does not impact our analyses because these analyses are always based on differences between paired observations. The stationarity of the TnG in terms of both location (translation) and orientation (rotation) can be appreciated qualitatively by observing the TnG in the TaO images presented within the manuscript. An unpublished investigation of TnG orientation (rotation) found small variations across utterances (Pedro et al. 2014), but these were deemed negligible.

corresponding vowels (metric B in the right panel of Fig 1). The point of the maximal constriction was assumed to be the point of the maximal elevation of the tongue body, and in cases when the tongue formed a longer constriction, the middle of this plateau was recorded.

- Tongue dorsum raising ("TDy"), visible in the midsagittal plane, was quantified as the distance in the vertical plane between the points of maximal constriction for the two corresponding vowels (metric C in the right panel of Figure 1). The point of maximum constriction was determined as above.
- Tongue dorsum advancement (combined fronting and raising, "TDA"), visible in the midsagittal plane was quantified as the Euclidean distance between the points of maximal constriction (metric D in the right panel of Fig 1).

Measurements of the tongue dorsum fronting, tongue body raising and the advancement of the tongue root were repeated in 20% of all tokens (i.e., in all of the [i] and [ɨ] tokens) in order to evaluate measurement uncertainty. The measurement uncertainty based on the comparison of the repeated measures was found to have a magnitude of 0.04 cm (cf. Csapo & Lulich 2015; Lulich et al. 2017, 2018; Charles & Lulich 2018, 2019). However, an additional source of uncertainty (which is usually not appreciated in ultrasound studies of speech) is the ultrasound beam width during image acquisition. For both the ultrasound system used in this study and 2D systems commonly used in phonetics research (e.g., the Ultrasonix RP system; Wrench & Scobbie 2008) the spatial resolution based on beam width has an uncertainty close to 0.2cm (Lulich et al. 2018). Lulich et al. (2018) measured the uncertainty due to the inherent noisiness of the ultrasound signal produced with this particular ultrasound system, and found that the uncertainty was less than 2mm, which is small compared with the magnitude of the observed effects. We therefore assume a threshold of 0.2cm in our evaluation of tongue dorsum and root differences between SCC and HCC vowels.

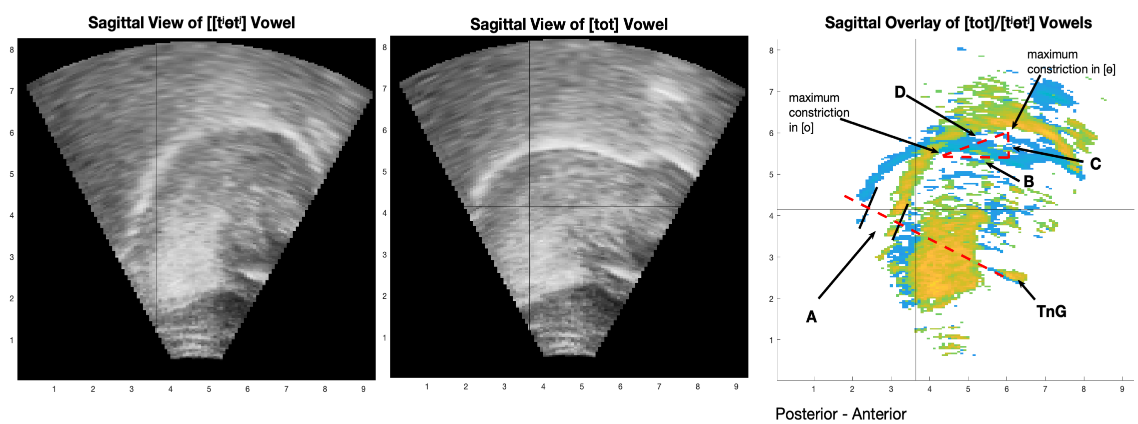


Figure 1: Measuring the differences in the position of the tongue. Left: A raw ultrasound image. Vowel in the soft-consonant context. Center: A raw ultrasound image. Vowel in the hard-consonant context. Right: TaO image for direct comparison of the SCC and HCC vowels. A – advancement of the tongue root, B – tongue dorsum fronting, C – tongue dorsum raising, D – combined effect of tongue dorsum fronting and raising. TnG – tendon of the genioglossus muscle. Front of the oral cavity is on the right of the pictures.

2.4 Statistical analysis[10]

Out of 832 tokens, 3.6% were excluded from further analysis because of poor image quality or corrupted data files. Statistical analyses focused on the dependent variables of tongue root displacement (TRA), tongue body (Euclidean) displacement (TDA), tongue body fronting (TDx), and tongue body raising (TDy). Independent variables included repetition number ('1', '2', or '3'), gender ('male' or 'female'), speaker

[10] The complete statistical analysis is included in the supplementary file.

(‘1’, ‘2’, ‘3’, ‘4’, ‘5’, ‘6’, ‘7’, ‘8’, or ‘9’), vowel (‘i’, ‘e’, ‘a’, ‘o’, or ‘u’), and consonant context (‘p’, ‘t’, ‘k’, ‘sh’). One-way ANOVAs were performed for each of the 4 dependent variables, to test for main effects of each of the 5 independent variables.[11] Thus, 20 analyses were performed, and a Bonferroni-corrected value of $\alpha = 0.05/20 = 0.0025$ was used to determine statistical significance.

Post hoc comparisons using Bonferroni-corrected t-tests were performed for independent variables with significant main effects, namely speaker, vowel, and consonant. There was thus a total of 52 comparisons (36 comparisons among speakers, 10 comparisons among vowels, 6 comparisons among consonants) for each dependent variable, or a total of 208 comparisons. An approximately Bonferroni-corrected value of $\alpha = 0.05/200 = 0.00025$ was used to determine statistical significance in these post-hoc comparisons

3 Results

3.1 Quantitative analysis

In the one-way ANOVA tests of main effects for each of the 5 independent variables (repetition number, gender, speaker, vowel, consonantal context), two independent variables – repetition number and gender – did not have a significant main effect on any dependent variable. We therefore only consider speaker, vowel, and consonant effects below.

Tongue dorsum raising (TDy). Contrary to expectations, tongue dorsum raising in SCC vowels was not observed in 214 out of 416 comparisons. The tongue dorsum was lowered by more than 0.2cm in 23% of all comparisons, while it was raised more than 0.2 cm in 22% of all comparisons. The average values by vowel for each speaker are summarized in Figure 2.

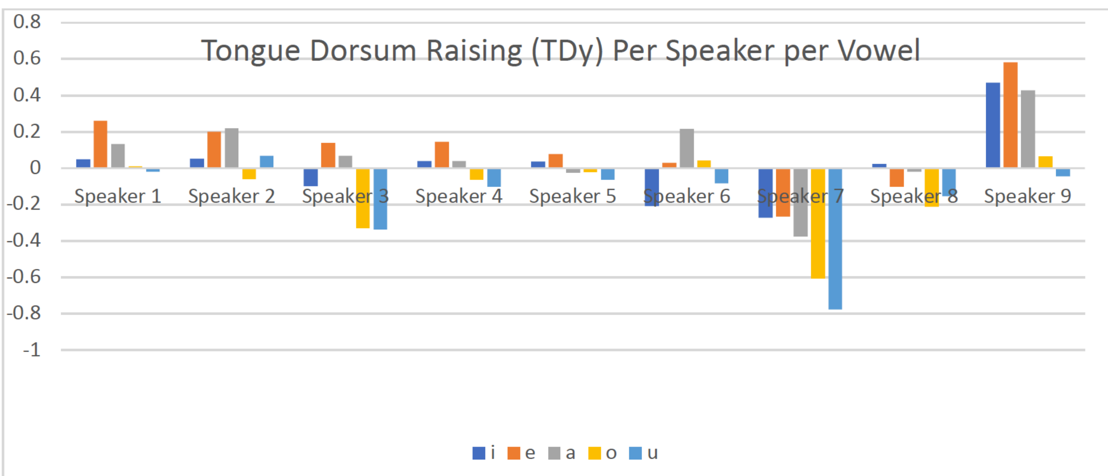


Figure 2: Average relative tongue dorsum raising at the point of maximum constriction in SCC vowels as compared to HCC vowel (in cm). Data from 9 speakers. 5 vowels in all investigated consonantal contexts.

All speakers show both relative lowering and raising on different occasions. There is also no consistent vowel effect. There is some speaker effect. Speaker 7 with mean raising of -0.507cm (negative “raising” indicates lowering) is significantly different from speakers 1, 2, 3, 4, 5, 6, 8, 9 (mean > -0.1686). Speaker 9 with mean raising of 0.232cm is significantly different from speakers 3, 4, 8, all with a mean raising of -0.04cm. Because of the variability in tongue dorsum height, including both raising and lowering, we

[11] Repetition round had no systematic effect. Thus, performing repeated measures ANOVA instead (which would reduce the power of the tests by increasing the number of variables under consideration) does not seem necessary.

therefore do not consider tongue dorsum raising any further, and conclude that [high] is not active in the contrast between soft and hard consonant-vowel sequences in Russian.

Tongue dorsum fronting (TDx). Tongue dorsum fronting is a better correlate of SCC vowels (Figure 3) with a median across all speakers/vowels/consonantal contexts of approx. 1.15cm. Approximately 8% of all corresponding pairs showed less than 0.5cm fronting. While the fronting effect is stronger and more systematic than the raising effect, most speakers (Speakers 1, 2, 3, 4, 5, 8) had occasional articulations with the maximum constriction point relatively retracted in SCC vowels. These exceptions constituted less than 2% of all comparisons.

SCC vowels have a significantly more fronted tongue dorsum than HCC vowels, with mean relative fronting of 1.23cm (sd=.68cm). We observe also the effect of the vowel. In particular, /i/ is significantly less advanced in soft contexts (mean = 0.693cm) than /a/, /o/, and /u/ (mean > 1.35cm). /e/ is significantly less advanced in soft contexts (mean = 0.841cm) than /o/ (mean = 1.456cm). The only significant consonant-context effect was the difference between the labial and posterior coronal context, that is, soft vs. hard /p/ was associated with significantly more advancement in the SCC vowel than in the case of soft vs. hard /ɕ/-/š/ pair (p=0.0001). Other comparisons were not significant (p>0.12). In general, /ɕ, š/ showed the smallest TDx differences, followed by /t/ and /k/ which were very similar, with /p/ showing the largest difference. A limited speaker effect was observed, that is, Speaker 1 (mean 0.780cm) is significantly different in terms of fronting strategies from speakers 2, 7, 9 (mean > 1.37cm).

Tongue root advancement (TRA). Advancement of the tongue root was a strong effect, with mean 1.043cm (stdev .5452cm), and approx. 7.5% of pairs under 0.5cm (Figure 4). The effect in back vowels tended to be bigger than in front vowels. /u/ exhibits significantly more advancement of the tongue root in soft contexts (mean = 1.340cm) than either /i/ or /a/ (mean < 1.0). There were no significant differences between consonantal contexts (p=0.0007 for /t/-/t^j/ vs. /k/-/k^j/; p = 0.0011 for /ɕ/-/š/ vs. /k/-/k^j/; p > 0.06 for remaining comparisons (α = 0.00025). Tongue root advancement, while not significantly different for any comparison by consonant context, was smallest for /t/-/t^j/ and /ɕ/-/š/, followed by /p/-/p^j/, with /k/-/k^j/ pair showing the largest difference.

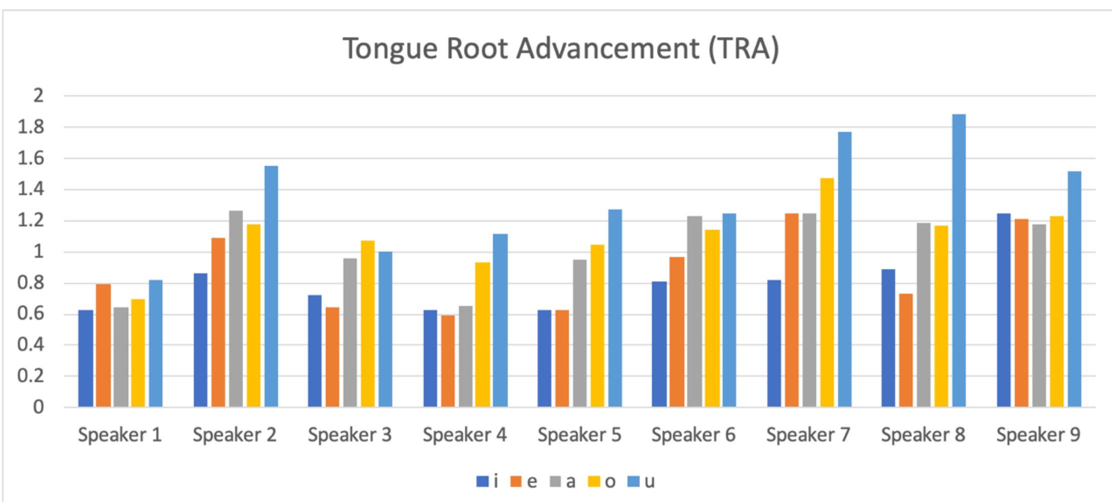


Figure 3: Average relative tongue dorsum fronting at the point of maximum constriction in the SCC vowel as compared to HCC vowel (in cm). Data from 9 speakers. 5 vowels in all investigated consonantal contexts.

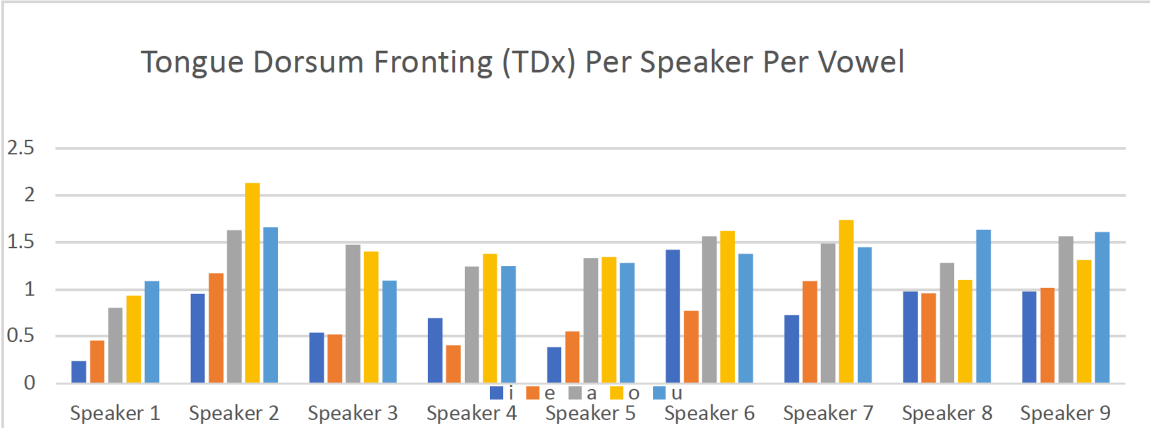


Figure 4: Relative tongue root advancement in the SCC vowel as compared to HCC vowel (in cm). Data from 9 speakers. 5 vowels in all investigated consonantal contexts.

Some speaker effect was observed. In particular: Speaker 1 (mean 0.6cm) is significantly different from speakers 2, 6, 7, 8, 9 (mean > 1.0cm), Speaker 4 (mean .822cm) is significantly different from speaker 7 (mean 1.354cm), and nearly significantly different from speaker 9 (mean 1.291cm) [p=0.0003].

Tongue dorsum advancement (TDA). Finally, a combined effect of raising and fronting of the tongue dorsum, dubbed 'tongue dorsum advancement,' is also systematically present (Figure 5) with a mean 1.276cm (sd .682cm), and about 7% of values falling below 0.5cm. It is highly correlated with TDx and TRA.

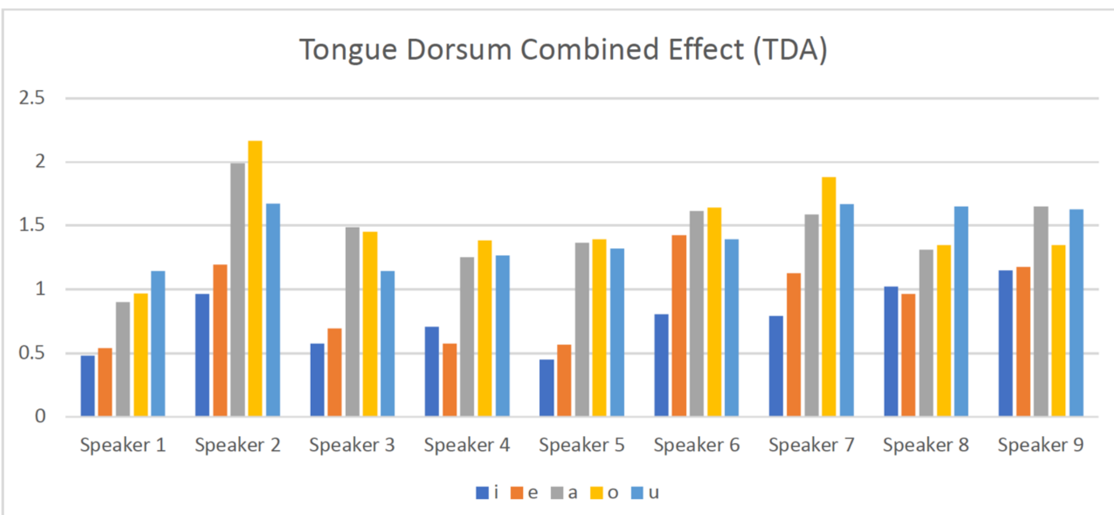


Figure 5: Relative tongue dorsum advancement (combined fronting and raising) at the point of maximum constriction in the SCC vowel as compared to HCC vowel (in cm). Mean values from 9 speakers. 5 vowels in all investigated consonantal contexts.

The quality of the vowel affects the amount of advancement (combined fronting and raising) of the dorsum. The vowel /i/ is significantly less advanced in soft contexts (mean = 0.732cm) than /a/, /o/, and /u/ (mean > 1.4). /e/ is significantly less advanced in soft contexts (mean = 0.878cm) than /o/ (mean = 1.5012cm). Speaker 1 (mean 0.817cm) is significantly different from speakers 2, 7, 9 (mean > 1.45cm). As for the consonantal context, soft vs. hard /p/ was associated with significantly more advancement of the vowel in soft contexts than soft vs. hard /ɕ, š/ (p=0.0001). Other comparisons were not significant (p>0.1).

General observation. Overall, the mean amounts of advancement in the tongue root (TRA) and tongue dorsum measures (TDA, TDx) were 1.043cm (sd=.545cm), 1.276cm, (sd=.682cm) and 1.232cm (sd=0.676cm), respectively. All three measures are significantly greater than 0 according to one-tailed, one-sample t-tests (p<0.0001), indicating greater advancement in SCC vowels.

The means by vowel are represented in Figure 6. The TRA effect is more consisent (smallest standard deviation) across different vowels than the remaining three measures. TDy is small and inconsistent. TDA and TDx are more sensitive to the quality of the vowel. For any individual vowel category, the standard deviation of the dorsum fronting is higher than for the advancement of the tongue root. The tongue dorsum tends to be fronted more in back vowels than in front vowels (although the highest means are for [a]). There is less dorsum fronting than tongue root advancement for front vowels and more dorsum fronting than tongue root advancement in back vowels.

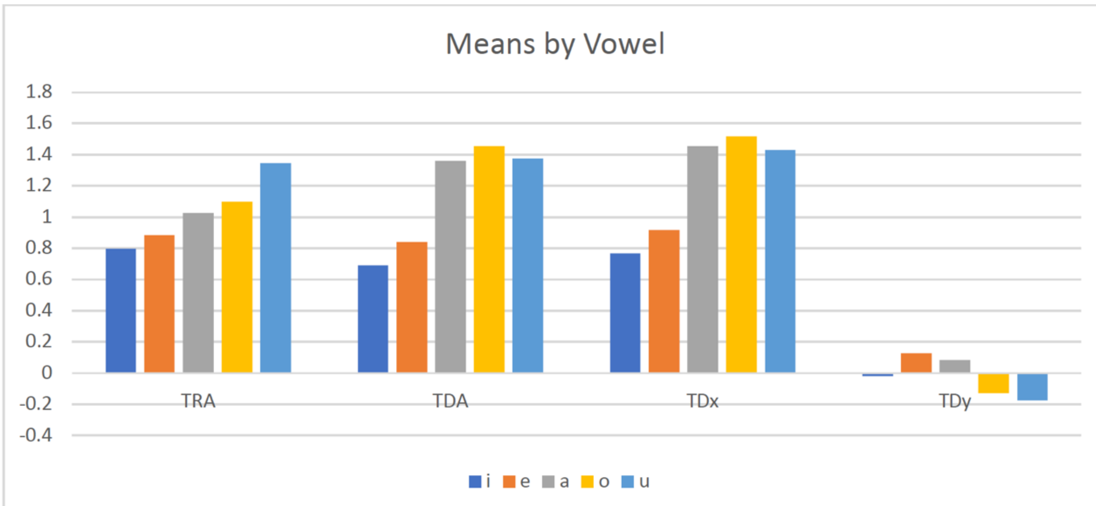


Figure 6: TRA (Tongue Root Advancement), TDA (Tongue Dorsum Advancement), TDx (Tongue Dorsum Fronting), and TDy (Tongue Dorsum Raising) in the SCC vowels as compared to HCC vowels (in cm). Mean values from 9 speakers. 5 vowels in all investigated consonantal contexts.

The means by consonant are represented in Figure 7. TDx, and TDA were significantly greater in the [p] context than in the [ɕ, š] contexts, TDy was significantly greater in the [p] than in the [t] and [ɕ, š] contexts, and all remaining comparisons (including all comparisons involving TRA) were not significant.

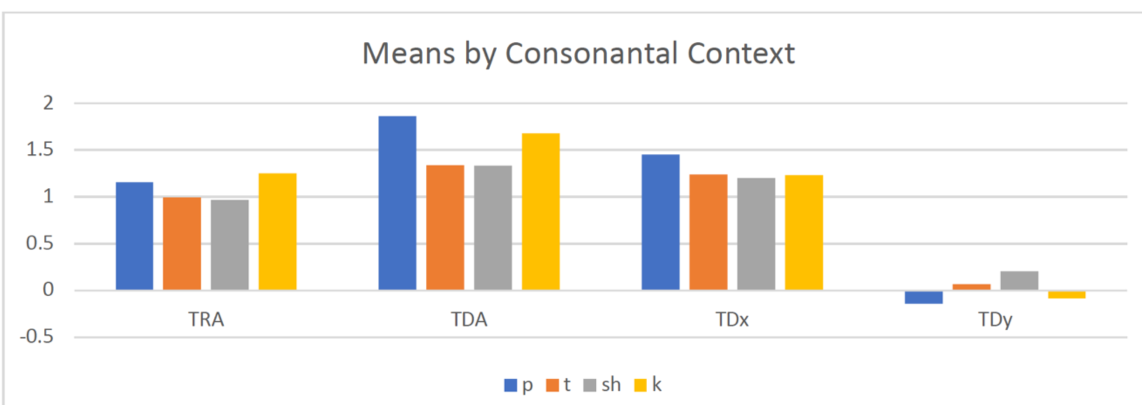


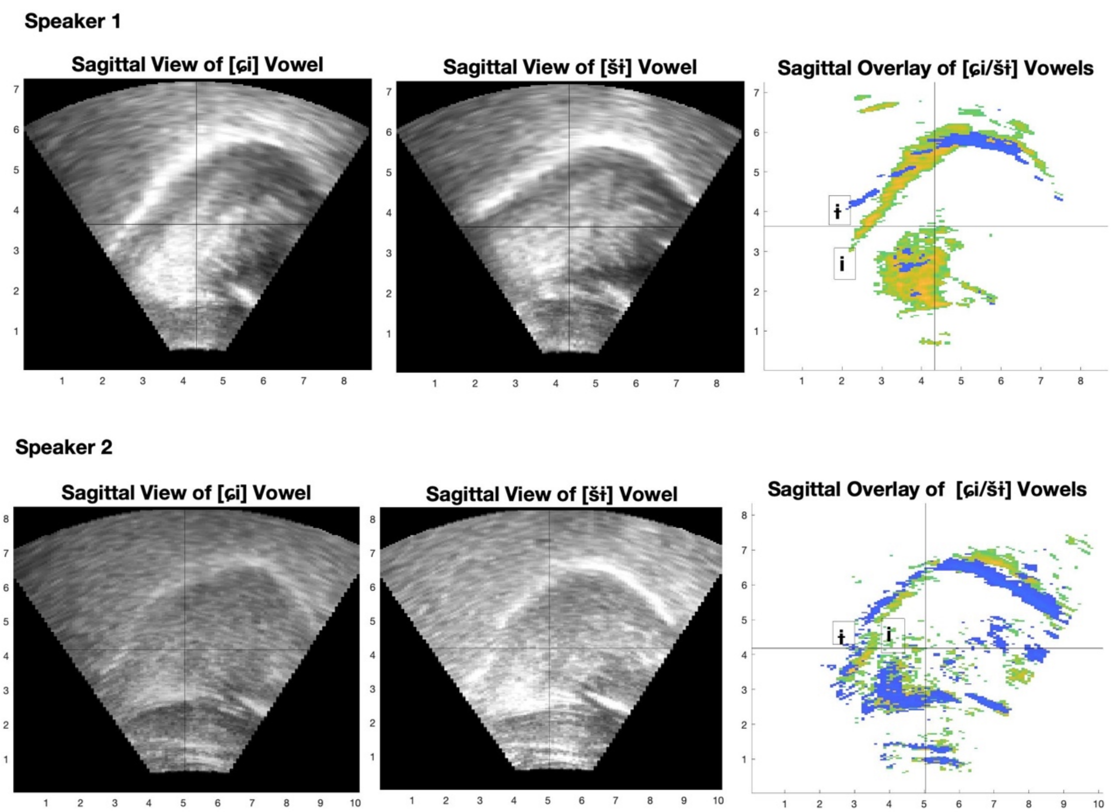
Figure 7: TRA, TDA, TDx, and TDy in the SCC vowels as compared to HCC vowels (in cm). Mean values from 9 speakers. All vowels in 4 consonant contexts.

3.2 Qualitative analysis

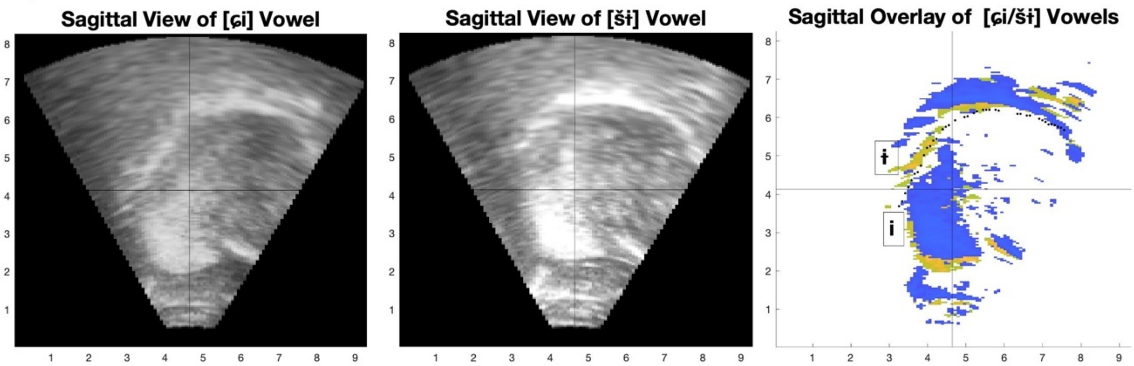
The following section presents the ultrasound images of the SCC and HCC pairs of vowels. Since the effects of the consonantal context were either not significant or of small size, in the following we will focus on the contexts of [š, ɕ], in which all of the vowel pairs were represented.

3.2.1 /i/ versus /ɨ/

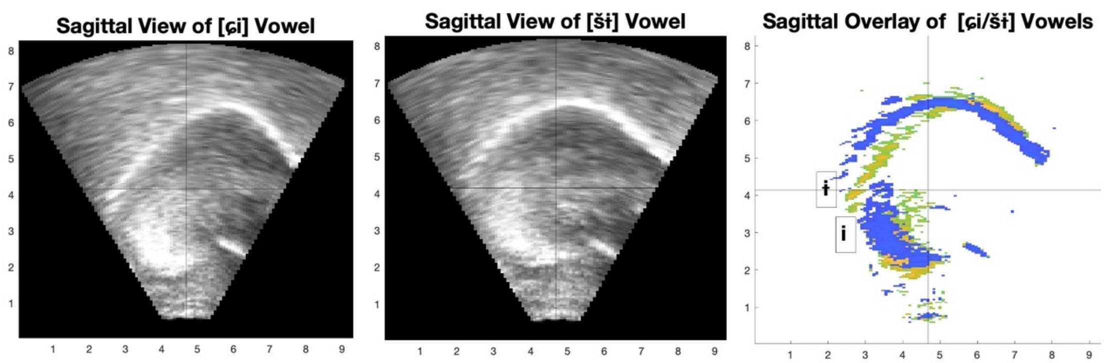
/i/ and /ɨ/ are the two high unrounded vowels in Russian. While /i/ is clearly a front vowel, the status of /ɨ/ in Russian is somewhat controversial. First, phonetically it shows a lot of variation. Koneczna & Zawadowski (1956: 30) describe two types of /ɨ/, one with the body of the tongue fronted to what they describe as 'postpalatum', and the other with the blade raised and forming a long flat constriction together with the dorsum. Both versions show a substantial enlargement of the oral cavity in comparison to the vowels /u, o, a/. Thus, Koneczna & Zawadowski (1956) strongly reject the description of /ɨ/ as a back vowel and refer to it as either central, for the former version, or mixed for the latter type. Matusevich (1948), Vinogradov (1952), Mirowicz (1953), Avanesov (1956: 98), Panov (1967: 41), and Bolla (1981: 66) describe the vowel as central, while Bulanin (1970: 46) refers to /ɨ/ as mixed (both front and back), describing it as articulated with the retraction of the back of the tongue. Figure 8 shows raw ultrasound images of the vowel /i/ (left panels), /ɨ/ (middle panels), and the corresponding TaO images (right panels) for each speaker. In some cases, we added a hand-traced tongue contour to aid in the interpretation of the images. In all TaO images, the blue-colored data represent the HCC vowel, and the green-colored data represent the SCC vowel. The tongue tip is on the right, and the tongue root is on the left.



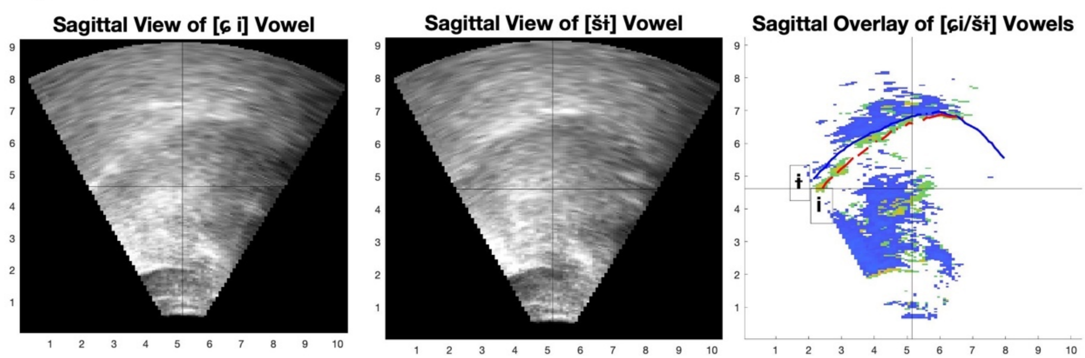
Speaker 3



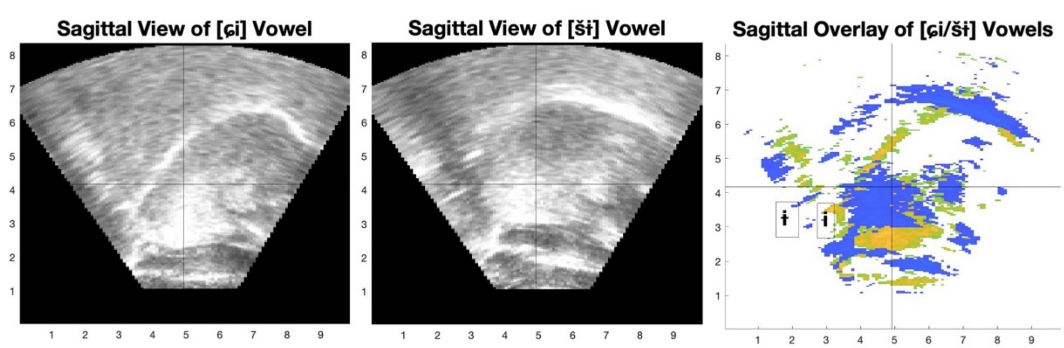
Speaker 4



Speaker 5



Speaker 6



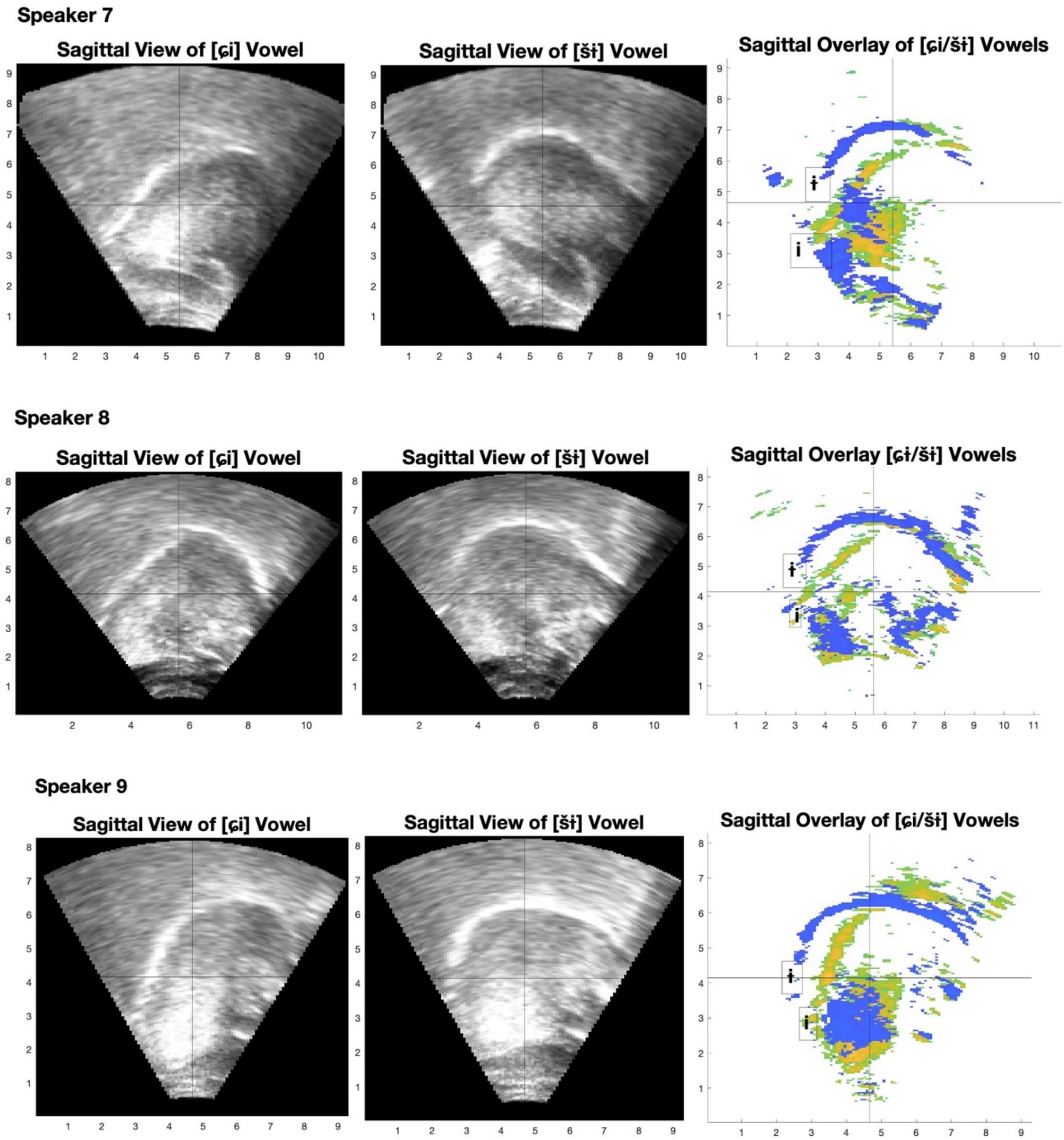


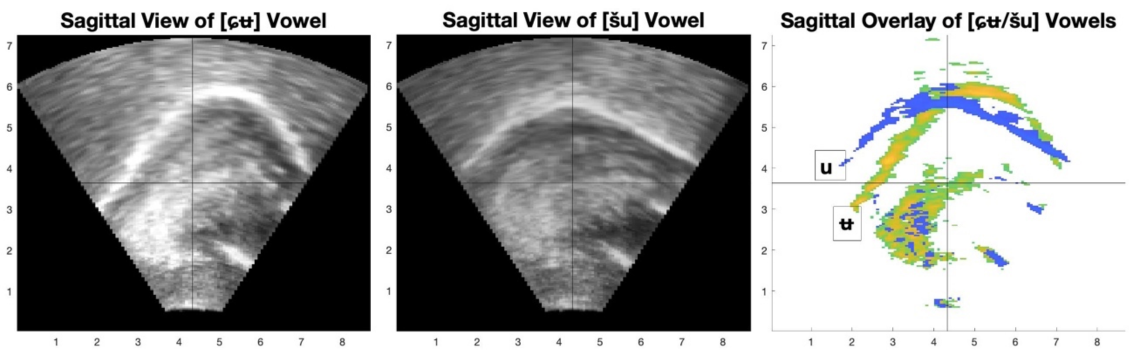
Figure 8: Raw ultrasound images for SCC /i/ (left) and HCC /ɨ/ (center), both in a stressed syllable, and TaO images (right) of the corresponding vowels for Speakers 1–9. Front of the oral cavity is on the right of the pictures

For Speakers 1 and 5, there is only a small difference in the position of the tongue body between /i/-/ɨ/. Most speakers (Speaker 2, 4, 6, 7, 9) have both conspicuous fronting of the dorsum and advancement of the tongue root for /i/, though Speakers 6, 7, 9 had a bigger effect than Speakers 2 and 4. Speakers 3, 5 and 8 have more advancement of the root than dorsum fronting. The relative advancement of the tongue root for /i/ is present in all speakers, so was fronting of the dorsum. For speakers 3, 5, 7, 8 in Figure 7, we observe actual lowering instead of raising of the tongue dorsum.

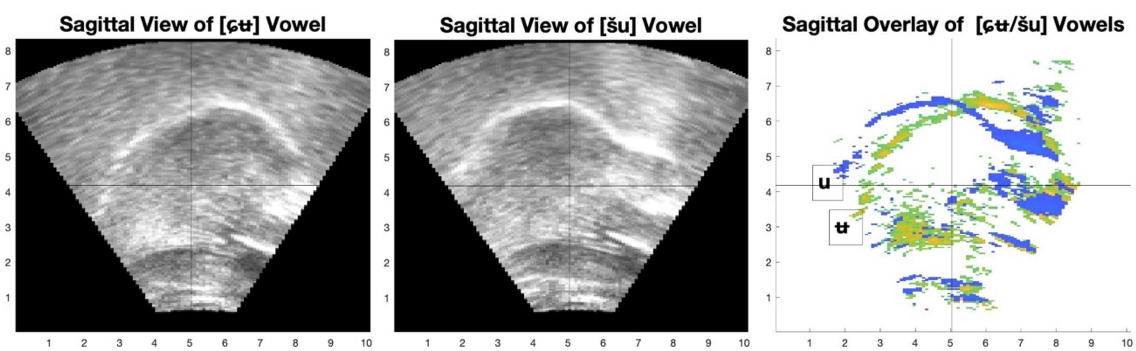
3.2.2 Variation in the production of /u/

Variation in /u/ is allophonic though the difference between the two allophones is parallel to the difference between the phonemes /i/ and /ɨ/. Figure 9 represents the ultrasound images of the two allophones in the context of [ɕ] and [š], in the same orientation as for /i/-/ɨ/ pair in the previous section, that is, with the tongue root left and tongue tip pointing right. For /u/, no speaker had a visible raising of the tongue dorsum in the context of a soft consonant, and one speaker (Speaker 8) showed instead a relative lowering of the tongue dorsum. All speakers had strong fronting of the tongue dorsum and advancement of the tongue root. Speaker 1 had a little more of the tongue dorsum effect than tongue root effect, Speaker 7 had a stronger tongue root advancement than dorsum fronting, but the remaining speakers had a comparable amount of tongue root advancement and tongue dorsum fronting.

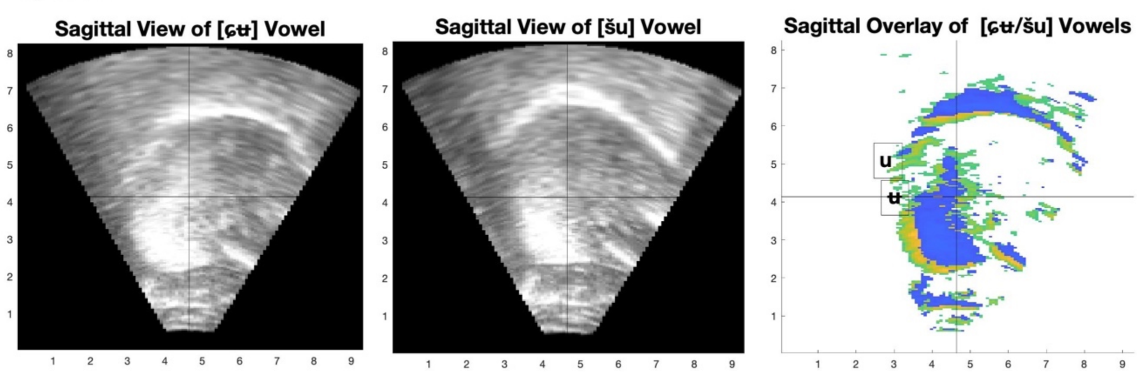
Speaker 1



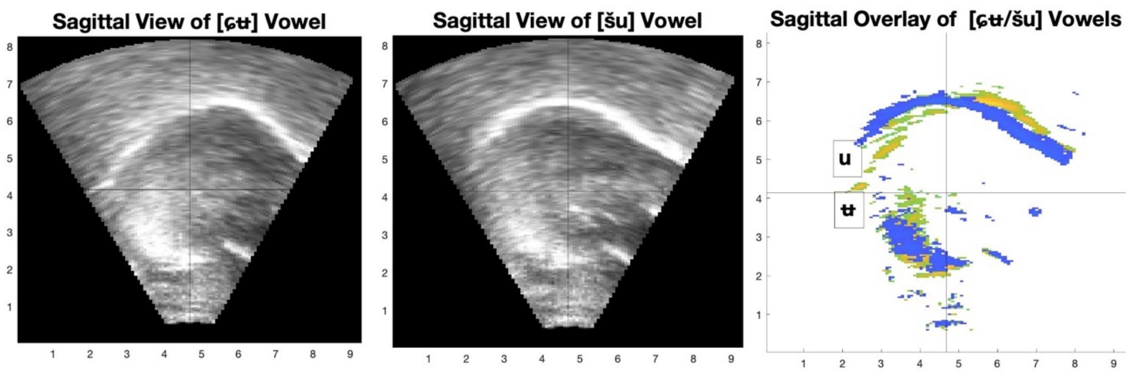
Speaker 2



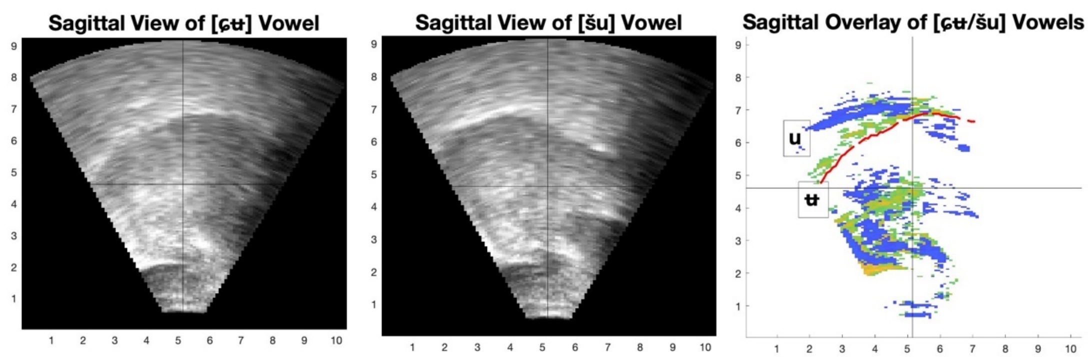
Speaker 3



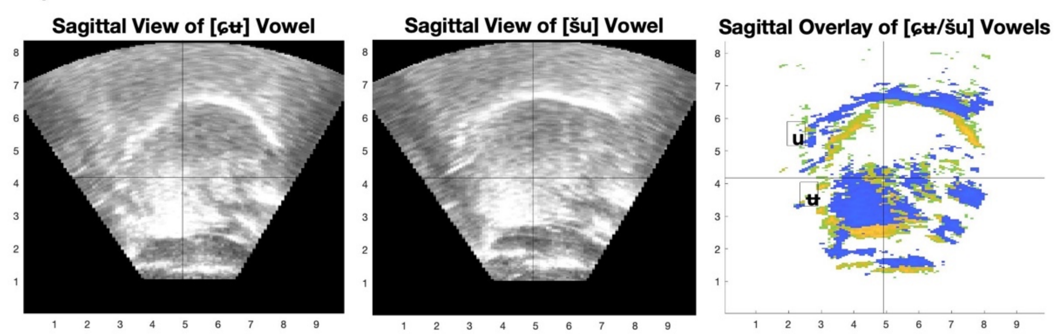
Speaker 4



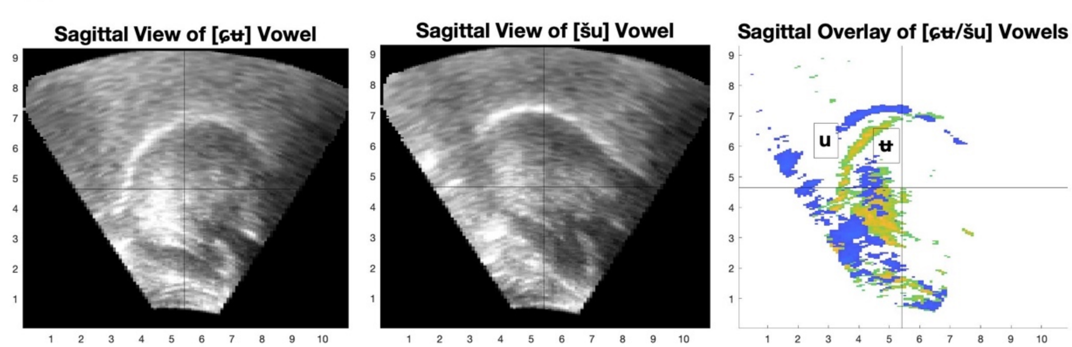
Speaker 5



Speaker 6



Speaker 7



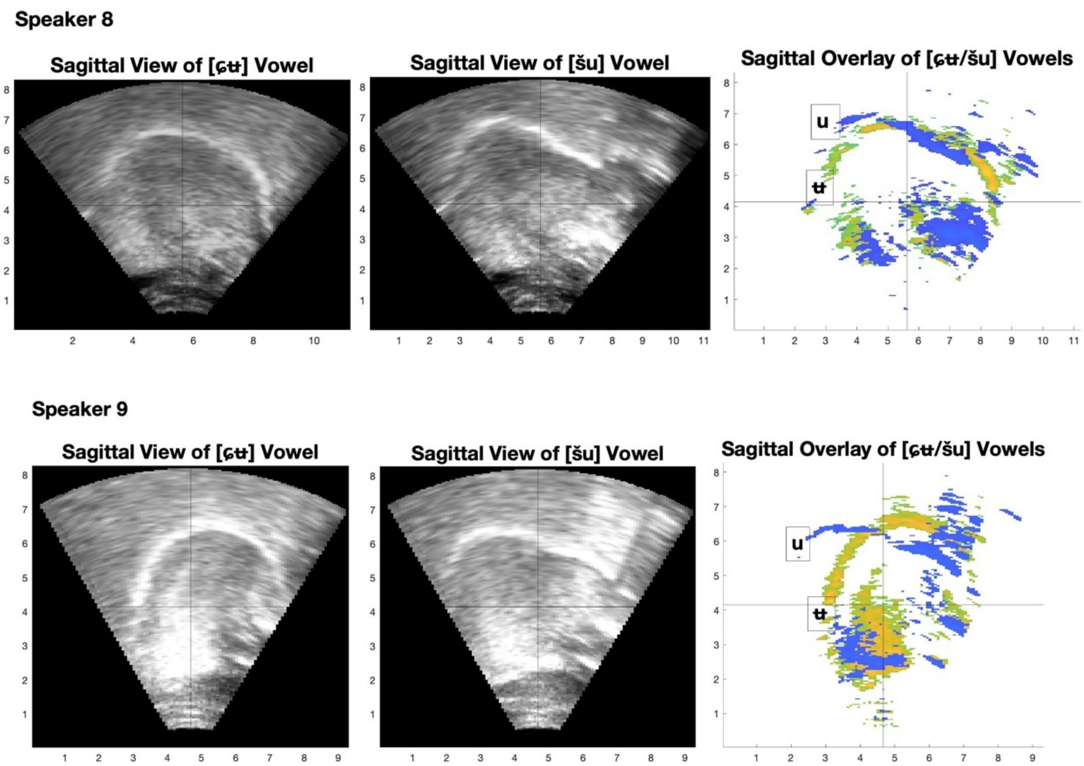
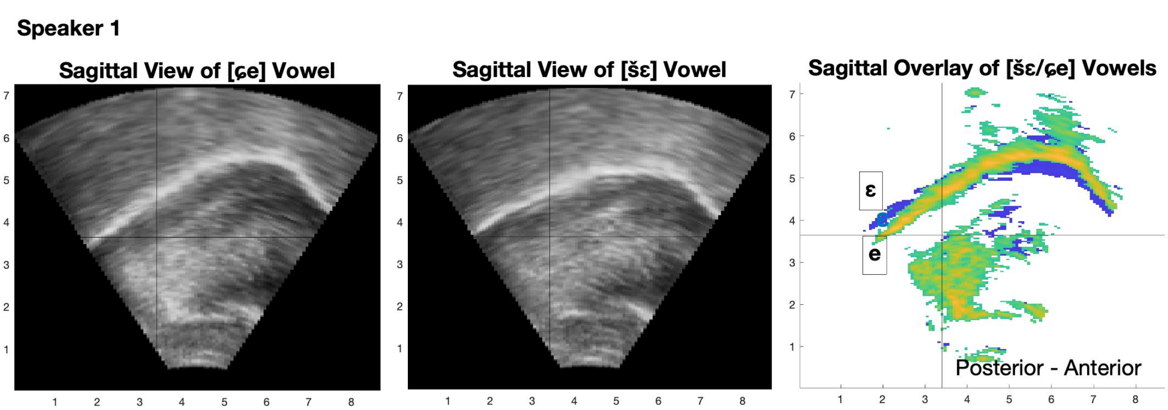


Figure 9: Raw ultrasound images for SCC [ʉ] (left) and HCC [u] (center), both in a stressed syllable, and TaO images (right) of the corresponding vowels for Speakers 1–9. Front of the oral cavity is on the right of the pictures.

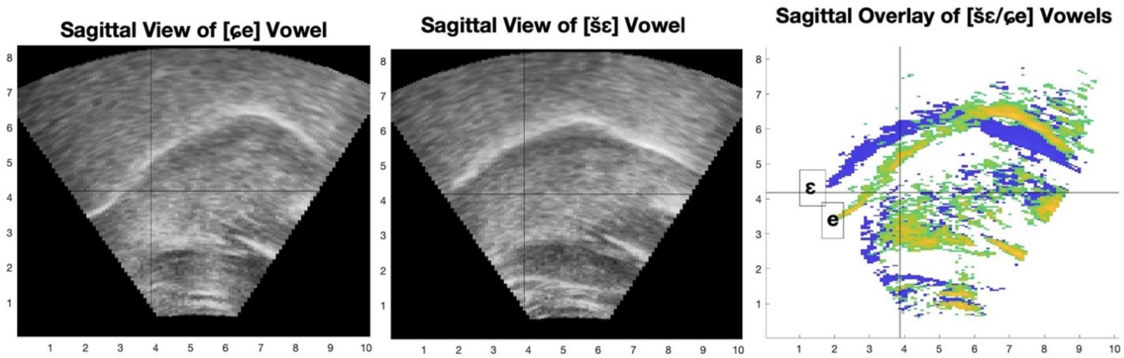
For /u/, no speaker had a visible raising of the tongue dorsum in the context of a soft consonant, and one speaker (Speaker 8) showed instead a relative lowering of the tongue dorsum. All speakers had strong fronting of the tongue dorsum and advancement of the tongue root. Speaker 1 had a little more of the tongue dorsum effect than tongue root effect, Speaker 7 had a stronger tongue root advancement than dorsum fronting, but the remaining speakers had a comparable amount of tongue root advancement and tongue dorsum fronting.

3.2.3 Mid front vowels

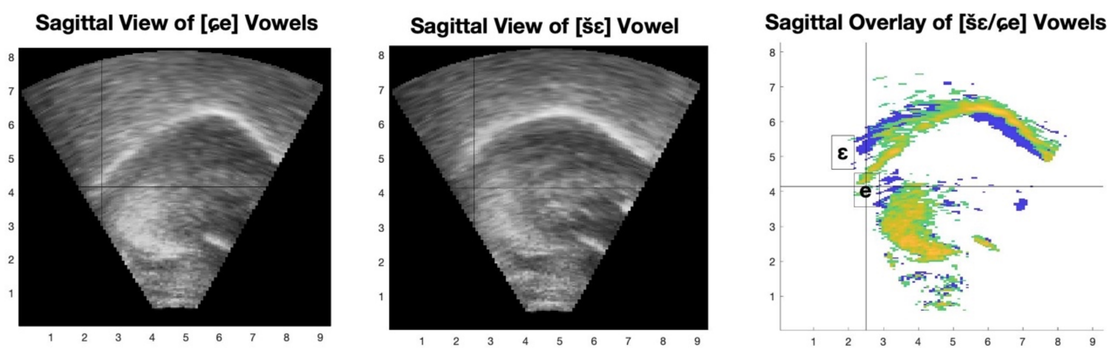
Figure 10 represents images of the two allophones of /e/ in the context of soft and hard voiceless posterior fricatives.



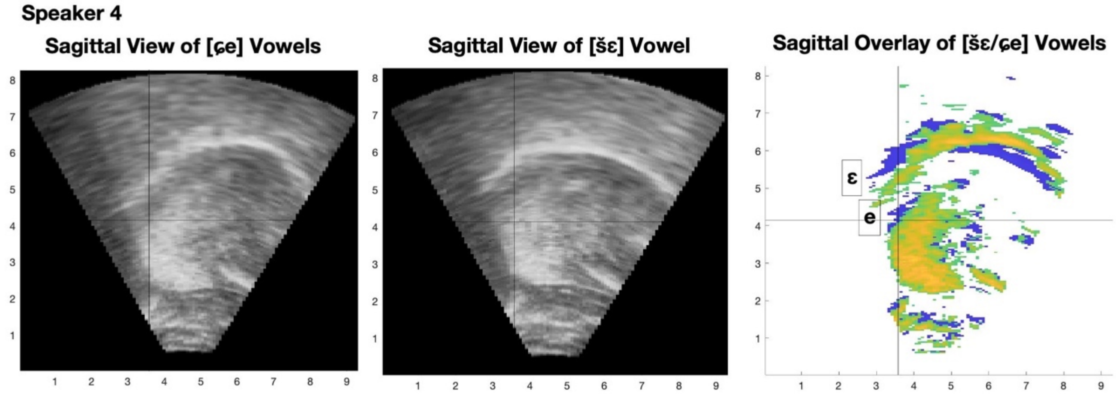
Speaker 2



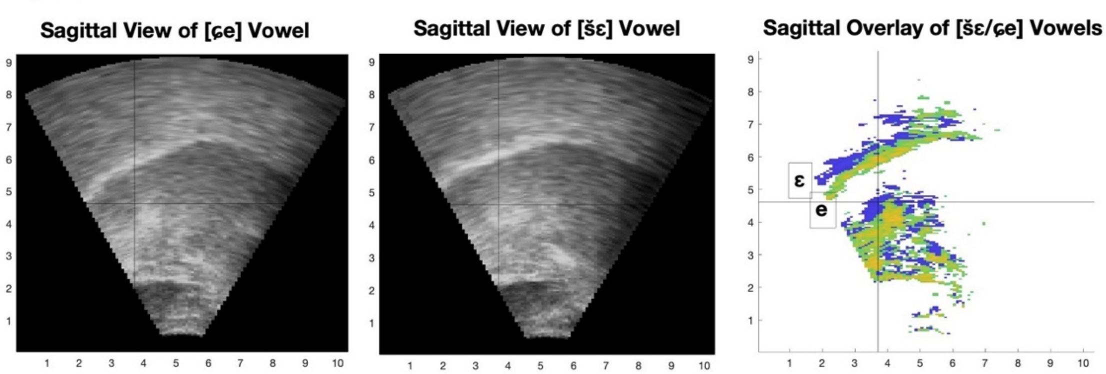
Speaker 3



Speaker 4



Speaker 5



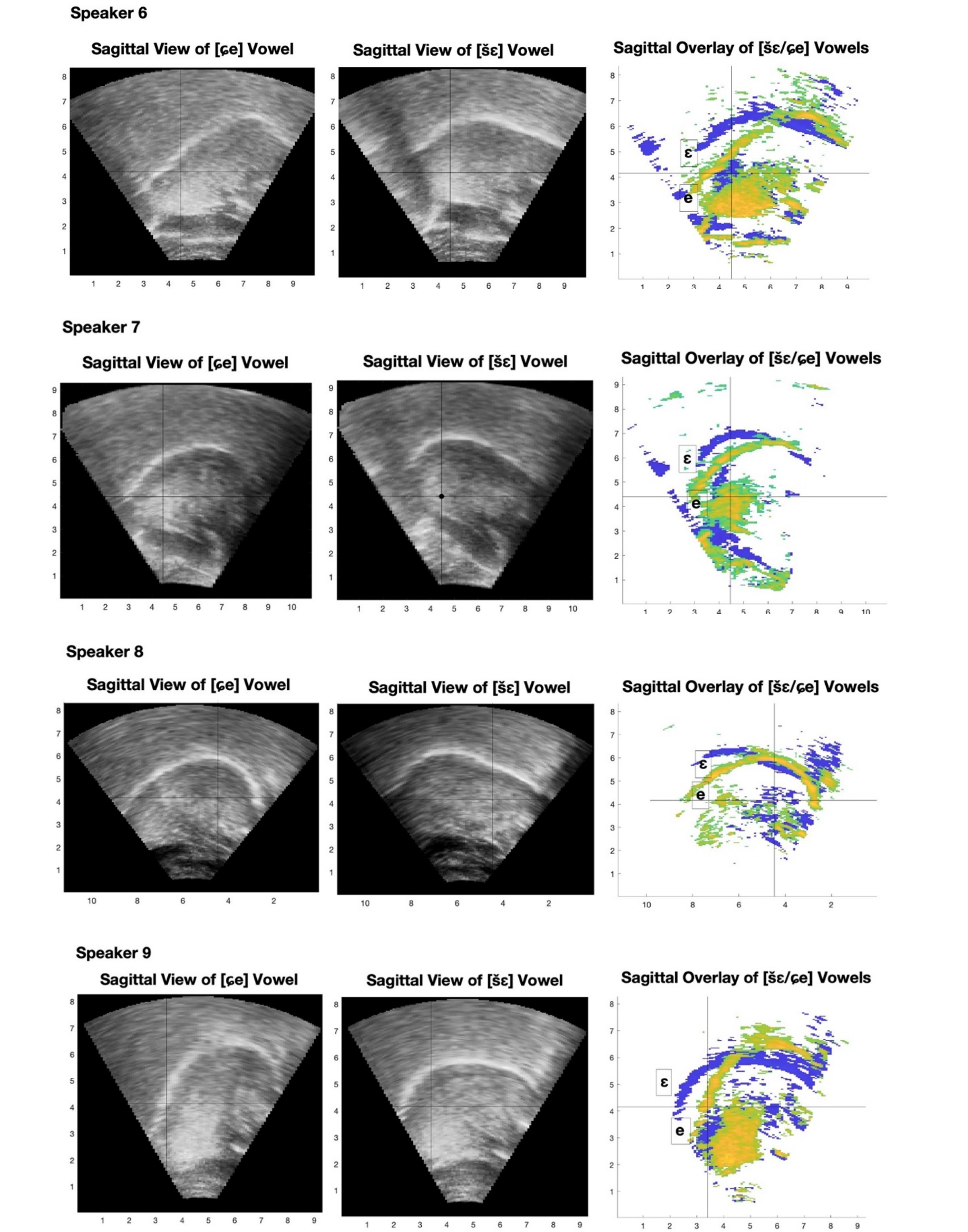
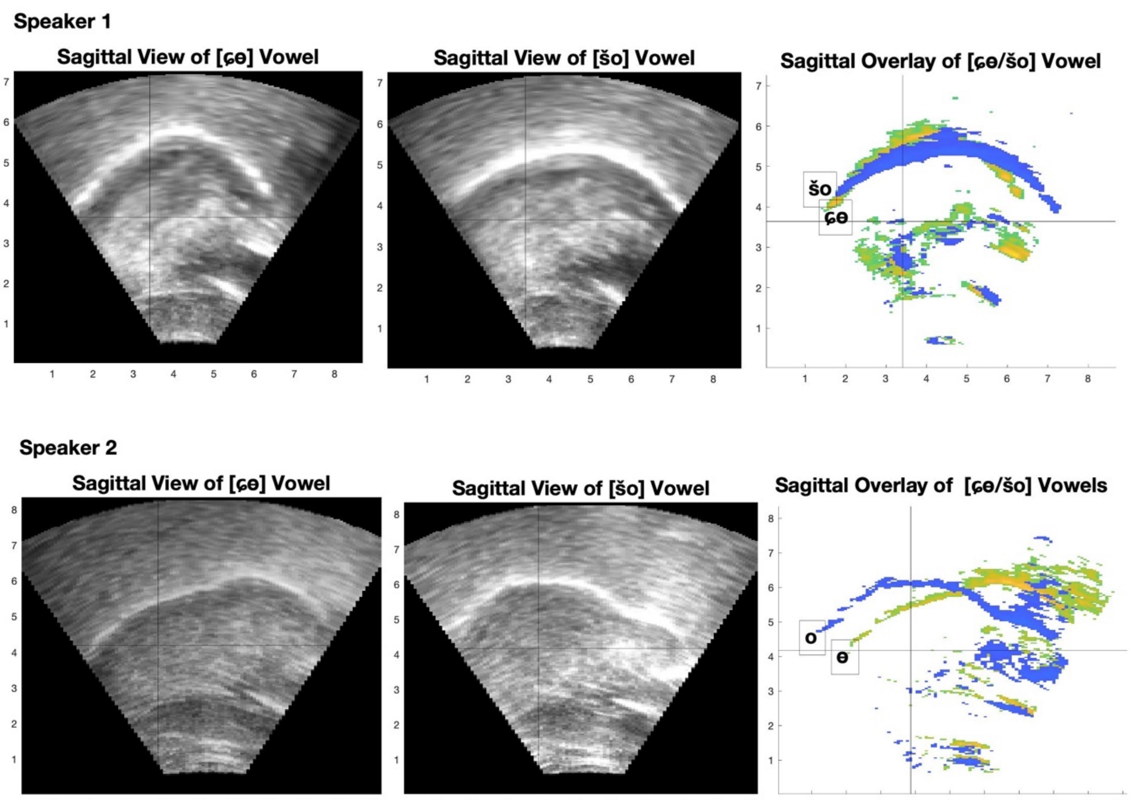


Figure 10: Raw ultrasound images for SCC [e] (left), and HCC /ɛ/ (center), both in a stressed syllable, and TaO images (right) of the corresponding vowels for Speakers 1–9. Front of the oral cavity is on the right of the pictures.

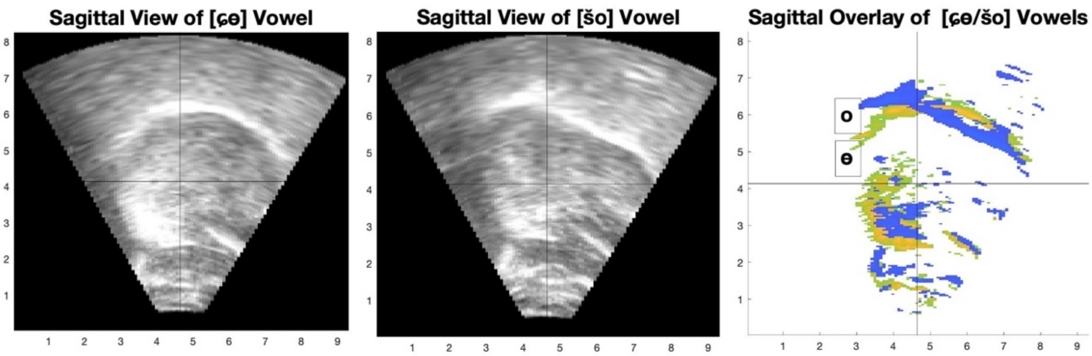
Tongue dorsum raising in the SCC is not consistent, with Speakers 1, 2 and 9 raising /ɛ/ in the SCC and Speakers 7 and 8 – instead lowering it, cf. TaO images in Figure 10. There is occasionally no substantial fronting of the tongue dorsum, e.g., Speakers 1, 3, 5 (cf. also Figure 13). Actually, Speakers 1, 7 and 9 show more advancement of the tongue root (given the way we identified the points on the surface of the tongue root and dorsum that we compared) than fronting. For the remaining cases there is roughly as much fronting of the dorsum as advancement of the tongue root. The advancement of the tongue root is a consistent feature of /ɛ/ in a SCC.

3.2.4 Mid back vowels

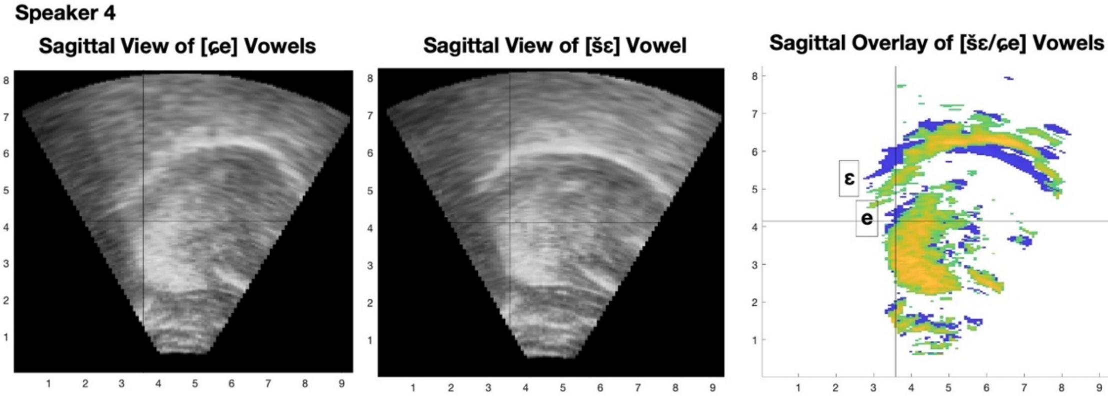
Koneczna & Zawadowski (1956) observe a narrowing of the pharyngeal cavity for the HCC vowels. They observe also an inverse correlation between the amount of the lip rounding and narrowing of the pharyngeal cavity and explain this as an alternative strategy to prolong the oral cavity (p. 22). For the soft consonant context, Koneczna & Zawadowski (1956) observe different levels of raising and fronting of /o/ for the two speakers from whom they collected the data. For one speaker in their study the tongue is only minimally fronted with an observable effect of the relative enlargement of the pharyngeal cavity (p. 22). Cavar et al. (2018) similarly argued that various strategies in the articulation of HCC vowels in Polish all serve the purpose of expanding the oral cavity as opposed to expanding the pharyngeal cavity in the SCC. Figure 11 depicts /o/ allophones in the context of /ɕ/ and /š/, respectively. For the posterior consonant contexts depicted, only Speakers 1 and 9 show some raising of the dorsum in the back mid vowel. All other speakers show no raising (less than 0.2cm, thus, judged to be in the error range) or even lowering (in Speakers 3, 7). All Speakers (and in all realizations) have both the fronting of the tongue dorsum and advancement of the tongue root.



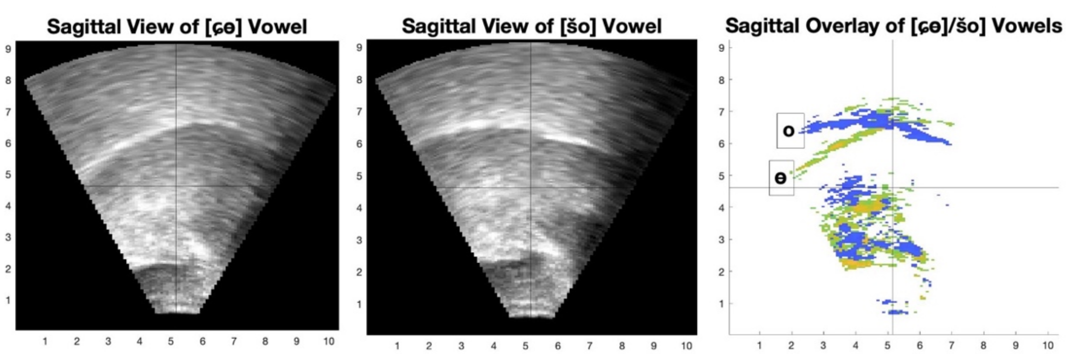
Speaker 3



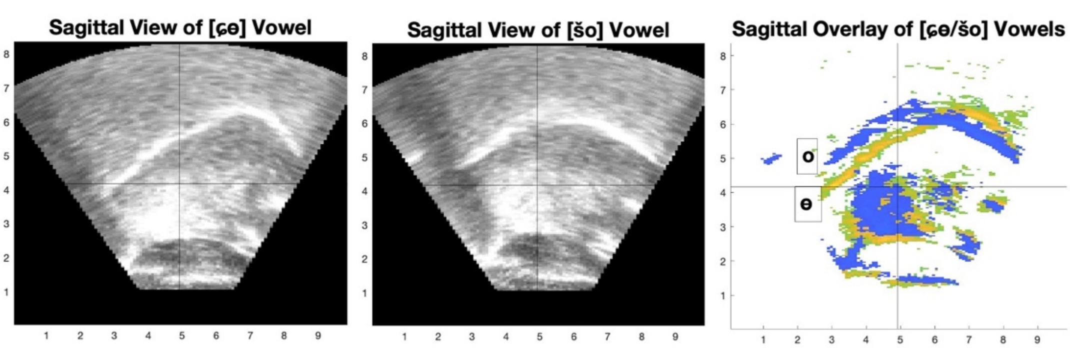
Speaker 4



Speaker 5



Speaker 6



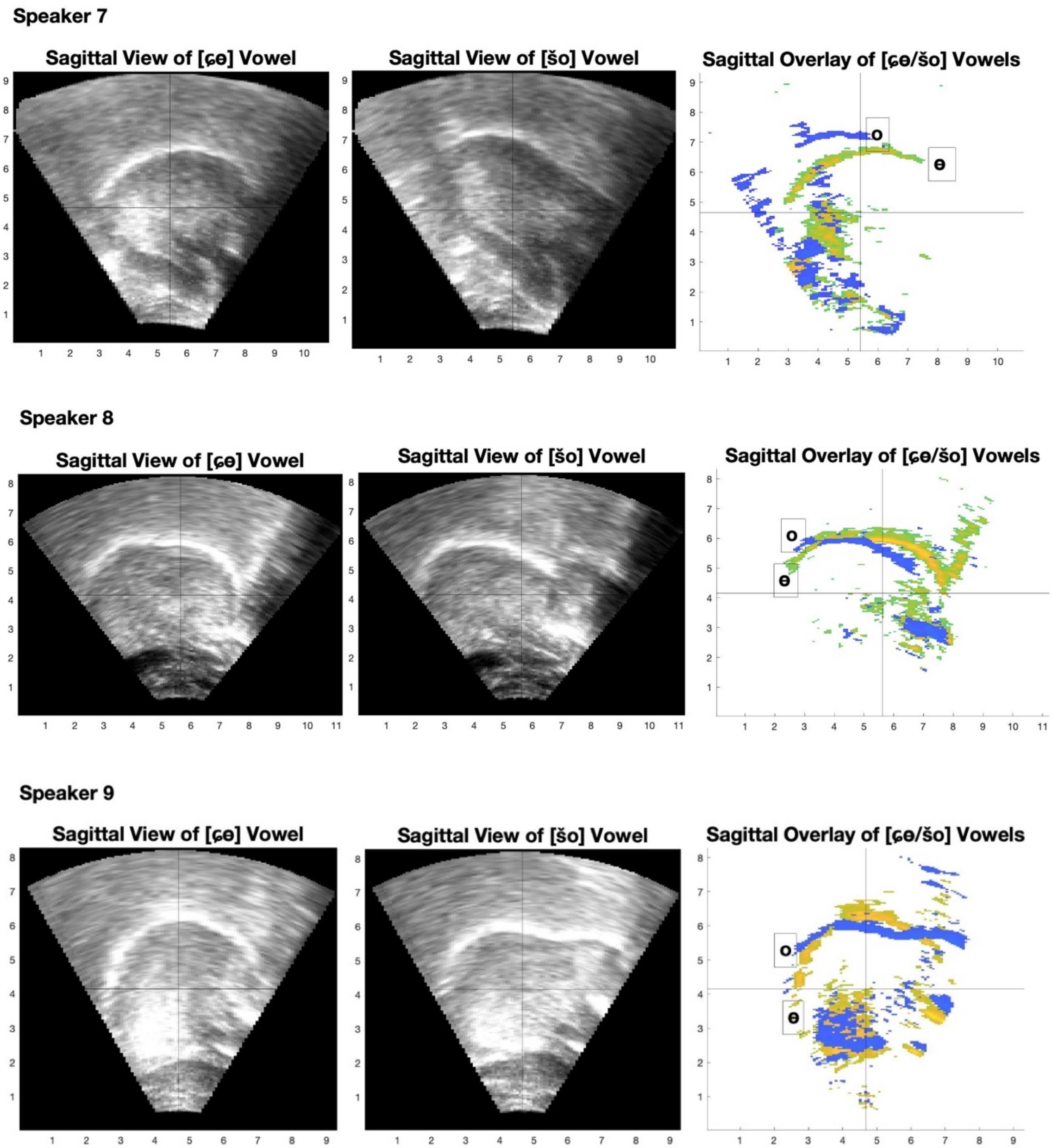
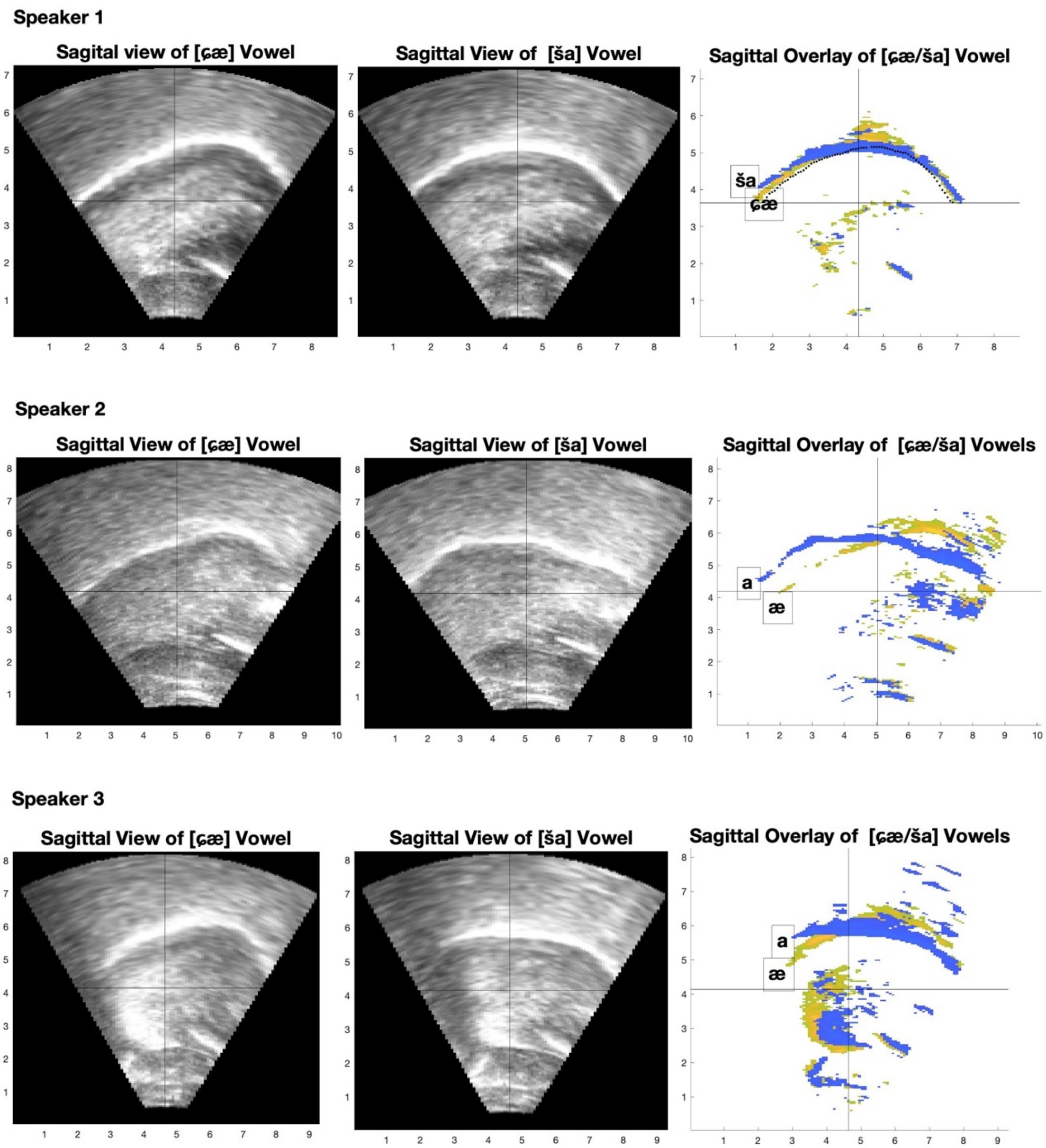


Figure 11: Raw ultrasound images for SCC [ɵ] (left), and HCC /o/ (center), both in a stressed syllable, and TaO images (right) of the corresponding vowels for Speakers 1–9. Front of the oral cavity is on the right of the pictures.

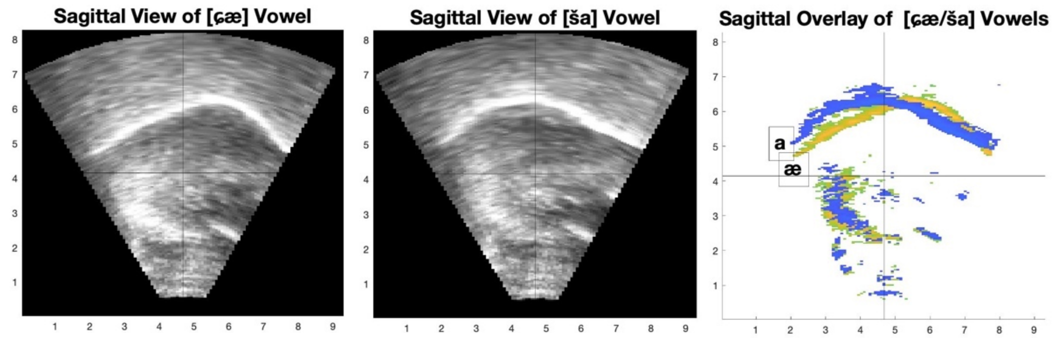
3.2.5 Low back vowel

There is phonemically only one low vowel in Russian, so the expectation might be that the fronting in the SCC would be more extreme than for other vowel allophones. Hamilton (1986) describes /a/ in the SCC as front [æ], while other back vowels in his account are in the same context fronted only to the central area. Koneczna & Zawadowski (1956) based on images from 4 speakers describe /a/ in a SCC as a central or even front vowel. They observe tension in the post-dorsal area for /a/ in the SCC and shifting of the whole tongue, including the tongue root, away from the pharyngeal wall, with raising of the hyoid bone, epiglottis and larynx (p. 17). They observe also more raising of the velum than in isolation or in the HCC (p. 18).

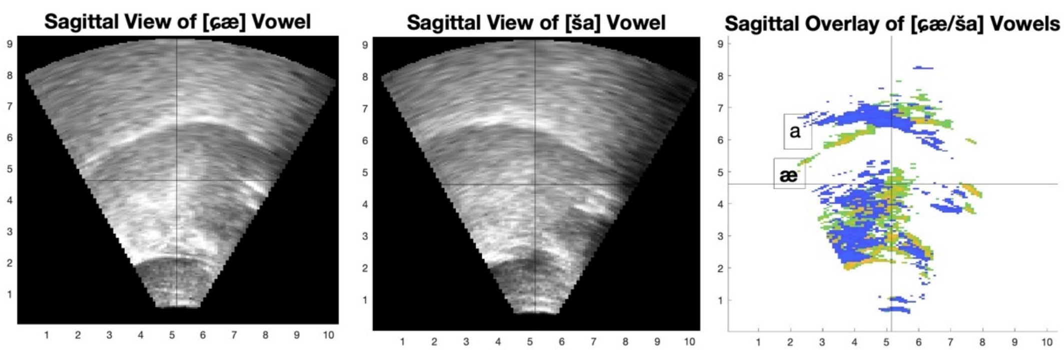
The study has confirmed Koneczna & Zawadowski's (1957) observation about the expansion of the pharyngeal cavity. This effect is very systematic. Also, fronting of the tongue dorsum for /a/ is more consistent than for other vowels (Figure 12). Some raising (0.2-0.3cm) is shown in Speakers 2, 3 and 9. The reminder of the speakers show no raising (Speakers 4, 5, 6, 8) or minimal lowering (Speaker 7). All speakers exhibit both fronting of the dorsum and advancement of the tongue root. The tongue root effect is slightly bigger than the effect of the dorsum fronting in Speakers 5 and 7. The dorsum effect is slightly bigger than the tongue root effect in Speakers 1, 2, 3, and 4. The remaining speakers have approximately as much dorsum fronting as tongue root advancement.



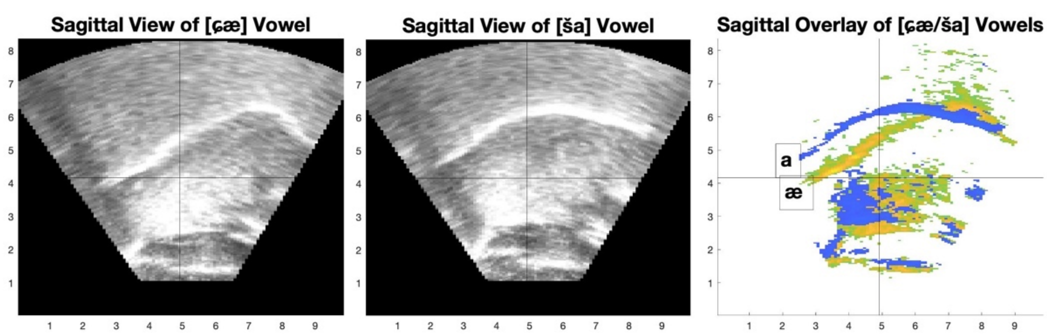
Speaker 4



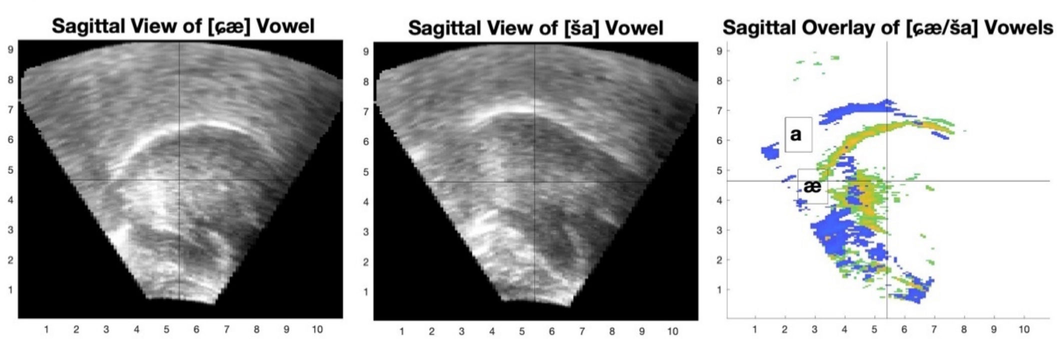
Speaker 5



Speaker 6



Speaker 7



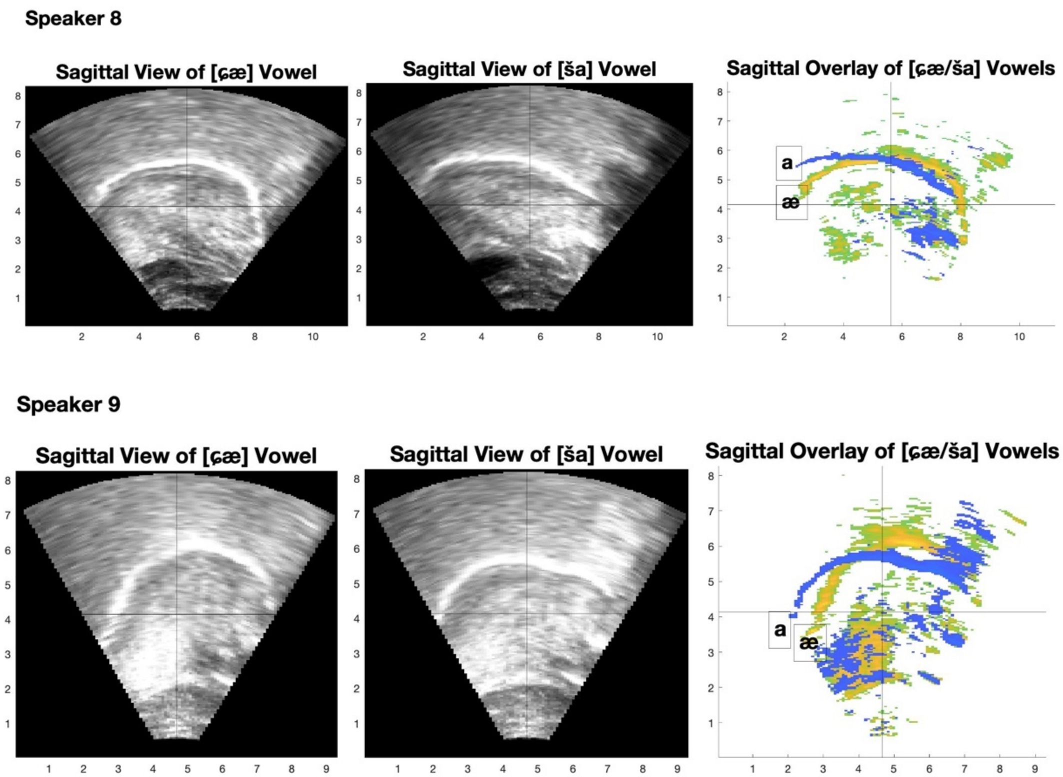
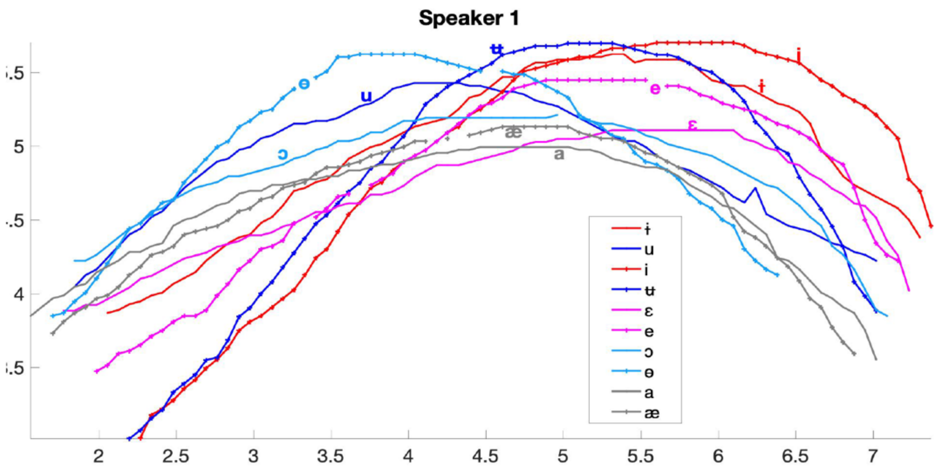


Figure 12: Raw ultrasound images for SCC [æ] (left), and HCC [a] (center both in a stressed syllable, and TaO images (right) of the corresponding vowels for Speakers 1–9. Front of the oral cavity is on the right of the pictures.

3.3 Comparison of vowels within individual speakers

Manually-drawn midsagittal tongue contours from each SCC and HCC vowel are shown for each speaker in Figure 13.[12] We show the contexts of inherently palatalized /ɕ/ and inherently hard /š/, where the softness quality of the consonant always overrides whatever palatalization effect a front vowel might trigger. Impressionistically, the area of the dorsum is for most speakers more crowded than the area of the tongue root (cf. especially Speakers 4 and 6). The overwhelming majority of SCC vowels show an effect on tongue dorsum. Lower SCC vowels tend to strongly raise the tongue dorsum (in comparison to the HCC counterparts) and back SCC vowels tend to strongly advance the dorsum; in many cases some degree of both fronting and raising of the dorsum can be observed. Crucially, underlying front vowels are not systematically realized as back in the context of the inherently hard /š/ and underlying back vowels do not systematically become front when following an inherently soft /ɕ/. In contrast, all speakers produced SCC vowels with a relative advancement of the tongue root in comparison to the HCC vowels. While the difference between the tongue root position for the pairs of vowels is systematic, front vowels in general (both SCC and HCC) tend to have a more advanced tongue root than back vowels and high vowels (both SCC and HCC) are produced with more tongue root advancement than lower vowels.

[12] The tongue contours in Figure 13 represent individual ultrasound frames from the first repetition, unless the first repetition was not recorded, or the image quality was poor. If the first repetition could not be used, the second repetition was used.


Speaker 1
ɨ
u
i
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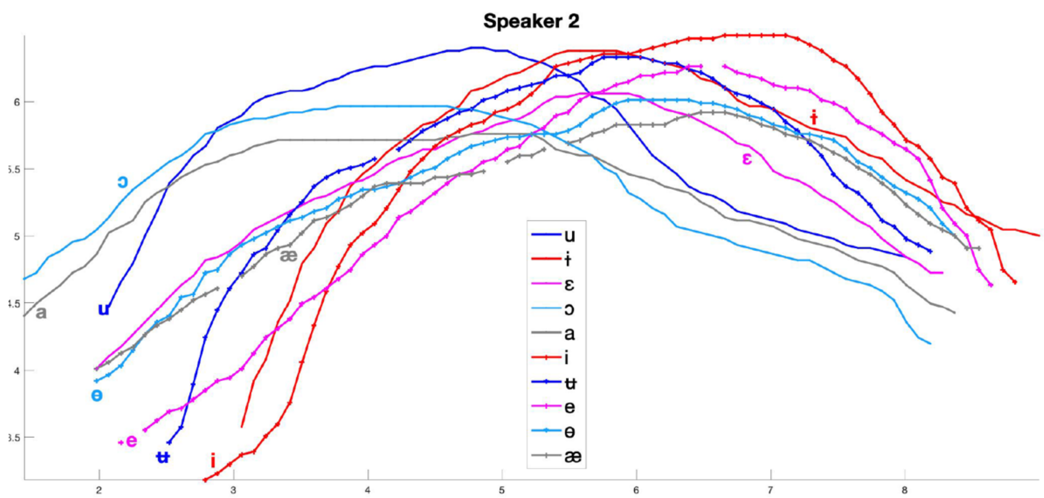
Speaker 2
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a
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ɵ
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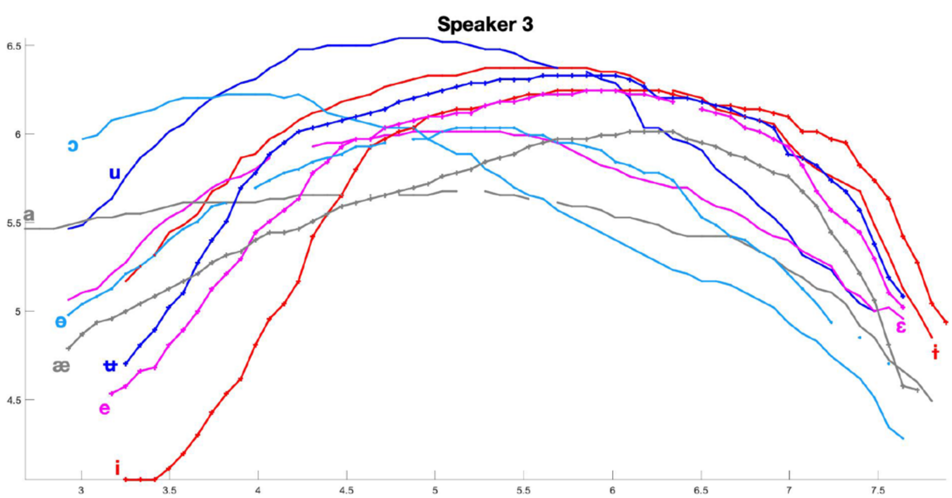
Speaker 3
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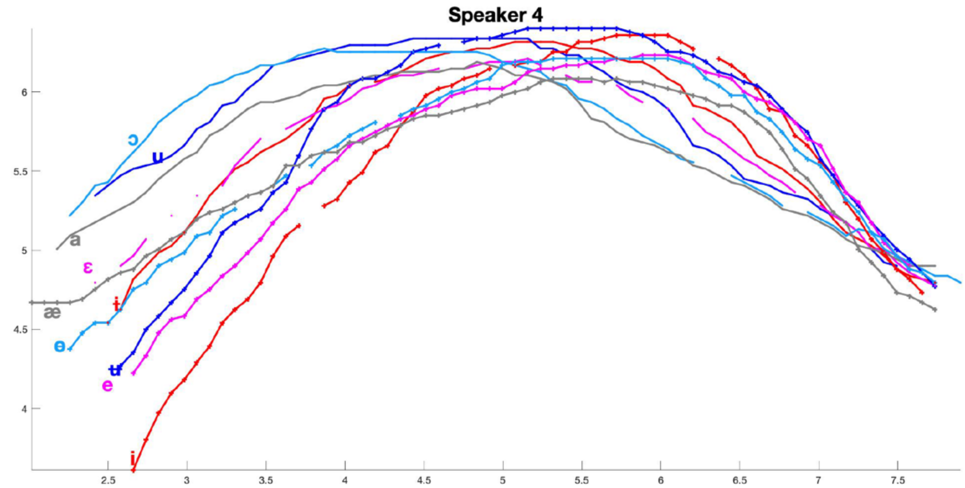
Speaker 4
ɔ
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e
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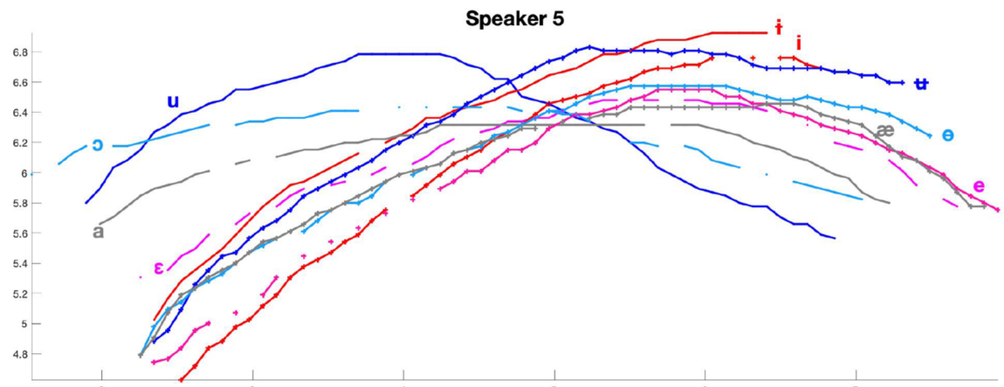
Speaker 5
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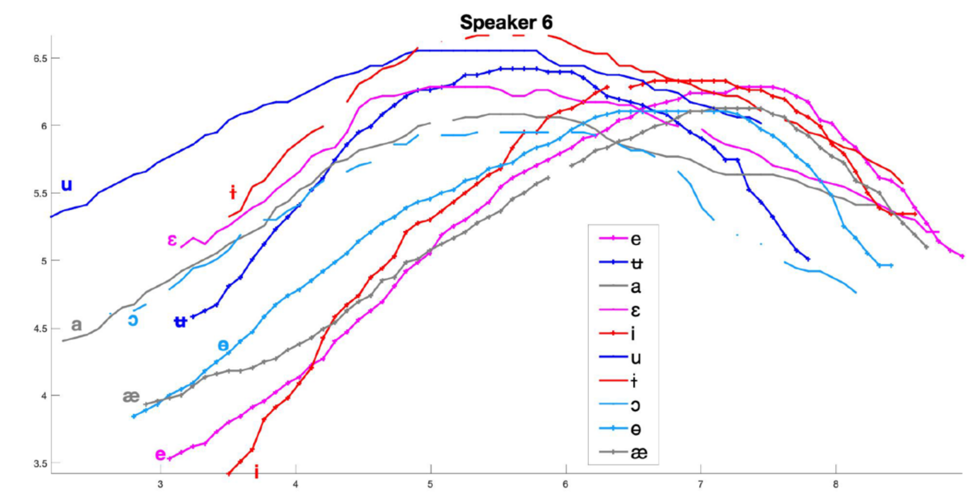
Speaker 6
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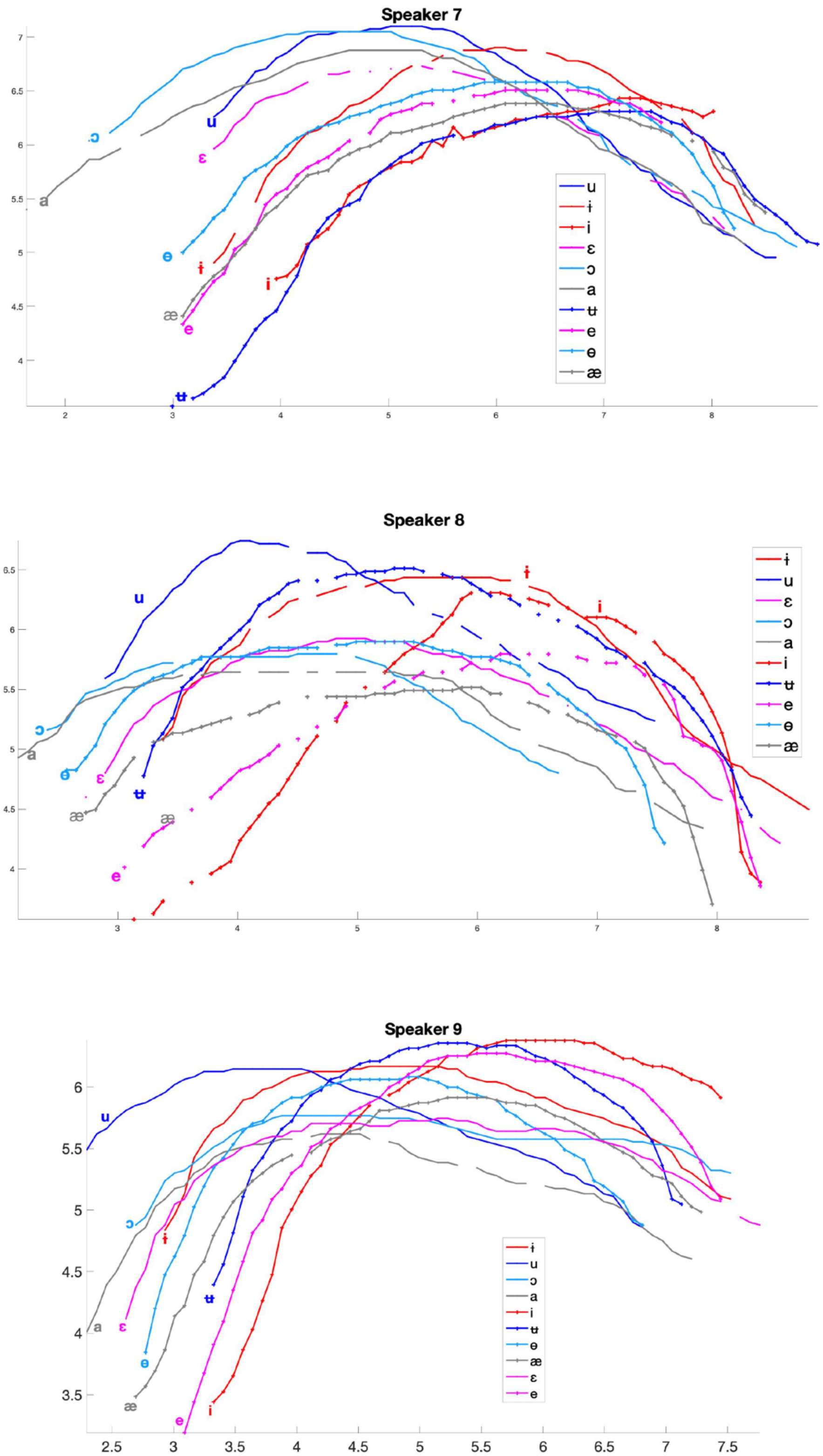

Figure 13. Overlaid tracings of the tongue surface in the bilateral posterior consonant context (/š/ versus /ɕ/). The front of the oral cavity is on the right. The tracings of SCC vowels are marked with small crosses. Back vowels: shades of blue. Front vowels: red and pink. Low vowels: grey

In Speaker 1, the position of the tongue dorsum in /u/ is substantially advanced and becomes similar to /ɨ/. However, the SCC /u/ is articulated with the tongue root substantially advanced in comparison to /ɨ/. SCC /u/ has also an identical position of the tongue root to SCC /i/. /o/ and /a/ do not front as much but both raise 'by one height level', that is, to a position comparable to high vowels in case of SCC /ɔ/ and to a position comparable with mid vowels for SCC /a/. Neither SCC /o/ nor SCC /a/ show much fronting. Crucially, SCC allophones do not all merge, and they do not merge with either /i/ or /ɨ/.

In Speaker 2, we observe a substantial fronting of all SCC. SCC [ɵ]and [æ] merge in the typical mid front vowel area, with the dorsum position somewhere between [e] and [ɛ], and with the tongue root position as for [ɛ]. SCC [ʉ] merges with HCC [ɨ] in the dorsal area, though the tongue root still differentiates them (/ɨ/ is more advanced in terms of the tongue root than [ʉ]). HCC [o] and HCC [a] are also very similar, both in the position of dorsum and tongue root.

Speaker 3 shows merging of SCC [ʉ, e] with SCC [i], especially in terms of the position of the dorsum. They still differ in the tongue root, with [i] more advanced than either [ʉ] and [e]. SCC [ɵ] merges with HCC [ɛ].

For speaker 4, all SCC vowels except for [æ] merge with SCC [i]. SCC [æ] is fronted and raised but not as high as [i]. As for the comparison of the SCC back vowels with HCC front vowels, in the high vowel area [ʉ] is similar to [ɨ] in the position of the dorsum but in the position of the tongue root it patterns closer to [e].

For speaker 5, [ʉ] merges with [i], while [ɵ] and [æ] merge with [e] in terms of the dorsum position. Furthermore, all SCC vowels cluster in terms of the position of the tongue root.

Speaker 6 shows a different strategy. [ɨ] and [ɛ] seem to be retracted to the back vowel area (comparable with HCC [o]). All SCC except for [ʉ] seem to merge with [i]. SCC [ʉ] remains in the high back vowel area, with the only difference between [u] and [ʉ] in the tongue root position.

For Speaker 7, [ʉ] merges with [i], [ɵ] and [æ] merge with [e]. [ɨ] is similar to the [ɵ]/[æ]/[e] cluster but shows more raising. On the other hand, mid [ɛ] patterns very close to [u]. A mid HCC /o/ is retracted more than HCC /u/ (and HCC /e/).

For Speaker 8, vowels remain relatively distinct with the exception of [ʉ], which approximates the position of [ɨ]. [ɵ] is still a back vowel and no relative raising is observed. [æ] is slightly fronted and raised but does not merge with front vowels. For this speaker, like for Speaker 7, [ɛ] is a vowel that is strongly retracted in a HCC.

Speaker 9 articulates SCC vowels relatively fronted and relatively raised in comparison to their HCC counterparts. Vowels all differ though the differences are small, in particular if we look at the dorsum. SCC /i, u, ɛ/ seem to cluster with respect to the position of the dorsum. HCC /ɨ/ and SCC /o/ are similar in terms of the shape and position of the dorsum, although the tongue root for HCC /ɨ/ is more retracted than for SCC /o/. SCC /a/ is similar to HCC /e/ in terms of the tongue dorsum and they differ in terms of the tongue root.

4 Discussion

Russian vowel allophony is triggered by the presence/absence of softness in the preceding consonant. It is not unreasonable to assume that the feature responsible for the variation in Russian vowels is the same feature that differentiates between soft and hard consonants in Russian. In the current study, we looked at the systematic articulatory correlates of the difference in softness realized across vowels/speakers/contexts. Softness in consonants – or palatalization – is traditionally expressed in terms of the SPE features [+high, -back]. The raising of the part of the tongue to the height characteristic of high vowels has been interpreted as a correlate of the feature [high]. The retraction of the place of maximal constriction along the front-back axis is interpreted as the correlate of the feature [back]. Apart from the effect on the tongue dorsum, we have observed also a systematic advancement of the tongue root in SCC, which can potentially be interpreted in terms of feature [ATR].

In Halle's (1995) feature geometry approach, both [high] and [back] hang off the Dorsal node, so palatalization could potentially be represented as spreading of [+high] as in Figure 14a, spreading of [-back] as in Figure 14b, or spreading of the whole Dorsal node, i.e., combined fronting and raising of the tongue dorsum, or the advancement of the tongue dorsum, as in Figure 14c.

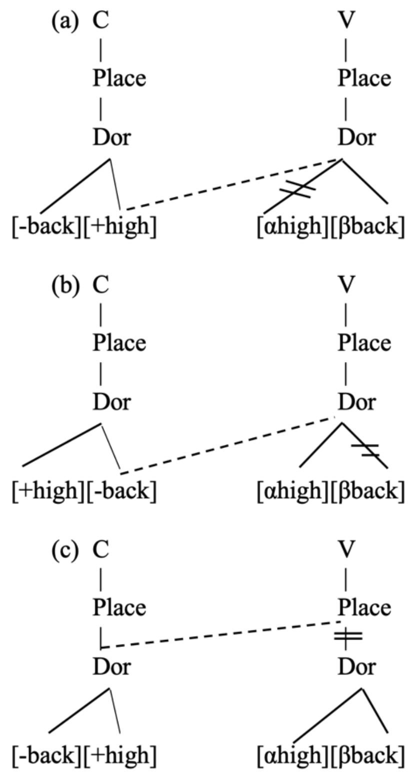

Figure 14: Potential effect of palatalized consonants on vowels under Halle's (1995) feature geometry

Clements & Hume (1995) and Hume (1992) offer an alternative feature geometry. Assuming that Coronal can be interpreted as a relative frontness of the maximum constriction, this model yields different predictions concerning palatalization only in cases which involve differences in the primary place of articulation (e.g., [k] vs. [ʃ], or [k] vs. [tš]). Since our study focused on cases of secondary palatalization (e.g., [t] vs. [tʲ], or [k] vs. [kʲ]), the two approaches yield equivalent results, with Halle's [-back] and [+high] functioning respectively like [Coronal] and [open] under the V-Place node in Clements & Hume (1995). Without making theoretical commitments, therefore, we adopt Halle's approach in the following discussion.

We want to stress again that while we assume phonological features must be abstract categories, we also believe that phonological features have phonetic correlates, and that these correlates, when systematically realized, can inform us about the nature of the abstract features themselves. This follows a long line of research in phonological feature theory, starting from Jakobson & Halle (1956), Chomsky & Halle (1968), and Halle (1983). With this in mind, we now turn to the examination of each of the potential analyses represented in Figure 14, followed by our proposed analysis that the softness distinction in Russian is driven by the feature [ATR].

4.1 Spread of [+high] alone

Our measurements revealed that raising of the tongue dorsum is not a consistent characteristic of SCC vowels. One of the reviewers points out that the upper portion of the vocal tract – which ultrasound does not image – is a curved surface, and so fronting may require lowering in some cases (for example) for reasons having to do with the shape of the palate rather than a lingual target as such. If raising is compromised to achieve fronting, this further supports the analysis that raising is secondary to fronting. Lacking raising as a systematic correlate, [+high] by itself, as in (14a), is not likely to be a 'softness'/palatalization feature. There is an obvious phonological argument in support of this finding, namely, only one of the three [+high] vowel phonemes (/i/, but not /ɨ/ or /u/) acts as an obligatory trigger of palatalization in preceding consonants in Russian, e.g., [dʲima] male name, but [dɨm] 'smoke', [duma] 'representative assembly'. At the same time, a non-high vowel /e/ triggers palatalization in the preceding consonant, e.g., [vodʲ+e] 'water' Loc.sg.

4.2 Spread of the Dorsal node

The traditional approach, going back to SPE, is that both raising ([+high]) and fronting ([-back]) of the tongue dorsum constitutes the best featural characterization of palatalization. In Halle's (1995) feature geometry, both features are under a single Dorsal node. If two or more features spread in a phonological process, they must be exclusively dominated by a common node. In the case of the features [high] and [back], the Dorsal node would have this function. Spreading of the whole node implies, however, that all of the features dominated by this node should spread together without exception. In other words, in a soft consonant context, vowels should all assume the tongue body position of /i/ (or of /ɨ/ if we accept that /ɨ/ is front), cf. (13c), neutralizing contrasts between vowels in SCC altogether. We can therefore reject the spread of the Dorsal node.

4.3 Spread of [-back] alone

Based on our measurements, the analysis represented by (13b) remains viable as long as the vowel /ɨ/ is not a front ([-back]) vowel. Under this condition, consonantal secondary palatalization and vowel softness allophony can be accounted for as an interaction of (under)specification and spreading of [-back]. Specifically,

Rule 1a. [Ø back] C → [-back] / __ [-back] V
Rule 2a. V → [α back] / [α back] C __

Rule 1a stipulates that vowels specified as [-back], i.e., /i/ and /e/, spread [-back] to a preceding consonant that is unspecified for the feature [back]. Thus, the vowels /i/ and /e/ cause consonants such as /p/, /t/, and /k/ which are neither inherently palatalized nor inherently hard, to become palatalized. Under this analysis, the vowel /ɨ/ must not be [-back], or it would also trigger palatalization. Rule 2a stipulates that consonants inherently specified for [back], such as [-back] /ɕ/ and [+back] /š/, spread their specification for [back] to a following vowel. In other words, consonants underspecified for palatalization, like /p/, /t/, and /k/ do not cause fronting or retraction of a following vowel, while [-back] /ɕ/ and phonemically palatalized stops such as /pʲ/, /tʲ/, and /kʲ/ and [+back] /š/ (as well as hard /ž/ and /ts/) drive the observed vowel allophony. Further, a sequence of an unspecified consonant followed by an unspecified vowel will be rendered as non-palatalized by a phonetic default.

The prediction of this account is that /i, e/ should always surface as back vowels after inherently hard consonants, and /u, o, a/ should always surface as front vowels after inherently soft consonants. However, these effects are unsystematic and gradient for both allophonic as well as the phonemic vowel pairs, as demonstrated in Section 3.3, which casts serious doubt about the viability of this scenario.

4.4 Spread of [+ATR]

The analysis in terms of [ATR] has received support from this study in that we observe systematic advancement of the tongue root in SCC vowels.[13] Although the analysis represented by (14b) perhaps

[13] Another commonly assumed correlate of [ATR], pharyngeal expansion can be inferred from the advancement of the tongue body, although it cannot be directly evaluated as the images do not show the back wall of the pharyngeal

remains viable if we reject the arguments in the previous section, we propose that there are several more reasons why spreading of the feature [+ATR] is a superior analysis. These reasons are drawn from phonological, as well as articulatory and physiological considerations.

4.4.1 Phonology

If the palatalization feature is [+ATR] and /ɨ/ is [-back, -ATR] the vowel inventory of Russian is fully symmetrical and we can account for *all* the vowel effects triggered by softness using the same mechanism, see Table 5.

Table 5: Vowel inventory with [+/-back]

	[-back]		[+back]	
	[+ATR]	[-ATR]	[+ATR]	[-ATR]
[+high]	/i/	/ɨ/	[ʉ]	[u]
[-high, -low]	[e]	[ɛ]	[ɵ]	[o]
[+low]	[a̟]			[a]

In contrast, the assumption that the dimension of contrast between /i/ and /ɨ/ is frontness of the dorsum renders a less symmetric vocalic inventory, cf. Table 6. Under this scenario, it is necessary to invoke the feature [+/-round] to distinguish between /ɨ/ and /u/ but also it is impossible to provide a systematic account for all vowel effects. In particular, distribution of /i/ versus /ɨ/ would be accounted for in terms of [+/- back]. This option is not available for mid vowels, where the allophones adjust in terms of [ATR] but not necessarily in terms of [+/- back]. Consequently, the same process would have to have two different accounts not because the mechanism is different but because of the network of distinctions in which a given vocalic phoneme participates.

Table 6: Vowel inventory with [+/-back] and [+/-round]

	[-back]		[+back]	
	[+ATR]	[-ATR]	[+ATR]	[-ATR]
[+high, -round]	/i/		/ɨ/	
[+high, +round]			[ʉ]	[u]
[-high, -low]	[e]	[ɛ]	[ɵ]	[o]
[+low]	[a̟]		[a]	

Furthermore, a specification [-back] for /ɨ/ would provide a more direct relationship between its phonological specification and its phonetic implementation. But if /ɨ/ is [-back], then [-back] is not likely to be a palatalizing feature, since /ɨ/ does not trigger palatalization in preceding consonants.

The proposed phonological analysis can be understood as an interaction of (under)specification and spreading of [+ATR]:

Rule 1b. [Ø ATR] C → [α ATR] / __ [α ATR] V
Rule 2b. V → [α ATR] / [α ATR] C __

We propose that the feature [+ATR] is the palatalizing "softness" feature in Russian, and that this is the specification of the phonemically palatalized consonants, the soft fricative /ɕ/, and the vowels /i/ and /e/. Further, we propose that /š/ (and other inherently hard consonants) and /ɨ/ are specified as [-ATR], and that consonants which are not inherently palatalized and the vowels /a/, /o/, and /u/ are underspecified for [ATR]. The feature [+ATR] is not meant to replace [-back] in vowels. The specification in terms of [+/-back] is

cavity. It is assumed here that a systematic advancement of the tongue root is alone sufficient to indicate a specification of a segment as [+ATR].

still necessary in the proposed system to distinguish between vowels. For instance, we argue that the vowels /i/ and /ɨ/ are both front ([-back]) and they differ in the value of [ATR]. On the other hand, [+ATR] effectively substitutes [-back] in the function of the palatalization feature in phonetically soft consonants.

Rule 1b stipulates that vowels specified for [ATR] spread their specification to an underspecified preceding consonant. Thus, /i/ and /e/ trigger palatalization in a preceding underspecified consonant, while /ɨ/ and the remaining vowels do not. Notice that this result is independent of the question whether /ɨ/ is [-back] vowel or not. Rule 2b stipulates that consonants specified for [ATR] spread their specification for [ATR] to a following vowel, thus driving the observed vowel allophony. Notice that Rule 2b allows hard consonants (e.g., /š/) to override the specification of /i/ and /e/, thus disallowing the sequences /š/+/i/ and /š/+/e/. For the sequences of an underspecified consonant followed by an underspecified vowel, a default would yield a sequence without palatalization.

4.4.2 Articulation

Articulatorily, our measurements suggest that an analysis of the observed vowel distribution in terms of [ATR] is superior to an analysis in terms of [-back]. Two observations are pertinent. First, although the tongue dorsum fronting and advancement measures were, on average, slightly larger than the tongue root advancement measure (means: TDx = 1.23cm; TDA = 1.28cm; TRA = 1.04cm), there was also greater variability in the two tongue dorsum measures, across vowels (cf. Figure 6), across consonants (cf. Figure 7), and overall (standard deviations: TDx = 0.68cm; TDA = 0.68cm; TRA = 0.55cm).

Further, consider the "hard" versions of front vowels in contrast to the "soft" versions of back vowels at the same height, i.e., SCC /u/ vs. HCC /ɨ/, and SCC /o/ vs. HCC /e/. The proposed [ATR] analysis suggests that the tongue root should be more advanced for the soft [u] and [o] than for the hard [ɨ] and [e]. Similarly, the analysis of 14(b) suggests that the tongue dorsum should be more advanced for the soft [u] and [o] than for the hard [ɨ] and [e]. Indeed, all three measures (TRA, TDA, TDx) showed more advancement/fronting in the soft [u] and [o] than in the hard [ɨ] and [e]. However, the effect of TRA (-0.34 cm) was more than two times larger than the effect of TDA (-0.14 cm) and TDx (-0.16 cm). All three measures had roughly equal variability (standard deviations: TRA = 0.63 cm; TDA = 0.65 cm; TDx = 0.58 cm). The TRA effect size was significantly greater than the effect of either TDA or TDx, according to two-sample t-tests ($p<0.003$). Furthermore, the TDA and TDx effect sizes were not significantly different than zero, while the TRA effect was (one-sample t-tests; TDx, $p > 0.039$; TDA, $p > 0.1$; TRA, $p < 0.001$; $\alpha = 0.05/3 = 0.0167$). Tongue root advancement is therefore a more consistent phonetic correlate of the soft vowels in contrast to the hard vowels, than either of the two tongue dorsum gestures.

One of the reviewers asks why the consistency of the effect would be an argument for favoring one or the other analysis. One observation would be that variation is commonly assumed to be a necessary prerequisite for language change. Thus, smaller variation can be taken to be a sign of a stable phonological system and of a strong link between the phonological abstract representation and its phonetic realization. Further, studies in psychology show that pattern recognition is a general cognitive strategy crucial for associative learning, categorization or even decision-making. For example, Wang et al. (2016) demonstrate that participants in a behavioral study fail to utilize more valid information within an inconsistent task structure. Patterns showing more variation are probably more difficult to learn. In the area of language, Kuhl (2000) calls the detection of similarities, or patterns, in language input a major requirement of language processing. Consequently, it is probably not far-fetched to claim that consistent articulation patterns are more likely to reflect phonological categories and less consistent articulation pattern are likely to be an enhancement, rather than the other way round. According to Anttila (2018), "Variation means that one meaning corresponds to multiple forms…. Phonological variation is a situation where the choice among expressions is phonologically conditioned, sometimes statistically, sometimes categorically." Dispersion is a related concept, and both variation and dispersion are clearly about the distribution of linguistic elements in the universe of linguistic objects, the variation refers to intra-category distribution, while dispersion refers to inter-category distribution. We refer to the former rather than the latter.

In the past, variation in phonological data that was not determined by phonological context was considered problematic and anomalous in generative grammar. Early attempts to address variation in the grammar referred to optional rules, multiple grammars of an individual speaker, or the stratification of the lexicon (Ito & Mester 1995, Anttila 2006). Classical generative approaches looked at language as a phenomenon internal to the speaker, and inter-speaker variation was consequently of no concern. On the other hand, Labovian approaches to investigating sociolinguistic variation have brought inter-speaker variation into sharper focus. The newer stochastic and probabilistic Optimality Theoretic approaches, such as, e.g., Boersma (1998), Boersma & Hayes (2001), Hayes (2008), Pater (2016), or usage-based models (Bybee 2001), can be informed by corpus data and include variation and frequency as a factor in forming individual grammars. Thus, the concept of variation has gained some ground in comparison to early generative approaches. Research on phonological variation thus far has generally begun with the a priori underlying category and ended with observations and explanations of the surface variation within the category. We take the opposite approach in this paper – from an examination of surface variation, we attempt to predict the categories.

The discussion we start here goes far beyond the scope of the current paper. The standard deviation values that we report conflate the intra- and inter-speaker-variation. Standard deviation measures presented in this paper are obviously not the only way to measure variation. The obvious way to follow-up is to test different variation measures, to test the effect on a larger set of data, and to test the variation measures as predictors for other phonological contrasts.

4.4.3 Physiology

Physiologically, we may account for the observed facts rather straight-forwardly on the basis of an analysis in which [+ATR] drives both consonant palatalization and vowel soft/hard allophony. If the feature [+ATR] has as its articulatory phonetic correlate the advancement of the tongue root, this may be accomplished merely by contracting the posterior genioglossus (GGp) muscle, cf. Figure 15. The GGp is a relatively strong muscle with good mechanical advantage for advancing the tongue root, as reflected in the following characteristics. First, the GGp contains a large proportion of large-diameter, slow-twitch muscle fibers (Saigusa et al. 2004, Stål et al. 2003; Zaidi et al. 2013; Sanders & Mu 2013). Other muscles of the tongue also have larger proportions of large-diameter, slow-twitch muscle fibers in the more posterior parts of the tongue body (Sanders & Mu, 2013; Zaidi et al. 2013; Stål et al. 2003). Large-diameter, slow-twitch muscle fibers can generate large contractile forces, do not fatigue easily, but are relatively sluggish. Second, the GGp contains two sets of motor endplates, while most other parts of the genioglossus, the styloglossus and hyoglossus muscles, and verticalis muscle only have one (Mu & Sanders 2010). The superior longitudinal muscle contains multiple sets of motor endplates, and the transverse muscle contains two sets (Mu & Sanders, 2010). Motor endplates are the sites of contractile force generation, so a larger number of motor endplates results in a larger contractile force. Third, muscle fibers of the GGp are oriented nearly parallel to the line along which the tongue root advances (cf. Netter 2019). This gives the GGp a clear mechanical advantage over other muscles, such as the transverse, superior longitudinal, and inferior longitudinal.

These properties of the GGp partially explain its role in maintaining airway patency for breathing, since it has the ability to pull the tongue root away from the posterior pharyngeal wall without fatiguing, even when lying supine (e.g., while sleeping). A further consequence of tongue root advancement, however, is tongue dorsum advancement, as demonstrated by Jang (2018) and Buchaillard et al. (2009) using biomechanical models of the tongue. Tongue dorsum advancement during GGp activation is a consequence of the fact that the tongue is a muscular hydrostat and must preserve its total volume (Gilbert et al. 2007). Thus, it is no surprise to observe tongue dorsum advancement in a context where [+ATR] is the active feature.

On the other hand, other mechanisms for advancing the tongue dorsum (c.f. [-back] as a palatalization feature as in (13b)) appear to be less efficient. There are no extrinsic tongue muscles oriented in a direction capable of advancing the tongue dorsum (cf. Wood 1979 and references therein) – all extrinsic tongue muscles aside from the genioglossus are oriented to retract the tongue dorsum, i.e., hyoglossus, which pulls down and back; styloglossus, which pulls up and back; palatoglossus, which pulls up and slightly back. Intrinsic tongue muscles by themselves also appear incapable of advancing the tongue dorsum (cf. Figure 5 in Buchaillard et al. 2009). A combination of muscles other than the genioglossus may be capable of advancing the tongue dorsum in palatalized consonants and soft vowel allophones, but at the cost of efficiency. Furthermore, such a combination would almost certainly be focused on contraction of muscles around the anterior part of the dorsum, which are composed of weaker, less fatigue resistant, and less sluggish muscle fibers (Stål et al. 2003; Sanders & Mu 2013; Zaidi et al. 2013). Two considerations argue against such a mechanism for consonant palatalization and vowel softness in Russian. First, such a mechanism might preclude the need for tongue root advancement, and yet tongue root advancement is the most consistent articulatory correlate of vowel softness, and has the largest effect size in terms of hard front vowels vs soft back vowels. Second, a less sluggish and less fatigue-resistant mechanism would be less likely to exhibit either anticipatory or perseverative effects, whether those be characterized as gradient coarticulation or categorical feature spreading (cf. the proposal of Cavar & Lulich 2019, regarding the relationship of muscle fiber types and the features that participate in phonological harmony systems).

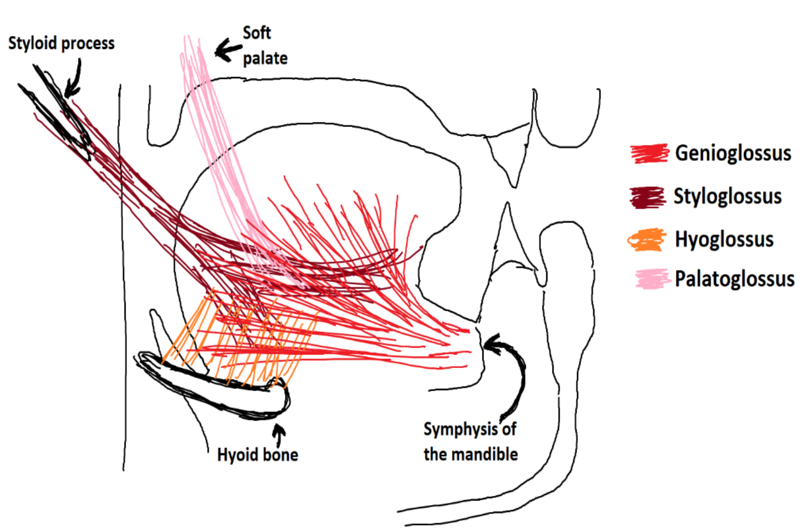

Figure 15: Extrinsic tongue muscles (cf. plate 70 in Netter 2019).

4.5 General discussion

These phonological, articulatory, and physiological arguments lead us to propose that both the phonemic and allophonic effects in Russian vowels can be accounted for in terms of the feature [ATR]. A consequence of this analysis is that the soft-hard distinction among consonants in Russian might also be better expressed in terms of [ATR] rather than [back] and/or [high]. While the feature [ATR] is usually used in reference to vowels, there is no a priori reason to exclude it from use in consonants as well (e.g., Halle & Stevens 1969; Trigo 1986; Vaux 1992, 1996; Cavar 2004, 2007; Lindau 1978; Rose 1996; Snider 1984; Hansson 2001; Beltzung et al. 2015; Lulich & Cavar 2019; Cavar et al. 2020).

Our proposed analysis is based on data from Russian vowels but evidence from other studies similarly demonstrates a prominent involvement of the tongue root in the articulation of palatalized consonants, notably in Polish (Lulich & Cavar 2019; Cavar et al. 2020), Russian (Matsui & Kochetov 2018), and Irish (Bennett et al. 2018). This cross-linguistic similarity recommends a reconsideration of palatalization processes, taking into account the role of the tongue root.

The reviewers raise the question of the correlation between [+ATR] and [-back] in palatalization and suggest at least two interpretations, one in terms of enhancement theory (e.g., Stevens & Keyser 2010), and another, in terms of the mechanical interdependence of physiological structures, which is the logic behind feature geometry (Sagey 1985, Halle 1995). Given the overwhelming physiological evidence, the latter approach seems to be justified. The resulting enhancement might be then a collateral, secondary effect. Consequently, the insight that the tongue root, together with the tongue dorsum, plays a role in palatalization should prompt a renewed discussion of the location of the [ATR] feature in feature geometry. Presented arguments support the placement of the [ATR] feature in a close proximity to the Dorsal node, perhaps as sister nodes under the Place node instead of [ATR] being a sister node of Laryngeal. At this point these are obviously stipulations and further research on the relation between voice features and tongue root features is necessary.

Another issue raised by reviewers relates to the acoustic correlates of palatalization. Palatalization has been defined in terms of F2 and F3 raising (Jakobson et al. 1952, cf. Kochetov 2006), while, as argued by the reviewer, pharyngeal expansion is primarily correlated with lowering of F1. Indeed, Trigo (1991: 115) assumes F1 to be the most reliable acoustic cue for tongue root distinctions but at the same time explains that the retraction of the root of the tongue depresses F2 and F3. Pharyngeal expansion is associated with both F1 lowering and F2 raising in many languages with confirmed [ATR] contrasts (e.g., Aralova et al. 2011 for Even; Quinn-Wriedt 2013 for Maasai, cf. Ladefoged & Maddieson 1996: 304). Similarly, Russian palatalization has been associated with both raised F2 and lowered F1, as well as generally increased distance between F1 and F2 (Ordin 2011 and references therein; Kochetov 2017). It can be shown (as in the present study) that tongue body fronting is partially correlated with pharyngeal expansion, and we are not aware of any studies that have specifically teased apart the roles of pharyngeal expansion and tongue body fronting in F2 raising.

Given gaps in the stimuli, any generalizations about /e/ are based on a single consonant context, unlike for /u, o, a/ which were recorded in four contexts. Similarly, only /u, o, a/ could be recorded in the context of a velar stop. A reviewer suggested to remove the data including /e/ and /k/-context. We are aware that this would improve the statistical analysis but would eliminate a substantial portion of the data showing the patterning of front vowels and weaken the point that should be evident from the qualitative results section that the described effect of the tongue root advancement is systematic for all vowels in all consonant contexts.

5 Conclusions

In this paper we examined different phonetic correlates of Russian vowel allophony triggered by soft (palatalized or palatal) consonants. Assuming that the systematic presence or absence of the phonetic correlate of a feature will inform us about the nature of the phonological contrast, we evaluated features [+high], [-back], the Dorsal node as a whole, and [+ATR] as potential features responsible for the observed vowel distribution and, consequently, for the softness distinction in Russian consonants. Having excluded [+high] on an empirical basis, and the Dorsal node on theoretical grounds, we argued for the approach with [+ATR] as the allophony feature in vowels and then, consequently, the palatalization feature – rather than [-back] – due to the resulting phonological symmetry, the consistency and strength of the effect, and the physiological underpinnings.

An explanation of vowel allophony in Russian in terms of [ATR] is descriptively adequate, phonetically-grounded, surface-true and systematic. Further, the effects we analyze in this paper provide a strong argument to treat 'soft' or palatalized consonants in Russian as [+ATR]. While we do not present articulatory data of consonants in this paper, this analysis is also supported by earlier literature on Russian, as well as recent studies of palatalization in other languages such as Irish and Polish.

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