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ARTICULATORY PROPERTIES OF ESTONIAN PALATALIZATION BY RUSSIAN L1 SPEAKERS

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Abstract. We studied the articulatory and temporal properties of Estonian palatalization by Russian L1 Estonian L2 speakers and compared the results to Estonian native speakers. The tongue movement of 24 Russian L1 and 21 Estonian L1 speakers were recorded with an electromagnetic articulograph. The speakers articulated phonologically contrastive word pairs and *i*-stemmed nouns where the final consonant was palatalized. Previous research has shown that palatalization is generally realized by raising the tongue dorsum towards the hard palate. Consequently, the tongue becomes more anterior and wider. This rising of the tongue also lengthens the duration of the segments. The results showed that Russian L1 speakers' tongue dorsum was higher and more anterior when palatalizing consonants and the subsequent vowels. Compared to native speakers, their tongue was retracted and lower. Russian L1 speakers' duration of palatalized consonants and the vowels that preceded them were significantly shorter than in the control group. They did not use duration to differentiate palatalization in word pairs as native speakers do.

Keywords: palatalization, electromagnetic articulography, segmental duration, Estonian, Russian accent, second language acquisition, Carstens AG501

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1. Introduction

1.1. Motivation and aims

Russian native language (L1) speakers are the biggest language minority in Estonia, making up about 25% (330,206 speakers) out of the total Estonian population (Stats 2017). Knowing Estonian is essential because it helps the learners integrate into Estonian society and fully experience Estonian culture. In our previous study on Russian L1 Estonian L2 (second language) speech, learners of Estonian reported that they do not feel comfortable speaking Estonian because of their speech accent

(Malmi & Lippus 2021). Speaking a second language with an accent is usually not a big problem, and the learners are not expected to speak as fluently as native speakers do. Still, it can be an issue for some speakers because it is a distinct feature that separates language learners from native speakers and can create unnecessary stereotypes. For example, people with a nonnative accent often feel stigmatized and have problems communicating and blending in (Gluszek & Dovidio 2010).

This paper aims to study the articulatory and temporal realization of Estonian palatalization by Russian L1 speakers. It has been established (discussed in Section 1.2) that the native language of the learner affects the duration and the quality of the segments produced by the learners of Estonian. However, the realization of Estonian palatalization by learners has not yet been researched. In this study, we build upon the knowledge and use materials from the same experiments as in the previous articles: a study of the acoustic properties of Estonian L1 palatalization (Malmi, Lippus & Meister 2022), an articulatory study of Estonian L1 speakers' palatalization (Malmi & Lippus 2019) and a study of the acoustic properties of Russian L1 palatalization of Estonian (Malmi & Lippus 2021).

1.2. Background

Phonetic research on Estonian foreign-accented speech has mostly dealt with the production and perception of Estonian ternary quantity contrasts and Estonian vowel categories. Many learners of Estonian can distinguish and contrastively produce short and long length categories but not long and overlong (Meister & Meister 2011, 2012 for Russian L1; Meister & Meister 2014, 2017 for Latvian L1; Meister & Meister 2013 for Finnish L1; Leppik, Lippus & Asu 2020 for Spanish L1). In Russian and Spanish, the duration of segments is not contrastive; instead, it acts as a cue for word stress. In Latvian and Finnish, however, the duration is not solely used to signal stress. The problem is that pitch is also used to signal quantity in Estonian. Contrary to previous findings, Lippus, Pajusalu & Allik (2009) found that Russian L1 speakers did, in fact, distinguish Estonian three-way quantity contrast but did not use pitch as a cue as native speakers do.

Another factor contributing to a speaker having a foreign accent might be that Estonian has a large vowel inventory consisting of nine vowels. This is considerably more compared than, e.g., Spanish (5), Russian (6), and Japanese (5). Spanish, Russian, and Japanese L1

learners of Estonian managed to successfully produce the Estonian vowels that correspond to their counterparts in their native language, but they mainly had trouble with producing vowels such as /ɑ, y, ø, ɤ/ (Meister 2011, Leppik, Lippus & Asu 2018, Nemoto, Meister & Meister 2015). Depending on the native language of a speaker, there are many phonetic details such as duration, pitch, and vocalic inventory that can contribute to accented speech.

Foreign-accented speech arises because we have to adjust our perceptual categories of L1 to perceive, and thus produce, L2 in a native-like way. Numerous studies have proven this, and the findings have been summarized in major L2 theoretical models such as Speech Learning Model (SLM – Flege 1995), Revised Speech Learning Model (SLM-r – Flege & Bohn 2021), Perceptual Assimilation Model (PAM – Best 1995) and in the Perceptual Assimilation Model accommodated for L2 learning (PAM-L2 – Best & Tyler 2007). SLM and SLM-r state that an L2 sound will be relatively easily acquired when not present in L1 because of its novelty. When we focus on foreign accent, then, arguably, the most problems will arise from L2 sounds that are similar to L1 sounds. In such cases, speakers are not as sensitive to the differences between the sounds, and they do not feel the need to form a new category, thus relying on the knowledge from L1 to produce an L2 counterpart. This is also called *equivalence classification*. The L2 sound is assimilated to the closest L1 sound, and a composite category is created which consists of features from both languages. This does not mean that they will stop learning. According to SLM-r, all of the input they receive is still used to expand existing categories regardless of the speaker's age.

Perceptual Assimilation Model (Best 1995) and PAM-L2 (Best & Tyler 2007), a model that is adapted to L2 learning, describe how the learners perceptually assimilate unfamiliar L2 sounds to the articulatorily similar sounds in their L1 phonetic inventory. The correct assimilation of sounds can only be achieved by identifying the articulatory gestures that underlie the sounds. When a learner is faced with a phonological category similar to one in their L1, it will be used as a good example for discriminating the contrast in L2, and no additional learning is required. If the category in L2 cannot be linked with a category in L1, then perceptual learning (improvement through experience) is needed to detect the contrast.

A categorical phenomenon similar in Estonian and Russian is palatalization. It is a coarticulatory process in which the place of articulation

of a consonant is modified by a high vowel or a palatal glide /j/ that follows it (Kochetov 2011). Palatalization in Estonian (Teras & Pajusalu 2014) and Russian (Avanesov 1972) can be categorized as secondary palatalization. This means that consonants acquire a secondary palatal place of articulation while the primary place of articulation remains. With full palatalization, the primary place of articulation shifts to a palatal region of the mouth. Although palatalization exists in Estonian and Russian, it is more widespread in the latter. Almost all consonants can have a secondary palatal place of articulation in Russian, but in Estonian, this can only be applied to the alveolar consonants /l, n, s, t/. In both languages, palatalization can occur on the boundary of the first and second syllable or at the end of the word, but word-initial consonants can only be palatalized in Russian (Ordin 2010).

In Estonian and Russian, palatalization can change the lexical meaning of words in phonologically contrastive pairs. For example, in Estonian: *sulg* [sulːk] 'bracket' ~ *sulg* [sulʲːk] 'feather' or in Russian: *ел* [jel] 'ate' ~ *ель* [jelʲ] 'spruce'. In Estonian this contrast has been caused by language change in which the word-final vowel was lost (Kask 1972). In the case of the apocope of /i/, the consonant was palatalized but in the case of other vowels, it was not. There are also cases of phonetic palatalization in which the lexical meaning does not change when the consonant is not palatalized. For example, *i*-stemmed nouns like *vann* sg nom 'bath' [vɑnʲː] or *tonn* sg nom 'ton' [tonʲː]. Another key difference for the learner is that palatalization in Estonian is not marked in orthography but is in Russian, for example, by a modifier letter ь which denotes the softening of the preceding consonant. In the case of Estonian, the learners do not have any orthographic cues indicating palatalization.

Articulatory research for Estonian (Kutser 1935, Ariste 1943, Eek 1971, Meister & Werner 2015) and Russian (Kochetov 2002), and acoustic research for both Estonian (Lehiste 1965, Teras & Pajusalu 2014, Malmi, Lippus & Meister 2022) and Russian (Avanesov 1972, Bolla 1981, Kochetov 2002, Kochetov 2017) have shown that the consonant is palatalized by fronting and raising the tongue dorsum towards the hard palate while the primary constriction remains. The tongue has also been shown to be wider in Estonian (Kutser 1935, Ariste 1943, Eek 1971, Meister & Werner 2015). The rising of the tongue is a cross-linguistic property of palatalization which in acoustic studies is described by a rise of F2 frequency in the preceding vowel or in a change in center of

gravity (Ocotepec Mixe – Hamann & Heriberto 2007; Korean – Kim 2012; Latvian – Urek 2016; Polish – Cavar 2004; Connemara Irish – Ní Chiosáin & Padgett 2012). This does not mean that languages follow the same pattern, as articulatory settings are language-specific. Similar segments may be articulated differently in different languages. For example, X-ray data of English and French speakers show that their speech rest position is language-dependent (Gick et al. 2004, Wilson & Gick 2013). This suggests that there is a starting point from which the segments can fluently combine, and this starting point varies between languages.

Any added secondary articulatory movement to the primary gesture affects the duration of the segments, as well. The longer duration of such segments is not only motivated by articulation. It is also used to enhance palatalization perception (Ordin 2010). The research on the duration of consonants is contradictory and is probably language- and phoneme-specific. Sources claim that the duration of Russian /t/ is lengthened (Bolla 1981, Kochetov 2002, Kochetov & Radisic 2009) but the duration of Russian /s/ can be shortened (Bolla 1981) or lengthened (Kochetov & Radisic 2009). We failed to find that palatalization had any effect on the duration of the consonants in our articulatory study (Malmi & Lippus 2019) and our acoustic study (Malmi, Lippus & Meister 2022) of Estonian palatalization. On the other hand, the vowels that precede palatalized consonants have been shown to be longer (Lehiste 1965, Liiv 1965, Bolla 1981, Zsiga 2000, Cavar 2004, Kavitskaya 2006, Kochetov 2006, Ordin 2010, Teras & Pajusalu 2014, Stoll, Harrington & Hoole 2015, Malmi & Lippus 2019, Malmi, Lippus & Meister 2022).

Before analyzing articulatory data in the current study, we did an acoustic analysis on a group of Russian L1 Estonian L2 speakers and compared their production to Estonian L1 speakers (Malmi & Lippus 2021). We found that the Russian group tended not to palatalize long word-final consonants while Estonians do palatalize them, but the preceding vowels' duration was similar to the Estonian L1 group. We also tested whether Russian L1 speakers palatalize word-initial consonants because it is a feature in Russian but not in Estonian. We found that the F2 range of their vowels that followed the consonants was similar to Estonian L1 speakers, but the duration was longer. The current paper will give an articulatory account of how Russian L1 speakers use palatalization in Estonian compared to native Estonian speakers.

1.3. Research questions and hypothesis

Our research questions are as follows: What are the articulatory and temporal properties that describe Russian L1 Estonian L2 palatalization in contrastive word pairs and in *i*-stemmed nouns? Are these properties similar to or different from Estonian L1 speakers' productions?

Recognizing palatalization from the text might be a problem for the learner because it is not marked in orthography in Estonian as it is in Russian. Based on predictions by SLM-s and PAM-s, the Russian L1 speakers' palatalized tokens will be different from native speakers. This is because when learners are faced with a category that is similar in both L1 and L2, then the learner will not be sufficiently sensitive to the fine acoustic and articulatory detail that differentiates them. Thus, we hypothesize that the position of their tongue and any temporal cues will be different from native speakers' productions.

2. Materials and methods

The articulatory data for this study was recorded in the Phonetics Laboratory at the University of Tartu, Estonia, between 2018–2020. This study has been approved by the Research Ethics Committee of the University of Tartu.

2.1. Participants

The participants were asked to fill out a short questionnaire that included questions about their demographic background, the place of birth of their parents, what languages were spoken in their preschool and school, and their assessment of their language proficiency. Questions about their self-assessment were rated on a 5–point scale: overall language proficiency, spelling skills, and grammar abilities (1 – bad, 5 – good); questions about how much they read in Estonian (1 – rarely, 5 – often).

The Russian L1 group consisted of 24 speakers (17 female, 7 male, mean age 26 years, SD 8.7; hereafter Russian group). All of them were born and raised in Estonia. They reported that their native language is Russian and that they spoke Russian at home with their parents. Seventeen of them had attended a Russian-speaking preschool, while seven went to either an Estonian-speaking or a bilingual Russian-Estonian

preschool. Sixteen went to a Russian-speaking school, 5 to a bilingual school, and 3 to an Estonian-speaking school; eleven participants had a higher education, and 12 had a secondary education. Twenty one participants were students or worked in academia; one worked as an artist, one as a carpenter, and one as a journalist. They rated that their Estonian proficiency was good (4.2, SD 0.9); they were hesitant about their grammar (3.6, SD 1) and spelling (3.5, SD 1); they rarely read newspapers (2.3, SD 1.3) and fiction (2.2, SD 1.3) in Estonian.

The control group consisted of 21 native Estonian speakers (Estonian group; 11 female, 10 male, mean age 28 years, SD 6.2). They all went to an Estonian-speaking preschool and school. Seventeen of them had a higher or vocational education; four participants had a secondary education. Eighteen of the participants were university students or faculty members; one worked as a decorator, one as a carpenter, and one was unemployed. They rated their Estonian proficiency to be good (4.5, SD 0.5), their grammar and spelling were also good (both 4.3, both SD 0.6), and they read newspapers (3.6, SD 1.2) and fiction (3.3, SD 1.2) in Estonian, but not that often.

2.2. Materials

The data analyzed in this study includes two sets of words: a) 11 minimal pairs of monosyllabic words where the word-final consonant is either palatalized or not. The same words were used in a previous study of Estonian L1 speakers (Malmi & Lippus 2019, Malmi, Lippus & Meister 2022); b) 26 monosyllabic *i*-stemmed words in the nominative case with a word-final palatalized consonant (see Table 1 for examples). Malmi & Lippus (2021) analyzed the acoustic properties of these words uttered by Russian L1 speakers. The words for the experiment were checked to match the Common European Framework of Reference for Languages proficiency of B2 level or less by cross-referencing a word list by Kallas & Koppel (2020). L2 learners should be familiar with all of the words in the experiment because they should have acquired at least C1 level by the end of high school in Estonia.

The test words were embedded in a medial position of carrier sentences, followed by a comma and a word starting with the sequence [mi], e.g., *Külmal hommikul oli maas* ***hall*** [hɑlː]*, mida oli ilus vaadata*. ‘On a cold morning, the land was covered with **frost** that was beautiful to look at’, *Minu auto oli* ***hall*** [hɑlʲː]*, mitte valge.* ‘My car was **gray**,

not white.' The participants did not see the phonetic transcription of the words in the sentence and had to rely only on their prior knowledge for production. The consonants in the phonological pairs and the *i*-stemmed nouns are palatalized in a similar manner. The *i*-stemmed nouns were used in the current paper because they acted as a failsafe in case Russian L1 speakers do not differentiate between contrastive pairs.

Table 1. The test words used in the current study.

	Contrastive pairs				***i*-stemmed nouns**	
C2	**Non-palatalized**		**Palatalized**		**Palatalized**	
/l/	[mɑlː]	(name)	[mɑlʲː]	protractor	[sɑlʲː]	scarf
	[tɑlː]	3SG.GEN (pers. pron.)	[tɑlʲː]	stable	[bɑlʲː]	ball
	[hɑlː]	frost	[hɑlʲː]	gray	[kolʲː]	monster
	[mulː]	1 SG.GEN (pers. pron.)	[mulʲː]	bubble	[lolʲː]	dumb
	[pɑlkː]	wage	[pɑlʲkː]	log	[nulʲː]	zero
	[sɑlːv]	bin	[sɑlʲːv]	ointment	[pɑlʲː]	ball
	[tulpː]	column	[tulʲpː]	tulip	[pulʲː]	bull
	[sulːk]	bracket	[sulʲːk]	feather	[rolʲː]	role
/n/	[kɑnː]	jug	[kɑnʲː]	toy	[vɑnʲː]	bath
	[onː]	be.3SG.PRS	[onʲː]	hut	[pɑnʲː]	pan
					[punʲː]	plug
					[tonʲː]	ton
/s/	[kɑsː]	whether	[kɑsʲː]	cat	[bɑsʲː]	bass
	[kusː]	where	[kusʲː]	shush	[busʲː]	bus
	[lɑsːt]	child.SG.PART	[lɑsʲːt]	cargo	[losʲː]	castle
					[mɑsʲː]	mass
					[pɑsʲː]	passport
					[rɑsʲː]	race
					[tɑsʲː]	cup
/t/	[kotː]	wooden shoe	[kotʲː]	bag	[lutʲː]	pacifier
	[nutː]	crying	[nutʲː]	smarts	[mɑtʲː]	mat
	[rutː]	hurry	[rutʲː]	(name)	[mutʲː]	mole
	[pɑtːs]	pat	[pɑtʲːs]	braid	[potʲː]	pot
					[rotʲː]	rat
					[vɑtʲː]	cotton
					[vutʲː]	quail

2.3. Procedure

The articulatory data were recorded with a Carstens AG501 electromagnetic articulograph. The measurements were obtained with a 200 Hz sampling frequency. Two sensors were glued on the scalp behind the ears of the participant. A bite plate was used to normalize data between participants and for head correction. Five sensors were glued on the tongue (see Figure 1): the first sensor was glued on the midline of the tongue on the anteo-dorsum; the second sensor was glued 1 cm behind the first sensor; the third sensor was glued 1 cm to the right of the second sensor and the fourth sensor was glued to 1 cm the left of the second sensor; the fifth sensor was glued on the tongue blade, approximately 0.5 cm from the apex. A sixth sensor was also glued on the lower incision. In this study, we analyzed data from sensors 1–4. During the experiment, the experimenter observed the real-time positions of the sensors from a computer monitor and did random checks by looking at the participant's tongue. When a sensor came off or was loose, it was glued back in the same position as before. Each carrier-sentence was only recorded once.

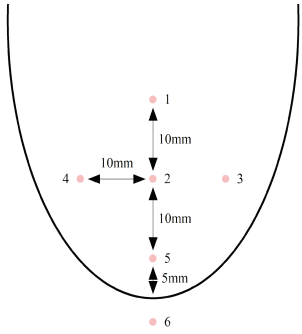

Figure 1. Schematic overview of the placement of the sensors on the tongue and the lower incision.

Simultaneously with the articulatory recordings, the acoustic signal was recorded to find the onset and offset times of the test words and segments. The acoustic recordings were automatically annotated using an ASR forced-aligner (Alumäe, Tilk & Asadullah 2018), and the alignment was manually corrected in Praat (Boersma & Weenink 2021). Any tokens which were misread or co-occurred with problems with the sensors were excluded. Misread tokens also consisted of words that were too archaic or unfamiliar for the reader. For example, the native speakers

palatalized consonants in words like *hall* [hɑlː], *õlg* [ɤlːk], or *kott* [kotː], while nonnative speakers did not always palatalize where necessary. From the Estonian group, we excluded 106 tokens; after manual revisions, the final dataset included 355 word pairs (out of 364) and 431 tokens of *i*-stemmed nouns (out of 528). From the Russian group, we excluded 238 tokens; their dataset included 157 tokens of word pairs (out of 395) and 554 tokens of *i*-stemmed nouns (out of 598).

In the current paper, we analyzed the data from sensors 1–4. The sensor on the anteo-dorsum (1) was used to estimate the height of the tongue. The sensor on the medio-dorsum (2) was used to estimate the anteriority of the tongue. Tongue lateral sensors (3–4) were used to calculate the width of the tongue by subtracting the data from the horizontal position of one sensor from the other. The articulatory data was time-normalized, and 100 equidistant measurement points from each vowel and consonant were used for the analysis.

2.4. Statistical analysis

Statistical analysis was carried out using the R software (R Core Team 2021). A Generalized Additive Mixed Model (GAMM) was used from the *mgcv* package (Wood 2017). The dependent variables were the height, width and the anteriority of the tongue, and the independent variables were palatalization, L1, the consonant and the preceding vowel. The GAMM models were checked and corrected for autocorrelation. A random intercept for the speaker was included in the model. The post-hoc testing was carried out by changing the intercept level of the model and then re-running the model again to get the estimated values and the differences between them. The p-values were corrected with Bonferroni-Holm correction.

Segmental duration values were tested with a Linear Mixed Model from the *lme4* package (Bates et al. 2015). The dependent variable was the duration of the vowel or consonant, and the independent variables were palatalization, L1, the consonant and the preceding vowel. A random intercept for the speaker was included. Post-hoc testing was carried out in the same way as in the GAMM models, but p-values were corrected with Benjamini-Hochberg method. The p-values were provided by the package *lmerTest* (Kuznetsova, Brockhoff & Christensen 2017).

3. Results

The results section is divided into four subsections. First, we will look at how the Russian group palatalize the relevant consonants in the word pairs (3.1), and then compare these results to those of the native speakers (3.2). After that, we will look at how the Russian group palatalize consonants in *i*-stemmed nouns compared to the Estonian group (3.3). Lastly, we will analyze the duration of segments (3.4).

3.1. Russian L1 articulation of vowels and following consonants in the word pairs

3.1.1. Height of the tongue dorsum

The height of the tongue dorsum was measured from Sensor 1 located on the anteo-dorsum.

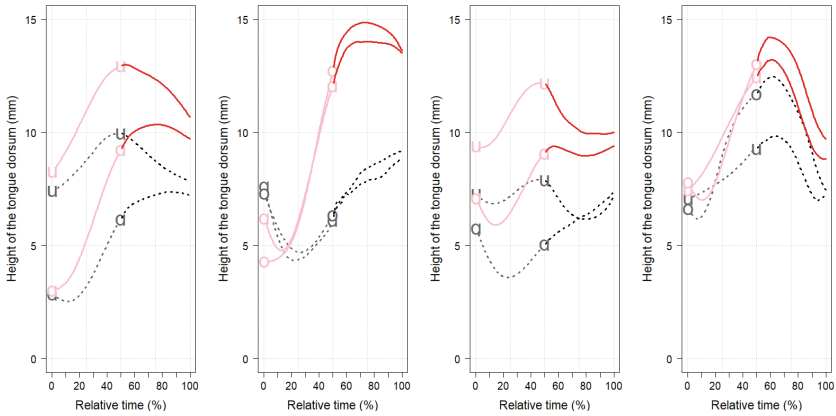

Figure 2. The height of the tongue dorsum (mm) within the sequence of vowels and consonants of the Russian group. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the respective segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%. Non-palatalized tokens are in gray/black dotted lines, and palatalized tokens are in pink/red solid lines.

Figure 2 and Table 2 shows that the tongue dorsum of the Russian group was always 1–3 mm higher when producing vowels that were followed by palatalized consonants compared to non-palatalized consonants (all vowel and consonant context combinations $p < 0.001$, see the upper half of Table 2 for details). Looking at the consonants, the tongue dorsum was 2–6 mm higher for consonants with palatalization compared to non-palatalized consonants (all consonant and vowel context combinations $p < 0.001$, see the lower half of Table 2 for details).

Table 2. Summary of the post-hoc GAMMs for the height of the tongue dorsum (mm) of the Russian group with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Non-palatalized		Palatalized			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	4.38	0.74	5.74	0.05	1.36	< 0.001
	/u/		9.31	0.73	10.47	0.07	1.16	< 0.001
	/ɑ/	/n/	4.52	0.74	7.74	0.09	3.22	< 0.001
	/o/		5.49	0.73	7.01	0.62	1.52	< 0.001
	/ɑ/	/s/	4.36	0.04	7.23	0.04	2.87	< 0.001
	/u/		7.33	0.73	10.49	0.06	3.16	< 0.001
	/o/	/t/	8.01	0.74	9.40	0.12	1.39	< 0.001
	/u/		7.77	0.73	10.03	0.05	2.26	< 0.001
CONSOANTS	/ɑ/	**/l/**	7.84	0.69	10.26	0.08	2.42	< 0.001
	/u/		9.29	0.11	12.02	0.12	2.73	< 0.001
	/ɑ/	**/n/**	7.38	0.71	13.89	0.16	6.51	< 0.001
	/o/		8.18	0.69	14.16	0.11	5.98	< 0.001
	/ɑ/	**/s/**	6.32	0.69	9.36	0.08	3.04	< 0.001
	/u/		6.67	0.69	10.20	0.11	3.53	< 0.001
	/o/	**/t/**	10.55	0.73	12.67	0.23	2.13	< 0.001
	/u/		8.77	0.69	11.45	0.09	2.68	< 0.001

3.1.2. Anteriority of the tongue

The anteriority of the tongue was measured with Sensor 2, which was glued on the medio-dorsum.

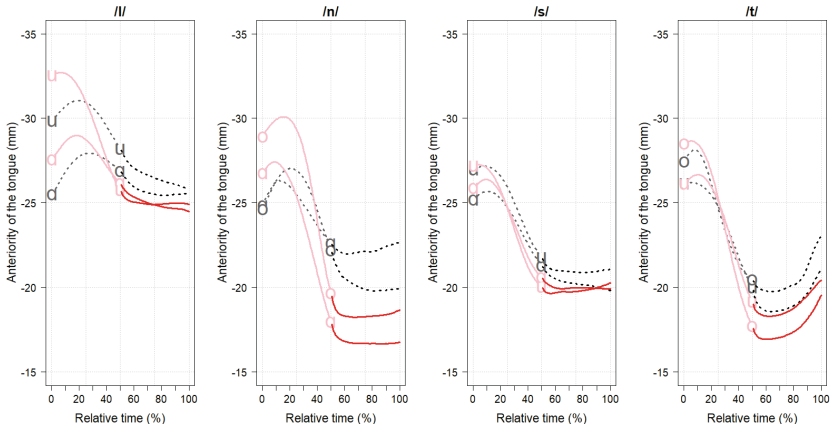

Figure 3. The anteriority of the tongue (mm) within the sequence of vowels and consonants of the Russian group. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%. Non-palatalized tokens are in gray/black dotted lines, and palatalized tokens are in pink/red solid lines.

The results showed that the consonant context affected the anteriority of the tongue while producing vowels (Figure 3, Table 3). The tongue was 0.45–1.34 mm more anterior while producing the vowel /u/ in the context of palatalized /n/, /s/ and /t/ (all $p < 0.001$). The production of /ɑ/ varied: in the context of palatalized /l/, the tongue was 0.59 mm retracted but in the context of palatalized /n/ and /s/, it was 0.57–1.23 mm more anterior (all $p < 0.001$).

For consonants, the position of the tongue was always 0.6–5 mm more anterior with palatalization (all consonant and vowels context combinations $p < 0.001$, see Table 3 and Figure 3), regardless of the vocalic context.

Table 3. Summary of the post-hoc GAMMs for the anteriority of the tongue (mm) of the Russian group with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Non–palatalized		Palatalized			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	–27.79	1.30	–28.38	0.06	–0.59	< 0.001
	/u/		–30.95	1.30	–29.61	0.09	1.34	< 0.001
	/ɑ/	/n/	–25.89	1.30	–24.66	0.12	1.23	< 0.001
	/o/		–25.59	1.30	–27.06	0.08	–1.47	< 0.001
	/ɑ/	/s/	–24.91	1.30	–24.34	0.06	0.57	< 0.001
	/u/		–25.25	1.30	–24.39	0.08	0.86	< 0.001
	/o/	/t/	–24.53	1.31	–24.32	0.18	0.21	0.234
	/u/		–24.63	1.30	–24.18	0.07	0.45	< 0.001
CONSOANTS	/ɑ/	**/l/**	–25.87	1.27	–25.26	0.07	0.60	< 0.001
	/u/		–27.21	1.28	–24.29	0.10	2.91	< 0.001
	/ɑ/	**/n/**	–22.53	1.28	–17.53	0.13	5.00	< 0.001
	/o/		–20.20	1.27	–18.86	0.09	1.86	< 0.001
	/ɑ/	**/s/**	–21.00	1.27	–20.14	0.07	0.85	< 0.001
	/u/		–21.00	1.27	–19.93	0.09	1.06	< 0.001
	/o/	**/t/**	–19.41	1.29	–17.59	0.19	1.81	< 0.001
	/u/		–19.71	1.27	–18.94	0.07	0.76	< 0.001

3.1.3. Width of the tongue

The width of the tongue was measured by subtracting the y-axis value of Sensor 3 from the y-axis value of Sensor 4. The sensors were glued on the sides of the tongue.

The results for vowels (see Figure 4 for mean values) showed that when /ɑ/ was followed by palatalized /l/, the tongue was 0.75 mm wider compared to the corresponding non-palatalized context ($p < 0.001$, see Table 4 for more details). When /ɑ/ was followed by palatalized /n/, the tongue was 0.6 mm narrower ($p < 0.001$), and when followed by palatalized /s/, it was 0.15 mm narrower ($p = 0.001$) than in the corresponding non-palatalized contexts. In the case of /o/ in the context of

palatalized /n/, the tongue was 0.16 mm narrower ($p = 0.015$) compared to the corresponding non-palatalized context. While producing /u/, the tongue was 0.21 mm wider ($p < 0.001$) in the context of /s/ and 0.32 mm wider ($p < 0.001$) in the context of /t/ compared to the corresponding non-palatalized contexts.

The results for consonants showed that when producing palatalized /l/ and /s/ in the context of /ɑ/, the tongue was 0.16–0.28 mm wider with palatalization (both $p < 0.001$; see Figure 4, Table 4). When palatalized /n/ was in the context of /ɑ/, the tongue was 1.51 mm narrower ($p < 0.001$) than compared to a non-palatalized /n/. When /n/ and /t/ were in the context of /o/, the tongue was 0.51–0.84 mm narrower with palatalization (both $p < 0.001$). The tongue was 0.5 mm narrower when palatalized /l/ was in the context of /u/ ($p < 0.001$) but 0.3 mm wider when palatalized /t/ was preceded by /u/ ($p < 0.001$).

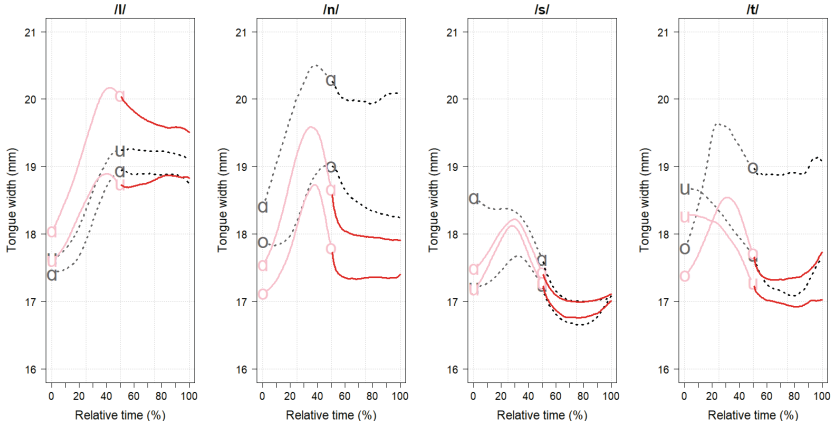

Figure 4. The width of the tongue (mm) within the sequence of vowels and consonants of the Russian group. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%. Non-palatalized tokens are in gray/black dotted lines, and palatalized tokens are in pink/red solid lines.

Table 4. The summary of the post-hoc GAMMs for the width of the tongue (mm) of the Russian group with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Non-palatalized		Palatalized			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	18.46	0.47	19.21	0.02	0.75	< 0.001
	/u/		18.30	0.47	18.25	0.03	–0.04	0.174
	/ɑ/	/n/	19.29	0.48	18.68	0.07	–0.60	< 0.001
	/o/		18.33	0.47	18.17	0.05	–0.16	0.015
	/ɑ/	/s/	18.17	0.47	18.02	0.04	–0.15	0.001
	/u/		17.43	0.47	17.64	0.05	0.21	< 0.001
	/o/	/t/	18.38	0.48	18.17	0.11	–0.20	0.063
	/u/		17.89	0.47	18.21	0.04	0.32	< 0.001
CONSOANTS	/ɑ/	**/l/**	19.30	0.49	19.58	0.04	0.28	< 0.001
	/u/		19.09	0.49	18.58	0.05	–0.50	< 0.001
	/ɑ/	**/n/**	19.45	0.49	17.94	0.06	–1.51	< 0.001
	/o/		18.47	0.49	17.63	0.04	–0.84	< 0.001
	/ɑ/	**/s/**	17.04	0.49	17.20	0.03	0.16	< 0.001
	/u/		16.80	0.49	16.82	0.04	0.02	0.615
	/o/	**/t/**	18.08	0.49	17.56	0.09	–0.51	< 0.001
	/u/		16.88	0.49	17.18	0.04	0.30	< 0.001

3.2. Russian L1 articulation of vowels and palatalized consonants in word pairs compared to Estonian L1 speakers

3.2.1. Height of the tongue dorsum

Figure 5 compares the height of the tongue dorsum of palatalized consonants and preceding vowels of the Russian group with the corresponding productions of the Estonian group. The results showed that when the Russian group produced /ɑ/ in the context of palatalized /l/, the tongue dorsum was on average 2.71 mm lower ($p = 0.004$, see

Table 5 for model estimates), and in the context of /n/, it was 3.01 mm lower (p = 0.006) than in the Estonian group. When /o/ was followed by palatalized /n/, the dorsum of the Russian group was 2.91 mm lower (p = 0.008). It was also 2.25 mm lower when /u/ was followed by /l/ (p = 0.031) and 2.51 mm lower when it was followed by /t/ (p = 0.047).

With consonants, the results in Figure 5 showed that compared to the Estonian group the tongue dorsum in the Russian group was 1.84 mm lower (p = 0.051, Table 5) when followed by palatalized /l/ and 3.01 mm lower when followed by palatalized /s/ (p = 0.029). The tongue dorsum of /u/ was 2.08 mm lower (p = 0.031) before palatalized /s/ and 2.01 mm lower (p = 0.039) before /t/.

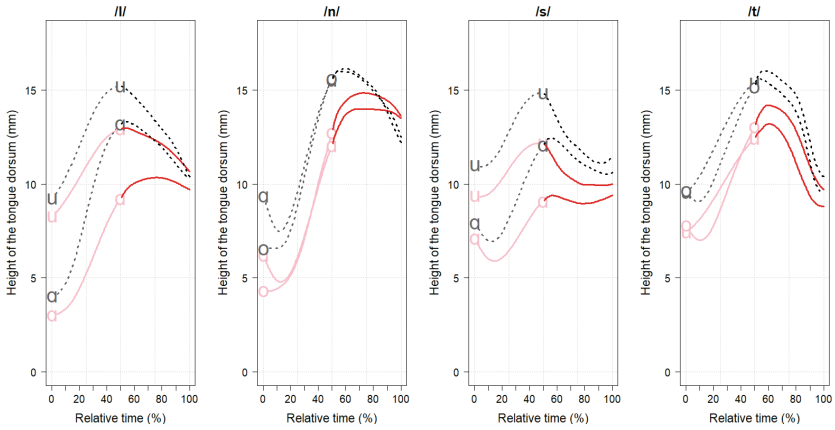

Figure 5. The height of the tongue dorsum (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian (dotted line in gray/black) groups. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

Table 5. The summary of the post-hoc GAMMs for the height of the tongue dorsum (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		Estonian L1			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	5.75	0.66	8.46	0.94	2.71	0.004
	/u/		10.43	0.66	12.68	0.95	2.25	0.031
	/ɑ/	/n/	7.59	0.66	10.60	0.94	3.01	0.006
	/o/		6.93	0.66	9.84	0.94	2.91	0.008
	/ɑ/	/s/	7.24	0.66	8.84	0.94	1.60	0.179
	/u/		10.47	0.66	12.84	0.94	2.36	0.114
	/o/	/t/	9.33	0.66	11.49	0.94	2.16	0.112
	/u/		10.05	0.66	12.56	0.94	2.51	0.047
CONSOANTS	/ɑ/	**/l/**	10.25	0.65	12.09	0.92	1.84	0.051
	/u/		11.94	0.65	13.20	0.93	1.26	0.174
	/ɑ/	**/n/**	13.69	0.65	14.96	0.93	1.27	0.169
	/o/		14.05	0.65	14.98	0.93	0.93	0.316
	/ɑ/	**/s/**	9.36	0.65	11.37	0.93	3.01	0.029
	/u/		10.19	0.65	12.26	0.93	2.08	0.031
	/o/	**/t/**	12.57	0.65	14.26	0.93	1.69	0.099
	/u/		11.49	0.65	13.50	0.93	2.01	0.039

3.2.2. Anteriority of the tongue

Anteriority of the tongue is presented in Figure 6. While articulating /ɑ/ that preceded palatalized /l/, the tongue dorsum of the Russian group was 5.7 mm more retracted ($p = 0.020$) than in the Estonian group (see model output in Table 6). When /u/ was followed by palatalized /l/, in the Russian group the tongues were on average 5.87 mm more posterior ($p = 0.004$); when followed by palatalized /s/, the tongue was 5.1 mm more posterior ($p = 0.026$), and when followed by palatalized /t/, the tongue was 5.73 mm more retracted ($p = 0.047$). When /o/ was

followed by palatalized /n/, in the Russian group tongues were on average 7.42 mm more posterior ($p < 0.001$), and when followed by palatalized /t/, 4.72 mm more posterior ($p = 0.037$) than in the Estonian group.

The results for consonants (Figure 6) showed that in the Russian group while palatalizing /l/ in the context of /ɑ/ the tongue was on average 4.9 mm more posterior than native speakers' tongues ($p = 0.015$, Table 7). The tongues of the Russian group while palatalizing /t/ in the context of /o/ were 4.88 mm more retracted ($p = 0.032$). In addition, in the Russian group /l/ was 5.24 mm more posterior ($p = 0.019$), /s/ was 4.8 mm retracted ($p = 0.025$) and /t/ was 5.4 mm more posterior ($p = 0.012$) in the context of /u/.

Table 6. The summary of the post-hoc GAMMs for the anteriority of the tongue dorsum (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		Estonian L1			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	–28.36	1.41	–23.19	2.01	5.17	0.020
	/u/		–29.74	1.41	–23.87	2.01	5.87	0.004
	/ɑ/	/n/	–24.77	1.41	–21.39	2.01	3.37	0.282
	/o/		–27.13	1.41	–19.71	2.01	7.42	< 0.001
	/ɑ/	/s/	–24.36	1.41	–21.02	2.01	3.34	0.139
	/u/		–24.31	1.41	–19.22	2.01	5.08	0.026
	/o/	/t/	–24.34	1.41	–19.61	2.01	4.72	0.037
	/u/		–24.15	1.41	–18.45	2.01	5.73	0.047
CONSOANTS	/ɑ/	**/l/**	–25.25	1.42	–20.32	2.03	4.92	0.015
	/u/		–24.44	1.42	–19.20	2.03	5.24	0.019
	/ɑ/	**/n/**	–17.72	1.42	–15.46	2.03	2.25	0.266
	/o/		–18.43	1.42	–15.15	2.03	3.28	0.106
	/ɑ/	**/s/**	–20.19	1.42	–16.66	2.03	3.54	0.081
	/u/		–19.91	1.42	–15.12	2.03	4.79	0.025
	/o/	**/t/**	–17.67	1.42	–12.79	2.03	4.88	0.032
	/u/		–18.87	1.42	–13.48	2.03	5.39	0.012

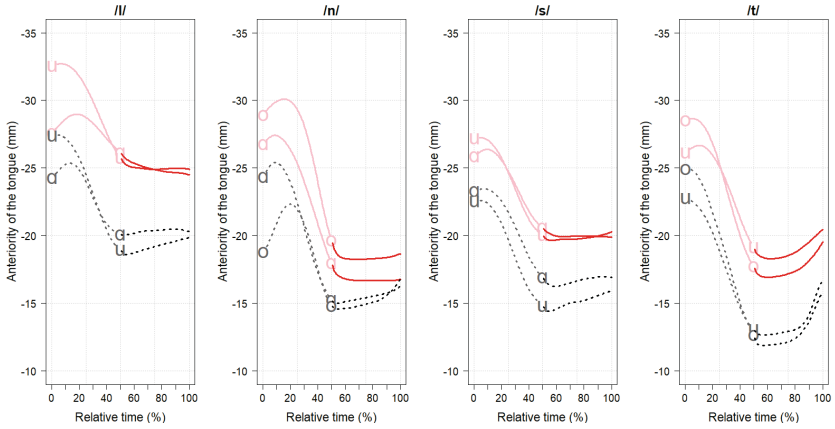

Figure 6. The anteriority of the tongue (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian (dotted line in gray/black) groups. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

3.2.3. Width of the tongue

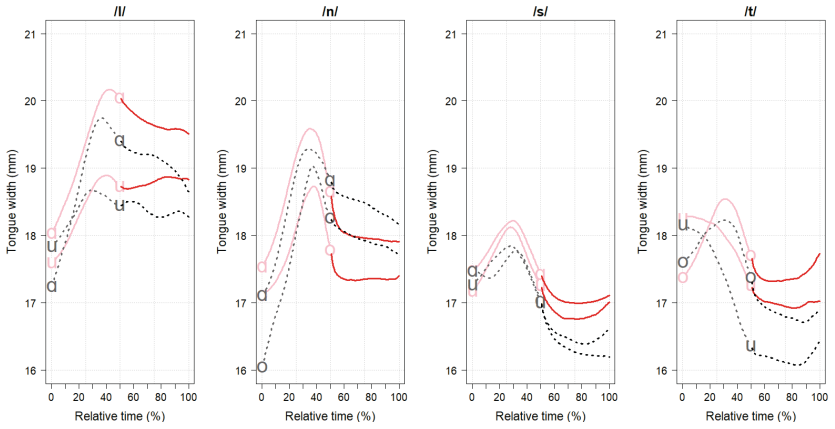

Figure 7. The width of the tongue (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian groups (dotted line in gray/black). The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

Table 7. The summary of the post-hoc GAMMs for the width of the tongue (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		Estonian L1			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	19.22	0.54	18.84	0.77	–0.37	0.633
	/u/		18.28	0.54	18.39	0.78	0.11	0.886
	/ɑ/	/n/	18.68	0.54	16.52	0.78	–0.16	0.834
	/o/		18.18	0.54	17.82	0.78	–0.36	0.642
	/ɑ/	/s/	18.03	0.54	17.49	0.78	–0.54	0.489
	/u/		17.64	0.54	17.53	0.78	–0.10	0.897
	/o/	/t/	18.19	0.54	17.93	0.78	–0.26	0.741
	/u/		18.19	0.54	17.47	0.78	–0.72	0.354
CONSONANTS	/ɑ/	**/l/**	19.59	0.54	19.59	0.77	–0.48	0.528
	/u/		18.62	0.54	18.36	0.77	–0.25	0.739
	/ɑ/	**/n/**	17.97	0.54	18.45	0.77	0.48	0.534
	/o/		17.64	0.54	17.93	0.77	0.29	0.699
	/ɑ/	**/s/**	17.21	0.54	16.35	0.77	–0.85	0.267
	/u/		16.83	0.54	16.52	0.77	–0.31	0.686
	/o/	**/t/**	17.59	0.54	16.85	0.77	–0.73	0.341
	/u/		17.17	0.54	16.17	0.77	–0.99	0.197

Although the mean values in Figure 7 show that in the Russian group tongues are wider on average in the case of vowels in the /l/ context, the model (see Table 7) showed no significant differences between the two groups.

3.3. Russian L1 articulation of vowels and consonants in *i*-stemmed nouns compared to Estonian L1 speakers

3.3.1. Height of the tongue dorsum

The results for tongue height (see mean values in Figure 8) of vowels in *i*-stemmed nouns showed that in the Russian group tongues were on average 3–3.8 mm lower than in the Estonian group in all contexts. The summary of model outputs with exact values are presented in Table 8.

Table 8. The summary of the post-hoc GAMMs for the height of the tongue dorsum (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		Estonian L1			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	5.99	0.69	9.81	1.12	3.82	< 0.001
	/o/		7.51	0.69	10.82	1.12	3.12	0.023
	/u/		9.62	0.69	12.63	1.12	3.01	0.011
	/ɑ/	/n/	6.87	0.69	10.35	1.12	3.48	0.009
	/o/		7.46	0.69	11.08	1.12	3.62	0.012
	/u/		10.71	0.69	14.13	1.12	3.42	0.029
	/ɑ/	/s/	6.61	0.69	9.76	1.12	3.15	0.009
	/o/		7.20	0.69	10.39	1.12	3.19	0.027
	/u/		10.02	0.69	13.00	1.12	2.98	0.013
	/ɑ/	/t/	7.01	0.69	10.54	1.12	3.54	0.012
	/o/		8.72	0.69	11.78	1.12	3.06	0.009
	/u/		10.23	0.69	14.06	1.12	3.84	0.008
CONSOANTS	/ɑ/	**/l/**	10.43	0.68	13.36	1.11	2.94	0.011
	/o/		10.29	0.68	12.87	1.11	2.58	0.023
	/u/		10.97	0.68	13.06	1.11	2.09	0.071
	/ɑ/	**/n/**	14.03	0.68	15.18	1.11	1.15	0.299
	/o/		13.83	0.68	15.41	1.11	1.58	0.155
	/u/		14.03	0.68	15.31	1.11	1.28	0.372
	/ɑ/	**/s/**	9.73	0.68	12.21	1.11	2.48	0.026
	/o/		9.94	0.68	11.76	1.11	1.82	0.102
	/u/		10.12	0.68	12.41	1.11	2.29	0.047
	/ɑ/		11.76	0.68	14.05	1.11	2.29	0.051
	/o/	**/t/**	11.94	0.68	14.51	1.11	2.57	0.029
	/u/		12.22	0.68	14.88	1.11	2.66	0.024

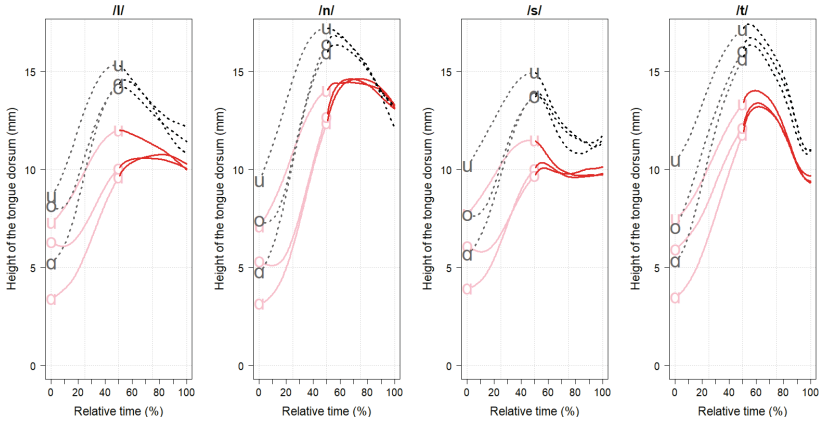

Figure 8. The height of the tongue dorsum (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian (dotted line in gray/black) groups. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

The results for consonants showed that in the Russian group the tongue was 2.94 mm lower for /l/ compared to the Estonian group ($p < 0.001$) and 2.5 mm lower for /s/ ($p = 0.026$) when they were preceded by /ɑ/. The height of the dorsum was 2.57 mm lower ($p = 0.023$) for /l/ and 2.58 mm lower for /t/ in the context of /o/. In addition, it was also 2.3 mm lower ($p = 0.047$) for /s/ and 2.7 mm lower for /t/ ($p = 0.024$) when preceded by /u/.

3.3.2. Anteriority of the tongue

The mean values for the anteriority of the tongue (Figure 9) show that in the Russian group in the context of /l/ the tongue is more retracted, but the models (Table 9) estimated that these differences are not significant. The position of the tongue in the Russian and Estonian groups was similar in all vocalic and consonant contexts.

Table 9. The summary of the post-hoc GAMMs for the anteriority of the tongue (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		Estonian L1			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	–28.31	1.39	–27.12	2.26	1.19	0.597
	/o/		–29.18	1.39	–27.47	2.26	1.71	0.450
	/u/		–27.97	1.39	–27.12	2.26	0.85	0.701
	/ɑ/	/n/	–25.64	1.39	–26.59	2.26	–0.04	0.985
	/o/		–23.32	1.39	–21.77	2.26	1.54	0.494
	/u/		–26.17	1.39	–24.03	2.26	2.13	0.346
	/ɑ/	/s/	–24.57	1.39	–24.56	2.26	0.01	0.997
	/o/		–24.12	1.39	–23.47	2.26	0.07	0.776
	/u/		–25.17	1.39	–23.66	2.26	1.51	0.504
	/ɑ/	/t/	–24.51	1.39	–24.17	2.26	0.34	0.880
	/o/		–25.00	1.39	–23.34	2.26	1.66	0.461
	/u/		–23.90	1.39	–21.57	2.26	2.33	0.303
CONSONANTS	/ɑ/	**/l/**	–25.00	1.36	–23.90	2.25	1.09	0.621
	/o/		–25.16	1.36	–24.02	2.25	1.14	0.607
	/u/		–25.44	1.36	–24.05	2.25	1.39	0.531
	/ɑ/	**/n/**	–17.88	1.36	–19.73	2.25	–1.85	0.403
	/o/		–18.89	1.36	–18.83	2.25	0.06	0.978
	/u/		–18.02	1.36	–18.82	2.25	–0.28	0.899
	/ɑ/	**/s/**	–19.76	1.36	–20.17	2.25	–0.41	0.852
	/o/		–20.47	1.36	–20.74	2.25	–0.26	0.904
	/u/		–19.95	1.36	–18.89	2.25	1.06	0.632
	/ɑ/		–17.91	1.36	–17.56	2.25	0.34	0.877
	/o/	**/t/**	–17.88	1.36	–16.78	2.25	1.09	0.622
	/u/		–18.23	1.36	–16.75	2.25	1.48	0.506

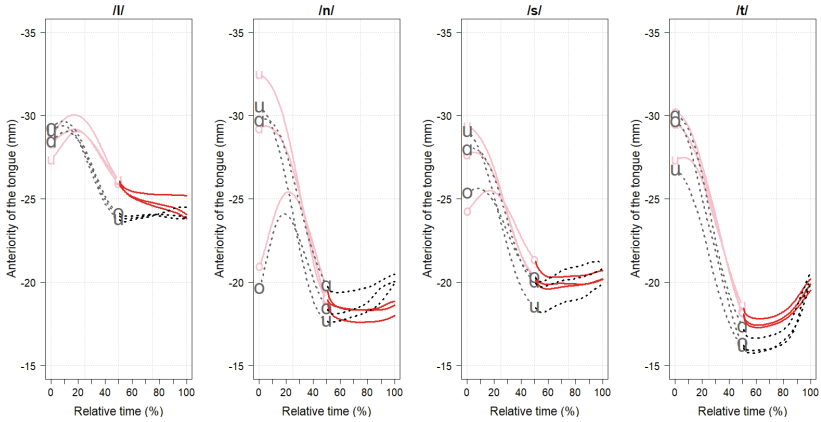

Figure 9. The anteriority of the tongue (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian (dotted line in gray/black) groups. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

3.3.3. Width of the tongue

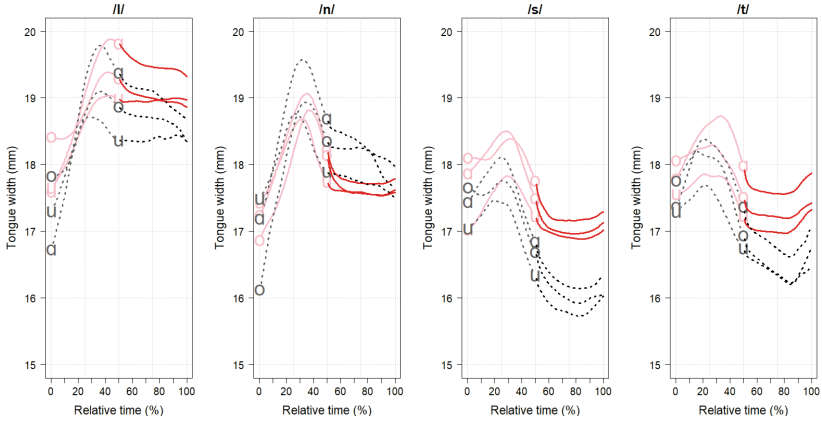

Figure 10. The width of the tongue (mm) within the sequence of vowels and consonants of the Russian (solid line in pink/red) and Estonian (dotted line in gray/black) groups. The beginning of the vowel and the vowel-to-consonant boundary is marked with the vowel character. The measurements were time-normalized in reference to the segment duration so that the boundary between the vowel (lighter color) and the consonant (darker color) is always at 50%.

The mean values for the width of the tongue (Figure 10) are in line with the models' estimates (Table 10), which show that the width of the tongue across all vocalic and consonant contexts is not significantly different between the two groups.

Table 10. The summary of the post-hoc GAMMs for the width of the tongue (mm) of the Russian and Estonian groups with pairwise comparisons of palatalization for each vowel and consonant. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

			Russian L1		**Estonian L1**			
	V1	**C2**	**Estimate**	**Std. err**	**Estimate**	**Std. err**	**Diff**	***p***
VOWELS	**/ɑ/**	/l/	18.96	0.46	18.74	0.74	–0.22	0.765
	/o/		18.86	0.46	18.55	0.74	–0.31	0.676
	/u/		18.52	0.46	18.29	0.74	–0.22	0.757
	/ɑ/	/n/	18.49	0.46	18.74	0.74	0.25	0.732
	/o/		18.35	0.46	18.46	0.74	–0.28	0.706
	/u/		18.04	0.46	18.21	0.74	0.17	0.817
	/ɑ/	/s/	18.19	0.46	17.66	0.74	–0.52	0.476
	/o/		18.16	0.46	17.46	0.74	–0.69	0.349
	/u/		17.48	0.46	17.11	0.74	–0.37	0.617
	/ɑ/	/t/	18.38	0.46	17.97	0.74	–0.41	0.585
	/o/		18.08	0.46	17.85	0.74	–0.23	0.754
	/u/		17.68	0.46	17.35	0.74	–0.32	0.658
CONSOANTS	/ɑ/	**/l/**	19.51	0.47	19.03	0.76	–0.48	0.527
	/o/		19.02	0.47	18.67	0.76	–0.35	0.644
	/u/		18.94	0.47	18.38	0.76	–0.56	0.459
	/ɑ/	**/n/**	17.93	0.47	18.28	0.76	0.36	0.639
	/o/		18.02	0.47	18.11	0.76	0.09	0.907
	/u/		17.48	0.47	17.72	0.76	0.24	0.752
	/ɑ/	**/s/**	17.11	0.47	16.28	0.76	–0.83	0.275
	/o/		17.23	0.47	16.09	0.76	–1.14	0.133
	/u/		16.95	0.47	15.87	0.76	–1.07	0.157
	/ɑ/		17.65	0.47	16.85	0.76	–0.80	0.293
	/o/	**/t/**	17.27	0.47	16.48	0.76	–0.79	0.296
	/u/		17.06	0.47	16.40	0.76	–0.66	0.389

3.4. Russian L1 vowel and consonant duration in word pairs

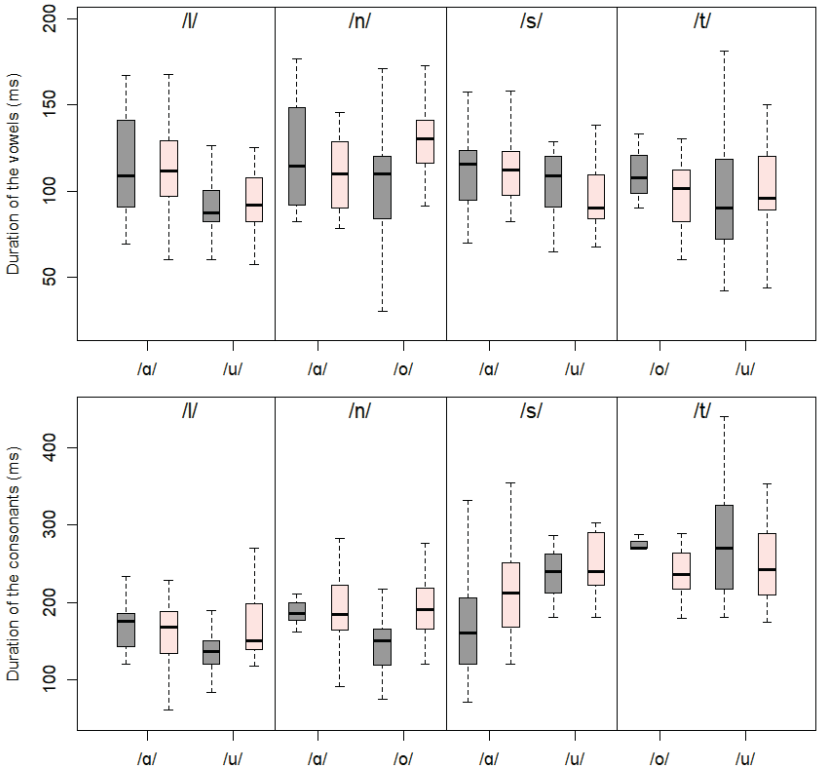

Figure 11. The Russian group mean duration (in milliseconds) of vowels (upper panel) and consonants (lower panel) in word pairs where palatalization differentiated meaning. Non-palatalized tokens are in gray and palatalized tokens are in pink.

Figure 11 shows the mean duration of vowels and consonants. The duration of /o/ in the Russian group was 23 ms longer before palatalized /n/ compared to the corresponding non-palatalized context ($p = 0.006$, see Table 11 for model estimates). When /u/ was followed by palatalized /t/, the duration was 13 ms longer than in the corresponding non-palatalized context ($p = 0.041$).

The duration of palatalized /l/ in the context of /u/ was 37 ms longer compared to a non-palatalized /l/ ($p = 0.012$). When /n/ was in the context of /o/, the duration was 47 ms longer with palatalization ($p < 0.001$). When /s/ was in the context of /ɑ/, the duration was 43 ms longer with palatalization ($p < 0.001$).

Table 11. The estimated duration (ms) of vowels (V) and consonants (C) and the durational difference between the non-palatalized and palatalized conditions in the Russian group. The upper half of the table lists the vowel measurements, and the lower half shows the consonant measurements.

	C2	**/l/**		**/n/**		**/s/**		**/t/**	
	V1	**/ɑ/**	**/u/**	**/ɑ/**	**/o/**	**/ɑ/**	**/u/**	**/o/**	**/u/**
V	Non–palat.	112	94	113	107	112	105	112	92
	Palatalized	114	97	114	130	115	99	102	105
	Difference	2	3	1	23	3	–6	–10	13
	p	0.617	0.704	0.880	0.006	0.591	0.341	0.470	0.041
C	Non–palat.	170	136	207	114	174	232	276	272
	Palatalized	167	173	189	191	217	247	235	252
	Difference	–3	37	–18	47	43	15	–41	–20
	p	0.735	0.012	0.326	< 0.001	< 0.001	0.238	0.129	0.076

3.5. Estonian L1 and Russian L1 vowel and palatalized consonant durations in word pairs

Table 12. The estimated duration (ms) of vowels (V) and palatalized consonants (C) and the durational difference between the Estonian and Russian groups.

	C2	**/l/**		**/n/**		**/s/**		**/t/**	
	V1	**/ɑ/**	**/u/**	**/ɑ/**	**/o/**	**/ɑ/**	**/u/**	**/o/**	**/u/**
V	Estonian L1	130	121	125	154	108	101	97	94
	Russian L1	115	97	114	129	114	98	93	106
	Difference	–15	–24	–11	–25	6	–3	–3	12
	p	0.011	0.008	0.200	0.002	0.321	0.646	0.661	0.091
C	Non-palat.	218	216	223	219	226	288	300	327
	Palatalized	166	175	118	191	218	248	234	252
	Difference	–51	–41	–35	–28	–8	–40	–66	–75
	p	< 0.001	0.046	0.101	0.147	0.555	0.018	< 0.001	< 0.001

Figure 12 shows the duration of vowels and consonants in the Estonian and Russian groups. In the context of palatalized /l/, in the Russian group duration of /ɑ/ was 15 ms shorter (p = 0.011), and /u/ was 24 ms shorter than in the Estonian group (p = 0.008, see Table 12 for estimate

values). When /o/ was followed by palatalized /n/, the duration was 25 ms shorter ($p = 0.002$) in the Russian group than in the Estonian group.

In the Russian group the duration of palatalized /l/ in the context of /ɑ/ was 51 ms shorter ($p < 0.001$), and in the context of /u/ it was 41 ms shorter ($p = 0.046$) than in the Estonian group (Figure 12, Table 12). The estimated duration of palatalized /s/ in the context of /u/ was 40 ms shorter in the Russian group compared to the Estonian group ($p = 0.018$). The duration of palatalized /t/ in the context of /o/ was 66 ms shorter and in the context of /u/, it was 75 ms shorter ($p < 0.001$) in the Russian group compared to the Estonian group.

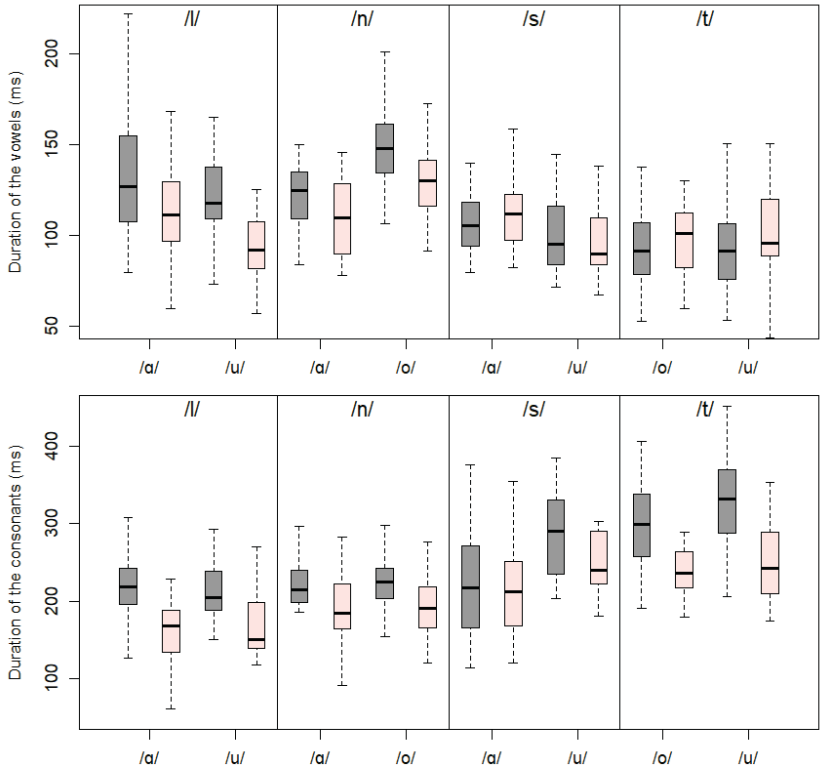

Figure 12. The mean duration (in milliseconds) of vowels (upper panel) and palatalized consonants (lower panel) in word pairs where palatalization differentiated meaning. The Estonian group marked with gray and Russian with pink.

3.6. Estonian L1 and Russian L1 vowel and palatalized consonant durations in *i*-stemmed nouns

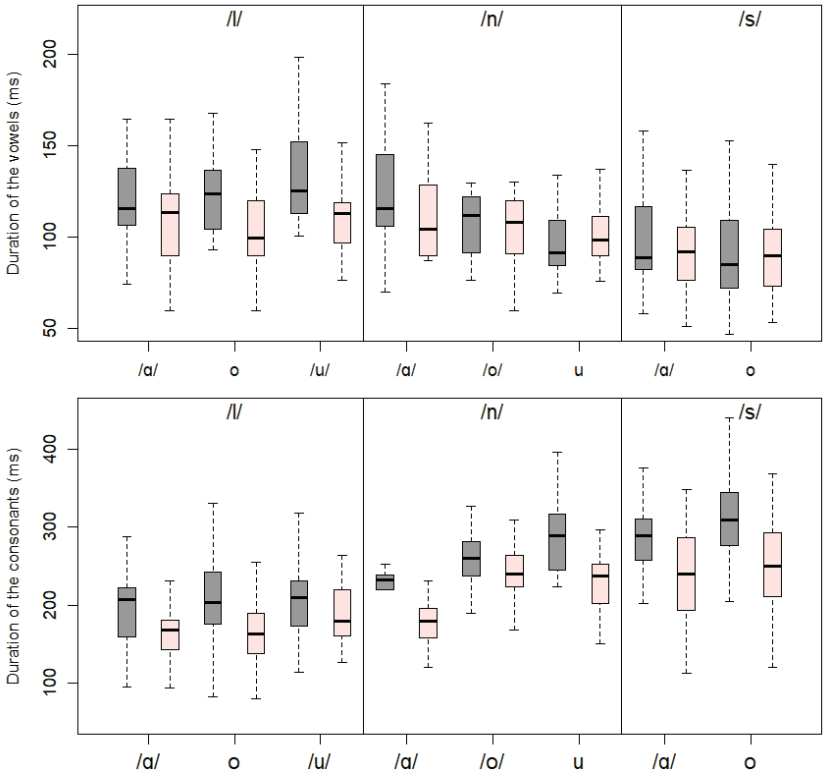

Figure 13. The mean duration (in milliseconds) of vowels (upper panel) and palatalized consonants (lower panel) in *i*-stemmed nouns in the Estonian (gray) and Russian (pink) groups.

Figure 13 shows that the duration of /u/ preceding palatalized /l/ in the Russian group was 19 ms shorter compared to the Estonian group ($p = 0.013$, see Table 13 for estimate values). The duration of /o/ followed by palatalized /n/ was 22 ms shorter ($p = 0.026$) than in the Estonian group.

For consonants, in the Russian group the estimated duration of palatalized /l/ in the context of /ɑ/ was 36 ms shorter ($p = 0.013$) and in the context of /o/ it was 35 ms shorter ($p = 0.019$) compared to the Estonian group. The duration /s/ in the context of /o/ was 39 ms shorter ($p = 0.033$) and in the context of /u/ it was 61 ms shorter ($p < 0.001$) compared to the Estonian group. The duration of /t/ was always 49–65 ms shorter (all $p < 0.001$) compared to the Estonian group.

Table 13. The estimated duration (ms) of vowels (V) and palatalized consonants (C) in *i*-stemmed nouns and the durational difference between the Estonian and Russian groups.

	C2	**/l/**			**/n/**			**/s/**			**/t/**		
	V1	**/ɑ/**	**/o/**	**/u/**	**/ɑ/**	**/o/**	**/u/**	**/ɑ/**	**/o/**	**/u/**	**/ɑ/**	**/o/**	**/u/**
V	Estonian L1	127	122	123	128	131	121	111	108	96	107	105	96
	Russian L1	118	110	104	119	109	116	117	106	100	101	97	97
	Difference	–9	–12	–19	–9	–22	–5	6	–2	4	–6	–8	1
	p	0.226	0.141	0.013	0.239	0.026	0.586	0.371	0.793	0.623	0.414	0.296	0.873
C	Non-palat.	201	198	211	204	211	225	277	281	289	305	290	313
	Palatalized	165	168	198	178	185	188	252	242	228	241	241	248
	Difference	–36	–35	–13	–26	–26	–37	–25	–39	–61	–64	–49	–65
	p	0.013	0.018	0.242	0.103	0.191	0.057	0.054	0.033	< 0.001	< 0.001	< 0.001	< 0.001

4. Discussion

We have aimed to describe the articulatory and temporal properties of Russian L1 Estonian L2 palatalization and to compare these results with native speakers' productions.

4.1. Russian L1 production in word pairs

Russian group did palatalize consonants in word pairs, but not consistently. There was a lot of variability in the Russian group, and thus we chose to analyze only those tokens in which the participant used palatalization to differentiate meaning. In doing so, we had to discard 238 tokens (from total of 395) because the participants palatalized consonants that should not be palatalized and/or did not palatalize consonants that should be palatalized.

When they did palatalize consonants, their tongue dorsum was higher and more anterior. In this, the rising and fronting of the tongue are consistent with the results from our articulatory study on Estonian palatalization (Malmi & Lippus 2019) and in line with findings from other languages (e.g., Russian – Kochetov 2002, Polish – Zygis & Pompino-Marschall 1999). The width of the tongue in the Russian group varied without a systematic pattern. As previous research has shown (Kutser 1935, Ariste 1943, Eek 1971, Meister & Werner 2015), the tongue should also be wider with palatalization because it is pressed against the hard palate.

When we compared their palatalized tokens to the Estonian group, we found that only in some vocalic and consonant contexts were these similar to native production. In many cases, the tongue dorsum in the Russian group was lower and more posterior than in the control group. The width of the tongue was similar between the groups. This indicates that the width of the tongue of Estonian L1 speakers in our current study also varied without a systematic pattern and that it is not a reliable measure for describing palatalization in Estonian.

The participants in our study were all born in Estonia and have lived there their whole lives. Even though their self-assessment of their Estonian proficiency was relatively high (average 4.1 on a 5-point scale), being very close to the native speakers' assessments (average 4.5), the variability in their production of palatalization was high. The results

suggest that recognizing palatalization from a text can be a problem for the learner even when their self-assessment is quite high.

4.2. Russian L1 consonants in *i*-stemmed nouns compared to Estonian L1 production

In addition to investigating production in phonologically distinctive word pairs, we also looked at how the Russian group articulates *i*-stemmed nouns where the final consonant should be palatalized, but where palatalization does not differentiate meaning (in other words, a corresponding, non-palatalized lexical item does not exist). Those test words were added as a failsafe in case the speakers in the Russian group might not recognize the words in contrastive pairs. In our previous acoustic study (Malmi & Lippus 2021), we found that Russian L1 speakers tended not to palatalize consonants in *i*-stemmed nouns. The aforementioned acoustic study only had eight participants, and they were younger and less educated than the speakers in the current study.

The results showed that, compared to the Estonian group, in the Russian group the tongue dorsum was lower when producing these consonants and the preceding vowels. However, the anteriority and the width of the tongue were similar. This shows that Russian L1 speakers probably palatalize word-final consonants in *i*-stemmed nouns but with a lower tongue dorsum.

The results from both contrastive word pairs and *i*-stemmed words suggest a pattern of language-specific articulatory settings (Gick et al. 2004, Wilson & Gick 2013) that differentiate both languages. The speakers achieve similar articulatory or maybe even perceptual goals with different strategies. Because of that, the realization of the corresponding segments is different.

4.3. Temporal properties of Russian L1 speakers compared to Estonian L1

Although the results of articulatory movements showed that the Russian group palatalized consonants somewhat similarly to native speakers, the duration of the vowels was not systematically longer. Consonants, on the other hand, showed some tendency to be longer with palatalization. When we compared their results to native speakers, we

found that both in phonological pairs and *i*-stemmed nouns, the duration of palatalized consonants and the preceding vowels were significantly shorter in Russian group. We did not test this, but the reason might have been that the Russian group had a faster speaking rate than native speakers did.

Numerous studies have shown that the articulatory gesture of raising the tongue towards the hard palate causes a longer duration of the vowels that precede palatalized consonants (e.g., Cavar 2004, Kavitskaya 2006, Teras & Pajusalu 2014, Malmi & Lippus 2019). In Estonian, we have not found a lengthening effect on the palatalized consonant (Malmi & Lippus 2019, Malmi, Lippus & Meister 2022). In Russian, the palatalized consonant is sometimes lengthened because of the aspiration that accompanies the consonant (Bolla 1981, Kochetov 2002, Kochetov & Radisic 2009). This might explain why Russian L1 speakers' consonants tended to be longer in the current study as well.

From our two studies (Malmi & Lippus 2021 and the current one), we can conclude that even though palatalization is salient in Russian, Russian L1 learners of Estonian produce the corresponding temporal properties differently from Estonian native speakers. The reason might be that the palatalized consonants were stressed and overlong in our study. Estonian is known for its ternary phonological quantity contrast, with short, long, and overlong vowels and consonants. In Russian, the duration is mainly used to indicate stress. Lya Meister (2011) has shown that Russian L1 speakers have problems acquiring and producing Estonian quantity degrees because of that.

4.4. Findings in the light of the Speech Learning Models (SLM and SLM-r) and Perceptual Assimilation Model (PAM and PAM-L2)

We confirmed our hypothesis, based on predictions by SLM-s (Flege 1995, Flege & Bohn 2020) and PAM-s (Best 1995, Best & Tyler 2007), that Russian L1 speakers' palatalized tokens are different from those of native speakers. This is presumably because, as learners, they are not sufficiently sensitive to the fine acoustic and articulatory details. According to SLM and PAM, the learners might classify Estonian palatalization as being equivalent to palatalization in Russian, and they map it directly onto their L2 without any additional learning. The learners are

attuned to their native language in the production of palatalization, and they use different motor patterns to achieve the segmental goals – these different patterns in articulation are manifested in a differing production of palatalization in Estonian.

4.5. Limitations and future perspectives

The use of Estonian palatalization can be difficult for Russian L1 speakers. Language learners and teachers should devote more time to studying its intricacies because it can contribute to Russian-accented speech in Estonian, and because it has a functional role in differentiating words. It would be useful to study the role of the duration of palatalization further since our research shows that – probably due to the different usage of duration in these two languages – the production of palatalization is also affected. It is also unclear how learners perceive Estonian palatalization and whether they successfully distinguish word pairs for which palatalization differentiates meaning. In addition, it would be interesting to look at how native speakers perceive palatalization that Russian L1 speakers produce. It might be that the articulatory and temporal differences that we found in the current study are also perceivably different for Estonian L1 speakers.

5. Conclusions

We analyzed the articulation of Estonian palatalization by Russian L1 Estonian L2 speakers in comparison to native speakers. The articulatory movements and segmental durations were measured within a sequence of word-final consonants and their preceding vowels in two contexts: a) word pairs where palatalization differentiates meaning, and b) *i*-stemmed nouns. The results showed that, although there was a lot of variability in the data, the Russian L1 speakers effectively differentiated between palatalized and non-palatalized words; with some exceptions, their productions were mostly similar to Estonian L1 speakers, although the tongue dorsum tended to be lower and more posterior. In *i*-stemmed nouns, their tongue dorsum was lower, but the anteriority and width were similar to those found in native Estonian L1 production. Russian L1 speakers produced palatalized consonants and the preceding vowels with a significantly shorter duration than native speakers did.

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Kokkuvõte. Anton Malmi, Pärtel Lippus, Einar Meister: Vene emakeelega kõnelejate Eesti palatalisatsiooni artikulatoorsed ja temporaalsed tunnused. Artiklis uuritakse, kuidas vene emakeelega kõnelejad hääldavad eesti keele palatalisatsiooni. Varasemad uurimused on näidanud, et konsonanti palataliseeritakse keeleselja tõstmisega kõva suulae poole. Sellega kaasneb ka eespoolsem keele asend ja laiem keele jaotus suulaes ning hääliku pikem kestus. Uurimismaterjal koosnes sõnadest, kus palatalisatsioon eristas tähendust ja *i*-tüvelistest nimisõnadest, mis lõppesid pika palataliseeritud konsonandiga. Testsõnu sisaldavaid lauseid salvestasime elektromagnetartikulograafiga. Katses osales 24 vene emakeelega ja 21 eesti emakeelega kõnelejat. Tulemused

näitasid, et vene emakeelega kõnelejate keel oli palataliseerimisele omaselt kõrgemal ja eespoolsem. Eestlastega võrreldes oli nende keel aga madalamal ja tagapoolsem. Vene emakeelega kõnelejad ei kasutanud palatalisatsioonipaarides kestust eristava tunnusena nagu emakeelsed kõnelejad seda teevad. Nende vokaalid ja konsonandid olid palatalsatsioonipaarides ja *i*-tüvelistes nimisõnades lühemad kui emakeelsetel kõnelejatel.

Märksõnad: palatalisatsioon, artikulograafia, kestus, eesti keel, vene aktsent, teise keele omandamine