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Juris GRIGORJEVS
Latvian Language Institute of the University of Latvia

ACOUSTIC CHARACTERISTICS OF THE LATVIAN SONORANTS

Introduction

The acoustic research of the Latvian sound system started in 60-ies of the 20th century, however it was limited by the available technical equipment. In 2000 a modern Phonetics laboratory was established at the Faculty of Philology, University of Latvia. Since then an extensive research of the Latvian vowels and obstruents has been performed. The Latvian sonorants were not in the focus of attention till the end of 2011. The need to include the acoustic characteristics of these sounds into their description for the new Academic Grammar of the Latvian Language prompted a pilot research of acoustic properties of the Latvian sonorants /l, ʎ, m, n ([n] and [ŋ]), ɲ, r/. The results of this study are reflected in the present article.

Background

According to the definition of sonorants these sounds are produced with a relatively free airflow, and a vocal cord position such that spontaneous voicing is possible, as in vowels, liquids, nasals and laterals (Crystal 1998, 354). Since the aim of the present study was to establish acoustic characteristics of the Latvian liquids and nasals, it was necessary to define the acoustic cues that could help distinguish these sounds from each other and also from other Latvian sounds. The literature dealing with the general acoustic properties of speech apparatus was chosen as a theoretical base for the completion of this task.

Nasals

The main properties of nasals (registered in English, Catalan, Thai, etc.) are as follows: low F_1 of about 300 Hz (sometimes called the “nasal formant”) that is well separated from higher formants, close spacing between formants that tend to be highly damped (i.e., they have large bandwidths reflecting a rapid rate of absorption of sound energy), and the presence of anti-formants whose frequencies are determined by the place of articulation (Johnson 2003, 157; Kent, Read 1992, 132).

The nasal consonants are produced with closure of the oral cavity and radiation of the sound through the nasal cavity, while the obstructed oral cavity acts as a side-branch resonator (Johnson 2003, 151; Kent, Read 1992, 130; Ladefoged, Maddieson 1998, 116; Pickett 1999, 113; Stevens 1998, 487–489). This sound produced in the nose is called a nasal murmur; its spectrum is dominated by a low frequency sound (limited to the region about 250 to 300 Hz) determined mostly by the main resonance of the large volume of the nasal passages constricted by the small nose openings (Pickett 1999, 113–114; Stevens 1998, 489). However, the volume of the sinuses, as well as the impedance of the walls, also plays a role in determining the frequency of this lowest resonance (Stevens 1998, 489). The murmur is similar to the vowel in having a number of spectral peaks but only one of these, the low frequency nasal formant, has an amplitude comparable to that of the vowel formants (Kent, Read 1992, 132). The nasal formant is accompanied by a number of much weaker resonances at higher frequencies. The formant bandwidths during nasal sounds are wider than those in non-nasal sounds, because the vocal tract with the nose open has greater surface area and greater volume, i.e., an enlarged surface and the inertia of air within the vocal tract absorb more sound (Johnson 2003, 151). The increased bandwidths of nasal sounds also cause the formant amplitudes to be reduced; therefore in spectrograms they appear lighter than the nearby oral vowels (Johnson 2003, 155). The second formant of the nasal murmur is in the range of 750 to 1000 Hz (neglecting the effects of pole-zero pairs resulting from coupling to the sinuses); it has low amplitude, since the relatively low frequency of the first resonance reduces the amplitudes of higher peaks in the transfer function (Stevens 1998, 490).

The movement of the oral tract for nasals is similar to that of stops, with rapid transitions, abrupt onset and offset of occlusion, and an occlusion interval of about 100 ms (Pickett 1999, 114). There may be some difference in the trajectories of the release, because in the case of nasal consonants there is no intraoral pressure to create extra abducting forces on the articulatory structure that forms the constriction (Stevens 1998, 489). The lead and lag of velar opening and closing, preceding and following the oral occlusion, are typically about 100 ms, and this causes nasalization of portions of vowels for about 100 ms preceding and following the oral occlusions of nasal consonants (Pickett 1999, 115). Since the average pressure above the glottis remains near atmospheric pressure, and if the vocal folds remain in a configuration for modal voicing during the time when there is closure in the oral cavity, the folds continue to vibrate in a normal manner during the production of a nasal (Stevens 1998, 488).

The nasal passages of a speaker remain constant in shape and size for different nasal consonants, and for this reason the murmur spectrum does not differ greatly among [m, n, ŋ]; however, there are some differences due to the different lengths of the connected but closed oral tract, longest for [m] and shortest for [ŋ] (Pickett 1999, 113). Both theoretical and empirical studies of the spectral properties of nasals indicate that this side chamber contributes to a spectral zero or anti-resonance (Ladefoged, Maddieson 1998, 116). Frequency components in the sound source that are near the resonant frequencies of a side cavity resonate in the side branch (they are "absorbed" in it) without making an appearance in the acoustic output of the acoustic tube system; so the frequency components that are near the resonant frequencies of the mouth are canceled, thus they become anti-resonances (also called "anti-formants" or "zeros") in the acoustic output (Johnson 2003, 154). The frequency of this zero is inversely related to the volume of the cavity, which in turn results from the position of the tongue (and other moveable tissues) in the front of the mouth. The frequency of the first nasal resonance and the oral zero are both higher the nearer the oral articulation is to the uvular region (Ladefoged, Maddieson 1998, 116). This can be illustrated by the data from Catalan: [m] – F_1=250 Hz, Z_1=?; [n] – F_1=280 Hz, Z_1=1780 Hz; [ɲ] – F_1=290 Hz, Z_1=2650 Hz; [ŋ] – F_1=300 Hz, Z_1=3700 Hz (Ladefoged, Maddieson 1998, 117). The first nasal formant and the frequency of oral zero are the only cues that help distinguish between nasals with different places of articulation, if they are presented to the listener isolated and the judgment has to be based on the murmur only.

For better understanding of relations between the sound articulation and acoustics tube models are used as an illustration. The simplest is a vocal tract approximation by a uniform tube. It must be noted that the tube model gives only a rough approximation of the vocal tract resonator, therefore the calculation of resonances and anti-resonances can show only general tendencies associated with the production of a particular sound and give only a basic understanding of its acoustics. Similarly as the production of /ə/ can be regarded having oral articulation where the vocal tract resonator is closest to the uniform tube, for nasals such an approximation can be found in the articulation of the uvular nasal /ɴ/. In this case the pharyngeal-nasal resonator is constructed from two tubes reflecting the pharyngeal cavity (9 cm) and the nasal cavity (12.5 cm) giving the total length of 21.5 cm (Johnson 2003, 152). A uniform tube of this length would produce formants at the following frequencies: F_1=407 Hz, F_2=1221 Hz, F_3=2035 Hz, F_4=2849 Hz. Such a tube resonates at lower frequencies than about a 17 cm long resonator for oral sounds. As a result, formants during nasal consonants are spaced closer. But the vocal tract is not a uniform tube. There is a constriction of the nasal tract at the nostrils, therefore each of the resonant frequencies have to be lower than the calculations suggest. The shape of the nasal passage varies from person to person, as well. Nasal consonants are generally weaker than vowels not only because of a larger resonant passage-way, but also because in nasals the vocal tract has side cavities like the sinuses and that the vocal tract is more constricted at the opening to the nasal passages. The sinuses function like Helmholz resonators, so their resonant frequencies, the frequencies of the anti-formants that they contribute to the spectrum, depend on the volume of the sinus and the dimensions of its opening (Johnson 2003, 152–157).

If the place of oral occlusion for a nasal is not uvular, there is a side-branch of the resonator made by the oral cavity. The length of this side-branch depends on the place of oral occlusion. The schematic representation of the resonator for the Latvian nasals (Figure 1) shows typical places of articulation and the corresponding tube model. For the tube model described above, the articulation of [m] would add an 8 cm long side-branch that would result in the anti-resonance Z_1=1094 Hz, whereas the articulation of [n] would add a 5.5 cm long tube that would produce the anti-resonance Z_1=1591 Hz (Johnson 2003, 152–155). Stevens has described nasal zeros calculated for a 19.6 cm long pharyngeal-nasal resonator (Stevens 1998, 494–513): for a 7-8 cm long oral cavity of [m] Z_1 is in the range of 1000-1200 Hz (in the given example Z_1=1100 Hz), for a 5-6 cm long oral cavity of [n] Z_1 is in the range of 1600-1900 Hz (in the given example Z_1=1900 Hz), but for about a 3 cm long oral cavity of [ŋ] Z_1 could be calculated as being within the range of 2900-3200 Hz (if the air is at the body temperature). These values can be compared with zeros observed in real languages:

[m]: Z_1=750 Hz (Johnson 2003, 157); Z_1=800 Hz (Pickett 1999, 138); Z_1=500-1500 Hz (Borden, Harris 1981, 115);

[n]: Z_1=1780 Hz, Z_1=1403 Hz (Ladefoged, Maddieson 1998, 117); Z_1=1400 Hz (Johnson 2003, 157); Z_1=1500-2000 Hz (Pickett 1999, 138); Z_1=2000-3000 Hz (Borden, Harris 1981, 115);

[ɲ]: Z_1=2650 Hz, Z_1=2094 Hz (Ladefoged, Maddieson 1998, 117);

[ŋ]: Z_1=3700 Hz (Ladefoged, Maddieson 1998, 117); Z_1=5000 Hz or higher (Pickett 1999, 138); Z_1=above 3000 Hz (Borden, Harris 1981, 115).

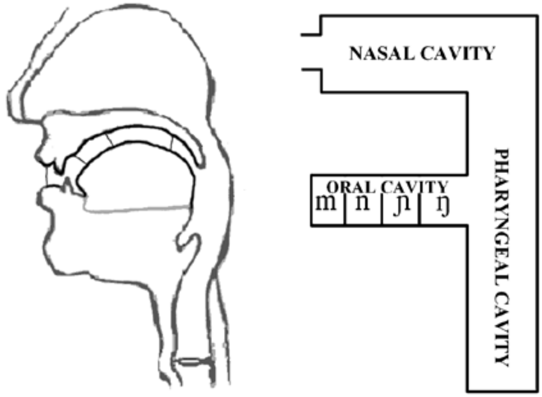


Figure 1. **The articulatory scheme of the nasal resonator and its approximation by a tube model** (the approximate length of the side branch made by the oral cavity is shown by lines connecting the active and the passive speech organs involved in building of an occlusion; the indicated articulatory areas correspond to the vertical lines in the tube model)

The conclusion can be drawn that in the majority of cases the calculated values of the zero for [m] are higher than those observed. The calculated values for [n] are close to those observed, whereas the calculated values for [ŋ] are lower.

The F1 transitions of nasal consonant articulation are often somewhat overridden by the changing pole-zero pattern form nasalization (Pickett 1999, 118) or zero insertion in the region of F1 and F2, which makes it difficult to analyze the different spectrum features that might be related to the tongue and lip articulations (Pickett 1999, 138). The murmur spectrum is strong in amplitude in the region below 500 Hz and relatively weak above 500 Hz, thus the differences in murmur features, mainly the location of the zero corresponding to the place of articulation, are not very prominent and nasals are poorly discriminable one from another on the basis of the voiced steady state portion isolated from the transitions which might precede or follow it (Pickett 1999, 138; Ladefoged, Maddieson 1998, 118). Perceptual experiments have demonstrated different tendencies – either that the nasal murmur and the transitions are roughly equal (Kent, Read 1992, 133–134; Ladefoged, Maddieson 1998, 118) in providing information on the place of articulation (mostly in VC syllables), or that the place of articulation is cued primarily by the transition segment and not by the murmur

(Kent, Read 1992, 134; Pickett 1999, 138). Experiments have shown that listeners are sensitive to vowel nasalization and use this information to make perceptual judgments about the neighboring consonants (Kent, Read 1992, 136).

Laterals

Laterals are sounds in which the tongue is contracted in such a way as to narrow its profile from side to side so that a greater volume of air flows around one or both sides than over the center of the tongue (Ladefoged, Maddieson 1998, 182). The laterals can be analyzed in a way that is very similar to the analysis of nasals, because lateral sounds are produced with a side branch that introduces an anti-formant in the output spectrum (Johnson 2003, 160). Thus, /l/ shares with the nasal consonants a steady state segment for which the transfer function contains both formants and anti-formants (Kent, Read 1992, 139). [l] has two discontinuities in the spectrum and amplitude, which are seen especially in the F1 and F2 regions; this is because the tongue tip makes, holds, and then releases its contact with the alveolar ridge (Pickett 1999, 110). F2 and F3 are closer together in laminal laterals than in apical ones (Ladefoged, Maddieson 1998, 197). The formant pattern of [l] during the constriction is prominent in the region of F3 and F4, in contrast to the other glides. The formants of [l] vary in location depending on the adjacent phonemes (Pickett 1999, 110). For the movement to the [l] constriction, there is a slight downward transition in F2 but little or no transition in F3 and F4 (Pickett 1999, 109). Although both liquids ([r] and [l]) are associated with a relatively rapid acoustic change between the consonant and vowel, it appears that the change for [l] tends to be faster than that for [r], especially with regard to F1 (Kent, Read 1992, 138).

The largest number of contrasting simple voiced lateral approximants known to occur in a language is four (Ladefoged, Maddieson 1998, 185). Places of articulation can range from dental (apical) to velar (dorsal) (Ladefoged, Maddieson 1998, 191).

The configuration of the vocal tract for laterals can be modeled with a uniform tube that has a short side branch, where the side branch is the pocket of air on top of the tongue (as in Figure 2, but without narrowing of the oral cavity). If the vocal tract length for [l] is 16 cm (10 cm from the glottis to the branch and the lateral outlet cavity of 6 cm) and the length of the pocket is 4 cm the resonant frequencies for a uniform tube are: F_1=531 Hz, F_2=1594 Hz, F_3=2656 Hz, but Z_1=2125 Hz (Johnson 2003, 160–161). This tube model is oversimplified, because the outlet cavity has a smaller diameter than does the

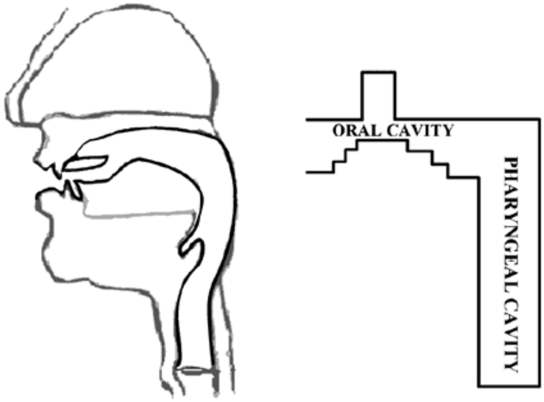


Figure 2. **The articulatory scheme of the resonator for [l] and its approximation by a tube model** (the side branch made by the tongue pocket is shown in both models)

tube from the glottis to the lateral constriction (Figure 2). The most important acoustic consequence of this is that the frequency of F1 is lower than it would be in a uniform tube. The spectral "signature" of laterality is an anti-formant between F_2 and F_3. There also seems to be an additional anti-formant in the spectrum at about 1 kHz, which may have resulted from the asymmetry of the lateral openings around the tongue (Johnson 2003, 163). For laterals without a secondary constriction involving the back of the tongue, the frequency of F2 appears to be inversely related to the volume of the oral-pharyngeal cavity behind the articulatory occlusion (Ladefoged, Maddieson 1998, 196).

It is possible to compare the calculated formant frequencies with the mean formant frequencies for /l/ in three different studies: Nolan: F1-360 Hz, F2-1350 Hz, F3-3050 Hz; Lehiste: F1-295 Hz, F2-980 Hz, F3-2600 Hz; Al-Bamerni: F1-365 Hz, F2-1305 Hz, F3-2780 Hz (Kent, Read 1992, 139). One can see that the uniform tube model predicts higher values of F1 and F2. On the basis of observations in different languages it is possible to derive the general pattern of formant values for laterals (Ladefoged, Maddieson 1998, 193–197):

- The first formant of lateral segments is uniformly low – typically below 400 Hz for male speakers, but it can be higher;
- The second formant may have a center frequency anywhere within a fairly wide range depending on the location of the occlusion and the profile of the tongue (the frequency is lower for velarized production);

- The third formant has typically a relatively strong amplitude and high frequency, and there may also be several closely spaced additional formants above the frequency of F3.

Trills

The primary characteristic of a trill is that it is the vibration of one speech organ against another, driven by the aerodynamic conditions (Ladefoged, Maddieson 1998, 217). Acoustic trills in linguistic use usually consist of two to five periods; and the most common of them involve 1) the tongue tip vibrating against the contact point in the dental/alveolar region (this is by far the most common type of trill consisting of two to three periods of vibration, but may contain only one or have more than three), or 2) the uvula vibrating against the back of the tongue (Ladefoged, Maddieson 1998, 218).

During the consonant production trills have the following structure (Ladefoged, Maddieson 1998, 219):

- The contacts are preceded by a short approximant or vowel-like sound of about 50 ms duration;
- After the contacts there is another approximant interval, lasting over 50 ms, with a similar formant structure to that seen in the open phase (this is part of the consonant duration, as the tongue does not move away from the consonantal position until the end of the articulation);
- The end of the consonant is indicated by an abrupt upward transition of the third formant, as well as a significant upward shift in F1.

A lingual flap (a one-tap trill) is made as a very rapid tongue movement from one vocal tract configuration, typically for a vowel, to a brief (compared to distinctive productions of /t/ and /d/, the flap has a short overall duration and a very brief closure period) contact with the alveolar ridge or the post-dental region, then the contact is followed by a rapid movement away from the constriction (Kent, Read 1992, 141). In its spectrographic appearance, the flap and the trill consisting of one vibration are remarkable primarily for their brevity, and it is problematic to distinguish these sounds. The main difference is in the force behind this action – it is muscular action for the flap, but the aerodynamic force for the trill.

Aims

The aim of this study is to provide significant acoustic characteristics for the Latvian sonorants /l, ʎ, m, n, ɲ, r/ (including allophone [ŋ]).

There are three nasal phonemes in Standard Latvian – the bilabial /m/, the dental /n/ and the palatal /ɲ/ (Laua 1997, 35, 39–40, 51). If /n/ is pronounced before a velar stop, it is articulated as the velar [ŋ] (Laua 1997, 40). Since the main distinction between nasals during the nasal murmur is provided by the oral anti-resonance, but in syllables – by formant transitions, the Latvian nasals will be characterized by the frequency values of the oral zero and values obtained from locus equations.

There are two lateral phonemes in Standard Latvian – the dental (as concluded from the recent EPG study by the author of the present article) or alveolar /l/ and the palatal /ʎ/ (Laua 1997, 45–48, 54). Since the formant pattern of these oral sounds is significant both during the lateral production and during the transition to the neighboring vowel, the Latvian laterals will be characterized by the frequency values of the first four formants and the lateral zero, as well as values obtained from locus equations.

There is one trill phoneme in Standard Latvian – the alveolar trill /r/ (Laua 1997, 48–49). Since the main characteristics of trills are very short occlusions and a vowel-like formant pattern during the open phase, the Latvian trill will be characterized by the frequency values of the first four formants and the duration of the closed and the open phase of vibration.

Method

The material of this study consists of symmetric CVC type syllables where C is one of the Latvian sonorant consonants [l, ʎ, m, n, ɲ, ŋ, r] and V is one of short monophthongs [i, e, æ, ɑ, ɔ, u], e.g., [lil], [lel], [læl], [lɑl], [lɔl] and [lul]. The material was recorded using the USB audio capture device EDIROL UA-25 attached to a computer and the head-mount condenser microphone AKG C520. The recording was done at 44.1 kHz sample rate and 16 bit quantization. Each syllable was pronounced three times by five informants, native speakers of Latvian (two female, three male) of the age between 30 and 45, who do not have any speech disorders or dialectal traces in their pronunciation.

The acoustic analysis of the acquired material (630 syllables) was performed using program Praat (version 5.3.03 by Paul Boersma and David Weenink). The acoustic analysis was done using wideband spectrograms, FFT and LPC spectral slices. LPC smoothing was performed with the number of peaks set to 26. Only the initial consonant of each syllable and the formant transitions to the following vowel were analyzed. The exception was made for measuring the duration of vibration phases of trills, which were measured in both syllable initial and syllable final trills.

Results and discussion

Nasals

First, the dynamic spectrograms of recordings were analyzed to choose the steady state part of the initial nasal for obtaining the spectral slice (FFT) and

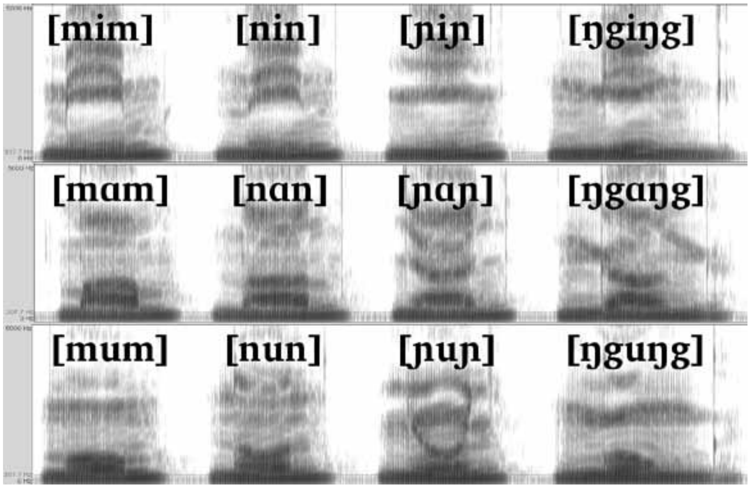


Figure 3. **The dynamic spectrograms of all Latvian nasals in the context of the corner vowels in CVC syllables**

to estimate F2 value at the beginning of CV transition, as well as F2 value in the middle of the vowel. The dynamic spectrograms of all Latvian nasals in the context of the corner vowels by a male informant are presented in Figure 3. It can be observed that the formant structure of each nasal differs in the context of different vowels, and this can be explained by different tongue body configurations for these vowels affecting not only the oral but also the pharyngeal cavity. The anti-resonances cannot be easily defined in the presented spectrograms (Figure 3).

To find the oral zeros the spectral slices made for the steady state of each nasal were used. The obtained FFT spectra were plotted along with LPC spectra (smoothing with 26 peaks) to determine the frequency region of the zero, because LPC analysis is based on the assumption that the vocal tract transfer function has no anti-formants (Johnson 2003, 157). The process is illustrated in Figure 4 on the example of a male speaker's first pronunciation of each syllable. The arrows point to the frequency region of the oral zero for each of the Latvian nasals in the context of the corner vowels (V = [i, ɑ, u]).

The region of the zero frequency was searched taking into account the length of the oral resonator. It can be observed (Figure 4) that the frequency of oral zero depends not only on the length of the side-branch, but also on the shape of it caused by the tongue configuration affected by the context

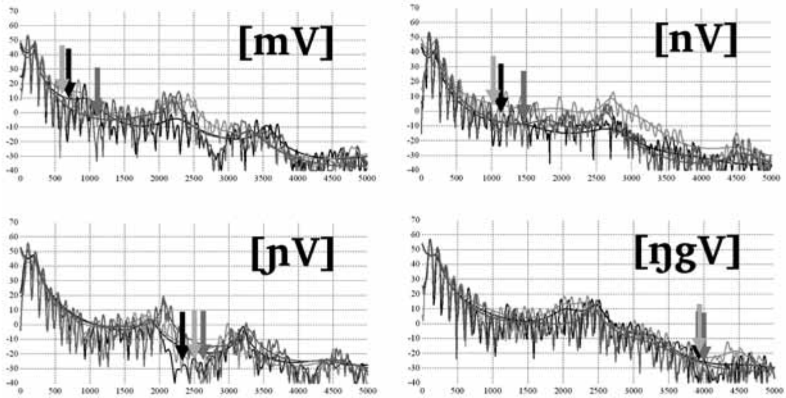


Figure 4. **The anti-resonances (zeros) of syllable initial Latvian nasals in the context of the corner vowels** (the locations of zero are shown by arrows – the dark grey for the context of [i], the black for the context of [ɑ], the light grey for the context of [u])

vowel. The obtained results show that the frequency of the oral zero apparently differs because of articulatory habits and gender differences of the informants. This is illustrated by the data of three informants in Table 1. It can be observed that the zero values differ not only between male (V1) and female (S1 and S2) informants, but also between both female informants. There is a clear pattern for each informant showing that shortening of the oral side-branch results in a higher frequency of the zero, and that the frequency ranges of zeros of different nasals do not overlap or overlap very little.

It was found that the oral zero for the Latvian **[m]** in the pronunciation of 5 informants was in the range of **600-1200 Hz**. It was higher (up to about 1300 Hz) only in the context of close front vowels. The mean value of [m] zero for male informants was about 850 Hz, for female – about 900 Hz.

The oral zero for **[n]** was found to be in the range of **1200-1700 Hz**. It was lower (up to about 1000 Hz) only in male pronunciation in the context of back vowels. The mean value of [n] zero for male informants was about 1150 Hz, for female – about 1420 Hz. The oral zero for **[ŋ]** was in the range of **2200-3500 Hz**. Only in a few cases it was higher (up to about 3600 Hz). The mean value of [ɲ] zero for male informants was about 2520 Hz, for female – about 3040 Hz. The oral zero for the Latvian **[ŋ]** was found to be in the range of **3500-4700 Hz**. There were occurrences when the zero was lower (up to about 3200-3300 Hz); these values were observed in the female

Table 1. **The measured anti-resonances (zeros) of syllable initial Latvian nasals produced in CVC syllables by three informants (V1 – male, S1 and S2 – female) in the context of all short monophthongs**

Speaker	Vowel	[**m**] (Hz)	[**n**] (Hz)	[**ɲ**] (Hz)	[**ŋ**] (Hz)
V1	**[u]**	600-700	1000-1200	2500-2700	3800-4300
	[o]	700	1000-1100	2200-2700	3700-4300
	[a]	700	1000-1300	2200-2700	3800-4300
	[æ]	800	1100	2200-2800	3800-4300
	[e]	1000-1100	1200	2200-2800	3800-4200
	[i]	1100-1200	1400	2400-2800	3800-4200
S1	**[u]**	700	1400-1500	2700	3500-3600
	[o]	700	1400-1500	3000-3100	3300-3700
	[a]	750-800	1400-1600	2700-3500	3300-3700
	[æ]	1000-1200	1300-1700	2700-3400	3800-4200
	[e]	1300	1300-1600	2800-3300	3700-4300
	[i]	1250-1300	1300-1700	2700-3300	4200-4700
S2	**[u]**	700-750	1200-1400	2800-3250	3800-4000
	[o]	750-800	1400	2800	3200-3800
	[a]	750-800	1400	2700-3500	3400-4600
	[æ]	700-1200	1300-1400	2700-3300	3500-4100
	[e]	700-1300	1300-1400	2700-3500	3500-4300
	[i]	800?	1250-1400	3400-3600	3500-4600

pronunciation in the context of the vowels [ɔ] and [ɑ]. The mean value of [ŋ] zero for male informants was about 4030 Hz, for female – about 3840 Hz. These numeric results suggest that the value of oral zero can be used to make a distinction between the Latvian nasals, although due to the low energy of the nasal murmur this cue can have very limited perceptual significance.

The zero values of the Latvian nasals agree fairly well with those listed in the theoretical literature. Thus the total range for the oral zeros of [m] was 600–1300 Hz that fits into the range of 500–1500 (Borden, Harris 1981, 115) which incorporates also the calculated values derived from the model and those observed in natural languages and listed by other authors (Johnson 2003, 154–157; Pickett 1999, 138; Stevens 1998, 494). The range for the oral zeros of the Latvian [n] was 1000–1700 Hz; and in the context of the same vowel the zero of [n] always had a frequency about 100 Hz higher than the zero of [m]. The zeros of [n] observed in Latvian (especially in male pronunciation) were generally lower than those observed in other languages

(Borden, Harris 1981, 115; Johnson 2003, 157; Ladefoged, Maddieson 1998, 117; Pickett 1999, 138) or theoretically predicted on the basis of a tube model (Johnson 2003, 155; Stevens 1998, 499). This can be explained by a dental articulation of [n] in Latvian instead of alveolar. The range for the zeros of [ɲ] was 2200–3600 Hz, and it was close to the values listed in literature (Ladefoged, Maddieson 1998, 117). The range for the zeros of the Latvian [ŋ] was 3200–4700 Hz; and in the context of the same vowel the zero of [ŋ] always had about 100 Hz higher frequency than the zero of [ɲ]. The zeros observed for the Latvian [ŋ] are in the range close to values observed for the corresponding sounds of other languages (Borden, Harris 1981, 115; Ladefoged, Maddieson 1998, 117).

If the transition segment is to be considered as the main cue determining the place of articulation for nasals (Kent, Read 1992, 134; Pickett 1999, 138), the F2 values are to be addressed since they are associated with the locus theory.

Table 2. **The mean values (in Hz) of F2 measured at the beginning of CV transitions (F_{2b}) and in the middle of the steady state of each vowel (F_{2s})**

Cons. \ Vow.		[i]		[e]		[æ]		[ɑ]		[ɔ]		[u]	
		F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}
[m]	male	*1717*	2194	*1429*	1846	*1331*	1543	*986*	1168	*907*	935	*819*	832
	female	*1834*	2647	*1729*	2168	*1584*	1791	*1202*	1317	*1118*	1158	*1000*	921
[n]	male	*1697*	2235	*1494*	1828	*1445*	1567	*1316*	1259	*1215*	985	*1219*	895
	female	*1843*	2625	*1767*	2143	*1816*	1829	*1621*	1339	*1472*	1140	*1464*	962
[ɲ]	male	*2130*	2225	*2047*	1984	*1934*	1647	*1873*	1392	*1842*	1065	*1876*	919
	female	*2674*	2598	*2458*	2230	*2382*	1894	*2442*	1442	*2317*	1247	*2373*	1100
[ŋ]	male	*2206*	2166	*2054*	1880	*1965*	1715	*1644*	1310	*1105*	948	*917*	912
	female	*2551*	2571	*2326*	2164	*2101*	1778	*1501*	1296	*1298*	1058	*1018*	913

To determine the locus of each nasal consonant F2 values were measured in the beginning of CV transition (at the release of the consonant) and in the midpoint of the steady state of the vowel. The mean values calculated for the male and female pronunciation separately are listed in Table 2. It can be observed that the value of vowel's F2 in the beginning of the transition and in the steady state of the vowel varies with respect to the quality of the consonant, but the tendencies can be different in the male and female pronunciation. The pattern in the F2 loci allowing a distinction on the basis of the place of articulation is discussed in greater detail further in the article in respect to the linear regression values for all Latvian sonorants.

Laterals

Similarly to nasals the analysis of the Latvian lateral approximants was started with the inspection of dynamic spectrograms. The formant values of the first four formants were measured in the steady state of each lateral, the portion of the steady state was used to obtain the spectral slice for FFT, and the value of vowel's F2 was measured at the beginning of CV transition, as well as in the middle of the steady state.

In the dynamic spectrograms it was observed that the Latvian laterals were characterized by a well defined formant pattern (in comparison to nasals) with abrupt changes in it at the moment of forming and release of the medial occlusion. F2 of laterals was clearly seen in all spectrograms, and in the pronunciation of all informants its frequency was always lower than 1500 Hz for [l] and higher than 1500 Hz for [ʎ]. So the frequency value 1500 Hz can be used as a boundary distinguishing between [l] and [ʎ] in spectrograms (Figure 5).

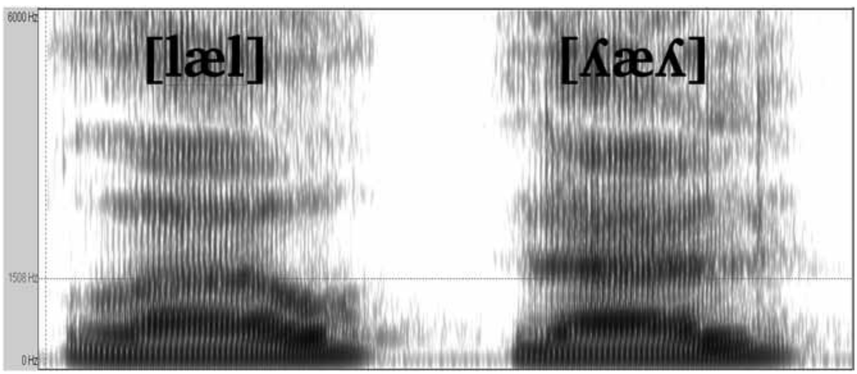


Figure 5. **The dynamic spectrograms of the Latvian lateral approximants in the context of [æ]** (the horizontal line at 1500 Hz shows the borderline between the possible F_2 for [l] and [ʎ])

Plotting on the same graph LPC spectra (obtained from FFT spectra applying smoothing with 26 peaks) of [l] (Figure 6) and [ʎ] (Figure 7) in the context of all Latvian vowels shows that the formant frequencies of [l] and [ʎ] do not depend directly on the formant frequencies of the vowel formants. Figures 6 and 7 show data obtained from the first pronunciation of CVC syllables by one male informant representing general tendencies observed in the pronunciation of all informants.

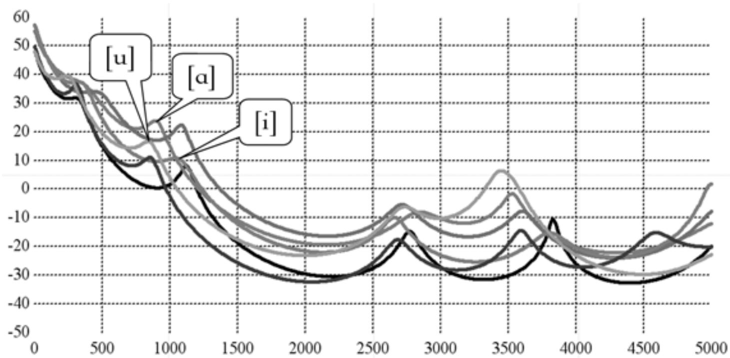


Figure 6. **The LPC spectra of the syllable initial [l] in the context of all Latvian short monophthongs produced by a male speaker** (the F2 peaks are marked for [l] in the context of the corner vowels)

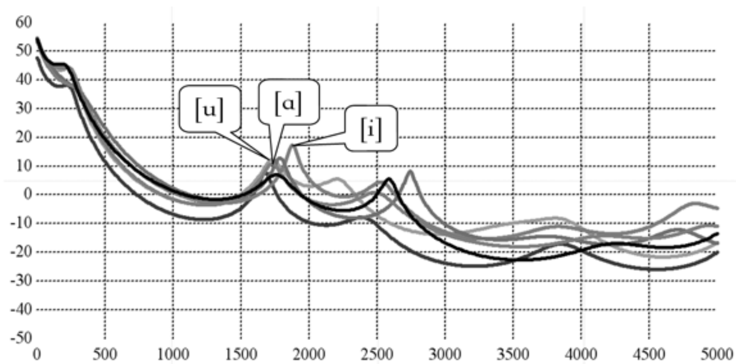


Figure 7. **The LPC spectra of the syllable initial [ʎ] in the context of all Latvian short monophthongs produced by a male speaker** (the F2 peaks are marked for [ʎ] in the context of the corner vowels)

The first formant of [l] (Figure 6) reveals greater dependency on the place of constriction in the vocal tract during the production of the vowel than on the openness of the context vowel, i.e., [l] in the context of vowels with a constriction in the velar region ([ɔ, u]) has the lowest values of F1, with a constriction in the pharyngeal region ([æ, ɑ]) – medium values, and with a constriction in the palatal region ([i, e]) – the highest values of F1.

The first formant of [ʎ] (Figure 7) exhibits very little dependency on the context vowel, because in Latvian the production of [ʎ] requires a contact of the front of the tongue dorsum with the frontal part of the hard palate, thus determining a particular tongue shape that allows very little freedom for coarticulatory adjustments.

The second formant of [l] (Figure 6) depends roughly on the frontness of the context vowel, i.e., if [l] is in the context of back vowels ([ɑ, ɔ, u]) it has lower F2 values (usually under 1000 Hz), but in the context of front vowels ([i, e, æ]) the F2 values are higher (usually above 1000 Hz). For F2 of [ʎ] the same tendency can be observed (Figure 7), except that F2 is located above 1600 Hz and the deviations of its values are smaller. According to the present data lip rounding does not have a significant influence on the value of F2 or higher formants of [l], but it lowers F3 values of [ʎ]. The ranges of the first four formant values of the Latvian lateral approximants in the pronunciation of all five informants are listed in Table 3. Comparing the formant values of the Latvian laterals with those listed in the reviewed literature it can be stated that in the majority of the described languages formant values of [l] fit into ranges found for the Latvian laterals (Kent, Read 1992, 139; Ladefoged, Maddieson 1998, 193–197).

Table 3. **The measured resonances (formants) of syllable initial Latvian laterals produced in CVC syllables by five informants (three male, two female) in the context of all short monophthongs**

CONSONANT	F_1	F_2	F_3	F_4
[**l**]	200–600 Hz	700–1300 Hz	2200–2800 Hz	3400–3800 Hz
[**ʎ**]	200–300 Hz	1600–1900 Hz	2200–2900 Hz	3800–4200 Hz

The lower values in the range of F2 for the Latvian [l] can be explained by its apical dental production and some velarization in the context of [ɔ] and [u]. Unfortunately in the reviewed literature there were no formant values listed for dorsal palatal laterals, therefore no comparison of values was possible.

To find the zeros of the Latvian laterals caused by the side-branch of the resonator made by the pocket of air on top of the tongue the spectral slices from the steady state of each syllable initial lateral approximant were used. The obtained FFT spectra were plotted along with LPC spectra (smoothing with 26 peaks) to determine the frequency region of the zero (like it was done for nasals). Such spectral plots for the Latvian laterals in the context of all short vowels were compared to find the zero with approximately the same frequency. The process is illustrated with the example of a male speaker's first pronunciation of each CVC syllable where [l] (Figure 8) and [ʎ] (Figure 9)

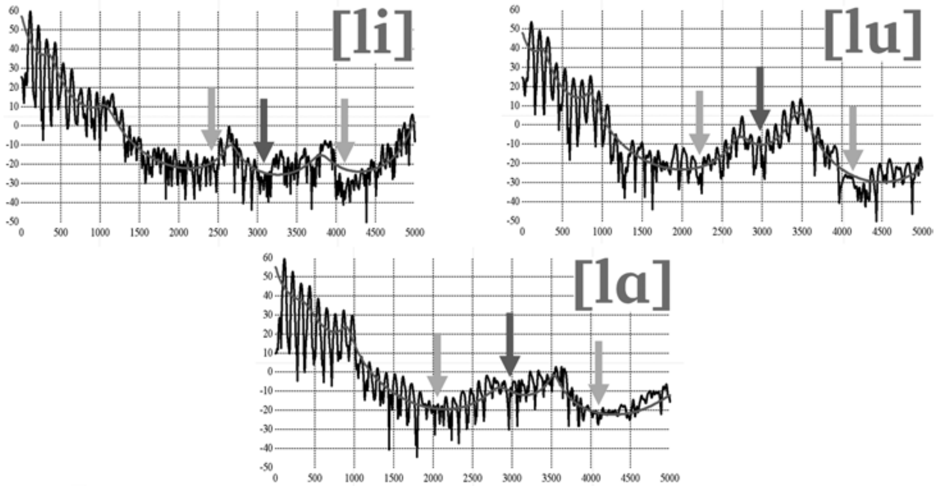


Figure 8. **The antiresonances (zeros) of the syllable initial Latvian [l] in the context of the corner vowels** (the location of zero is shown by arrows – the dark grey arrow points to the zero determined by the side branch of the resonator)

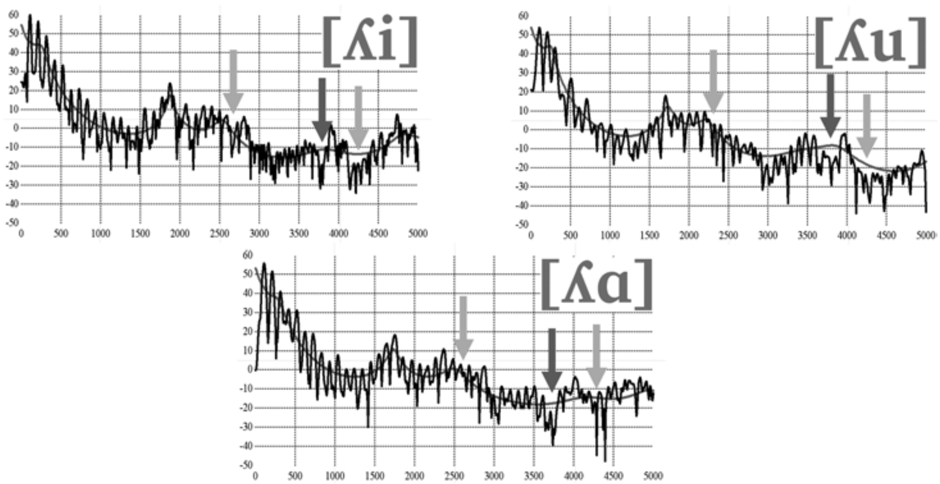


Figure 9. **The antiresonances (zeros) of the syllable initial Latvian [ʎ] in the context of the corner vowels** (the location of zero is shown by arrows – the dark grey arrow points to the zero determined by the side branch of the resonator)

was produced in the context of the corner vowels. The arrows (Figure 8 and 9) point to the frequency regions of the zeros, whose frequencies could be determined by the air pocket on top of the tongue, but the dark grey arrows specify the zero that seems to be common for all three vowel contexts and therefore depends on the size of the side cavity.

Since [l] in Latvian has apical dental production, it allows the tongue body some freedom to adjust for coarticulation with the context vowel, which in its turn can influence the shape and size of the side cavity on top of the tongue. This is a plausible explanation for a larger difference in the zero frequency of [l] in comparison to a small zero frequency deviation of [ʎ] observed in the data obtained for all five informants.

When analyzing the spectra of laterals only those zeros were registered whose frequencies were above 2000 Hz, because the air pocket for [l] approximated by a 4 cm long uniform tube as suggested by Johnson would result in the zero at 2125 Hz (J o h n s o n 2003, 161). It is very unlikely that in real articulation this pocket could be much longer therefore the frequency of the zero is unlikely to be lower than 2000 Hz.

The first four frequency values of the zero (above 2000 Hz) were measured for each lateral approximant produced by each of five informants. The obtained values of the possible zeros varied to great extent depending on the informant and the vowel context. The ranges of the first four zero values of the Latvian lateral approximants in the pronunciation of all five informants are listed in Table 4. The zero values that could result from the side cavity during the production of [l] and [ʎ] are marked in the table with bold font. Judging by the frequency values of the bold marked zeros (Table 4) the pocket of air on top of the tongue has a length of 2.6–2.9 cm for [l], and a length of 2.2–2.4 cm for [ʎ].

The author of the present article is aware of the fact that the choice of the zero is subjective and is not supported by articulatory data. If the condition that the laterality is signalized by a zero between F2 and F3 (J o h n s o n 2003, 163) is taken into account, the values of the first zero at or above 2000 Hz (Z_1 in Table 4) have to be considered as the only values corresponding the mentioned condition.

If the transition segment is considered as a feature characterizing the place of articulation and an acoustic locus of any consonant, it has to be addressed analyzing laterals as it has been done for nasals. To determine the locus of each lateral consonant the F2 values were measured (like for nasals) in the beginning of CV transition (at the release of consonant) and in the midpoint of the steady state of the vowel. The mean values calculated for male and female pronunciation separately are listed in Table 5.

Table 4. **The measured antiresonances (zeros) of the syllable initial Latvian laterals produced in CVC syllables by five informants (three male, two female) in the context of all short monophthongs** (the values without formatting show the most frequent range of zero frequencies, while the values in italics show the full range of zero frequencies, but the values in bold are believed to be determined by the side branch of resonator)

CONSONANT	**Z_1**	**Z_2**	**Z_3**	**Z_4**
[l]	2100-2200 Hz (*1900-2500 Hz*)	**3000-3200 Hz** (*2500-3200 Hz*)	3400-3700 Hz	4000-4200 Hz
[ʎ]	2200-2300 Hz (*2000-2600 Hz*)	3000-3200 Hz (*2800-3200 Hz*)	**3700-3800 Hz**	4200-4400 Hz (*4100-4600 Hz*)

Table 5. **The mean values (in Hz) of F2 measured at the beginning of CV transitions (F_{2b}) and in the middle of the steady state of each vowel (F_{2s})**

Cons. \ Vow.		[i]		[e]		[æ]		[ɑ]		[ɔ]		[u]	
		F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}
[l]	male	*1331*	2071	*1250*	1696	*1236*	1468	*1045*	1171	*917*	971	*907*	876
	female	*1504*	2495	*1463*	1910	*1330*	1620	*1145*	1303	*1111*	1138	*1040*	877
[ʎ]	male	*1981*	2112	*1830*	1892	*1806*	1647	*1737*	1363	*1665*	1098	*1640*	921
	female	*2377*	2471	*2270*	2172	*2179*	1847	*2094*	1559	*1916*	1272	*1856*	922

Trills

The analysis of the Latvian trills was also started with the inspection of dynamic spectrograms. The formant values of the first four formants were measured in the vowel-like open phase of vibrations, the portion of this phase was used to obtain the spectral slice for FFT, and the frequency value of the context vowel's F2 was measured at the beginning of CV transition, as well as in the middle of the steady state. The durations of the open and the closed phase of vibration were measured for both syllable initial and syllable final trills.

In the dynamic spectrograms it was observed that the Latvian trills in the open phase were characterized by a well defined vowel-like formant pattern with one to three short interruptions corresponding to the closed phase of vibration. Two most typical productions by two male informants are illustrated in Figure 10 (the first informant (to the left) produces the initial [r] with one vibration, but the second informant (to the right) – with 3 successive vibrations).

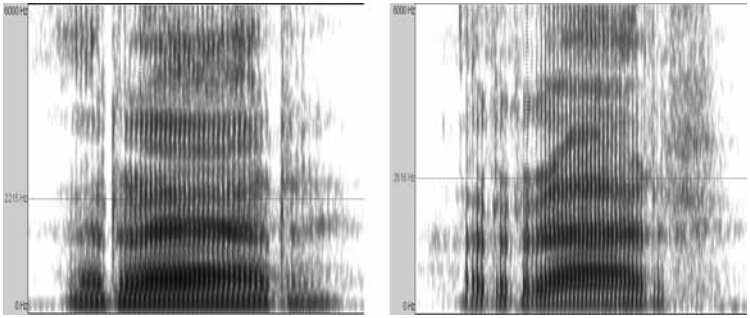


Figure 10. **The dynamic spectrograms of the Latvian trill [r] in syllables [rær] produced by two male informants**

In most cases the initial trill was produced with only one vibration, in some cases with two. The final trill was produced mostly with two vibrations, but it could also consist of one or three vibrations. If the initial trill was produced with only one vibration, it had a rather long open phase preceding the closed phase – ranging from 36 to 66 ms that roughly corresponds to the value of 50 ms mentioned in literature (Ladefoged, Maddieson 1998, 219). If there were several vibrations in the initial trill, the duration of the first open phase was between 31 and 44 ms, the succeeding open phases being 25 to 35 ms long. The closed phases displayed a pattern that agrees to the statement that the first closure in a trill often has a slightly longer duration than following ones (Ladefoged, Maddieson 1998, 218). On average the duration of the closed phase in trills with several vibrations was 20–25 ms. These values correspond to the notion (Ladefoged, Maddieson 1998, 218) that each complete cycle of trill occupies about 50 ms (25–35 ms open phase + 20–25 ms closed phase in the Latvian data). The full range of the closed phase duration was 14–35 ms in both kinds of trills, i.e., in trills with one and several vibrations. Approximately the same duration values were observed for both the syllable initial and syllable final trills except that in the final trills the last open phase could reach duration up to 133 ms.

Plotting on the same graph LPC spectra of [r] in the context of all Latvian short vowels (Figure 11) shows that the formant frequencies of [r] depend on the quality of the context vowel. Figure 11 shows data obtained from the first pronunciation of CVC syllables by one male informant representing a general tendency observed in the pronunciation of all informants of this study.

In the context of close vowels ([i, u]) [r] had the lowest, in the context of mid vowels ([e, ɔ]) – medium, and in the context of open vowels ([æ,

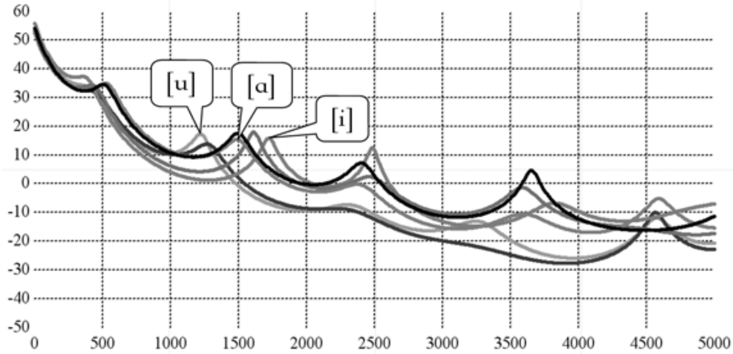


Figure 11. **The LPC spectra of the syllable initial [r] (open phase) in the context of all Latvian short monophthongs** (the F2 peaks are marked for [r] in context of the corner vowels)

ɑ]) – the highest frequency values of F1 (Figure 11). If the context vowel was produced with a constriction in the velar region ([ɔ, u]), [r] had the lowest frequency values of F2 (lip rounding facilitates the decrease of frequency), in the context of vowels produced with a constriction in the pharyngeal region ([æ, ɑ]) it had medium, but in the context of vowels with palatal constriction ([i, e]) – the highest frequency values of F2.

There was no apparent correlation of the F3 frequency of [r] with the quality of the context vowel, but the frequency of F4 was regularly lowered in the context of rounded vowels. The ranges of the first four formant values of the syllable initial Latvian trill (open phase) in the pronunciation of all five informants are listed in Table 6.

Table 6. **The resonances (formants) measured in the open phase of the syllable initial Latvian trill produced in CVC syllables by five informants (three male, two female) in the context of all short monophthongs**

CONSONANT	**F_1**	**F_2**	**F_3**	**F_4**
[**r**]	200–550 Hz	1150–1700 Hz	1900–2600 Hz	2900–4000 Hz

The data obtained in this study show that the Latvian trill [r] cannot be characterized by a specific frequency value (or region of values) of F3 because both the values of F3 and F4 display considerable differences in the pronunciation by different informants.

To determine the locus of the Latvian trill [r] F2 values were measured (like for nasals and laterals) in the beginning of CV transition (at the release of the consonant that was determined by changes in formant pattern) and in the midpoint of the steady state of the vowel. The mean values calculated for male and female pronunciation separately are listed in Table 7.

Table 7. **The mean values (in Hz) of F2 measured at the beginning of CV transitions (F_{2b}) and in the middle of the steady state of each vowel (F_{2s})**

Cons. \ Vow.		[**i**]		[**e**]		[**æ**]		[**ɑ**]		[**ɔ**]		[**u**]	
		F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}	F_{2b}	F_{2s}
[**r**]	male	*1837*	2154	*1618*	1840	*1459*	1546	*1388*	1288	*1199*	1031	*1113*	888
	female	*2139*	2529	*1825*	2039	*1764*	1678	*1644*	1375	*1399*	1207	*1199*	882

Loci

Finally, to check if the loci of all sonorants form the same pattern as the loci of the Latvian non-sonorant voiced consonants the measured values of each vowel's ([i, e, æ, ɑ, ɔ, u]) F2 in the beginning of CV transition and in the middle of the steady state were used as the ordinate and the abscissa respectively. The slope and y-intercept values of linear regression were calculated separately for male and female pronunciation of each consonant ([l, ʎ, m, n, ɲ, ŋ, r]). These values along with the slope and y-intercept values of the Latvian non-sonorant voiced consonants (Čeirane 2011, 49, 55) are listed in Table 8.

It can be observed (Table 8) that the slope and y-intercept values of the Latvian sonorants follow a pattern similar to that of voiced non-sonorants. It is even more obvious if the values listed in Table 8 are used to plot sonorants and voiced non-sonorants in the locus plane (Figure 12). In the locus plane the consonants are grouped according to the place of their articulation (the zones surrounded by dashed ellipses in Figure 12).

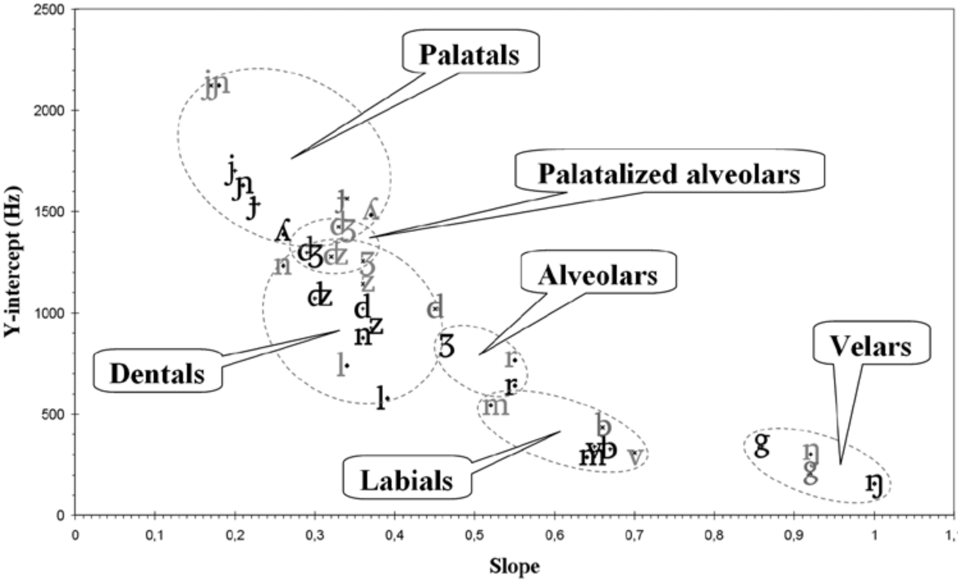
The overlap of the distribution zones is due to the arbitrary chosen size of IPA symbols in the plot. Judging by the values of y-intercept (Table 8) the boundary between the alveolars and labials would be in the vicinity of 590 Hz, but between the dentals and palatals – in the vicinity of 1310 Hz. This suggests an assumption that the slope and y-intercept values of consonants articulated at different places do not overlap, and that the Latvian sonorants can be distinguished (at least roughly) on the basis of the locus equations.

In the Latvian language the consonants [d], [ʣ] and [z] are dental, but [ʤ] and [ʒ] – alveolar. Comparing the slope and y-intercept values of these con-

Table 8. **The slope and y-intercept values (bold) for the syllable initial Latvian sonorants produced in CVC syllables by five informants (three male, two female) in the context of all short monophthongs** (for comparison the values of the Latvian non-sonorant voiced consonants [Č e i r a n e 2011, 49, 55] are added)

CONSONANT	Slope	Y-intercept	Slope	Y-intercept
[b]	0.67	326	0.66	434
[v]	0.65	338	0.70	311
[m]	**0.64**	**285**	**0.52**	**544**
[d]	0.36	1020	0.45	1020
[ʣ]	0.30	1073	0.32	1275
[z]	0.37	927	0.36	1142
[n]	**0.36**	**875**	**0.26**	**1232**
[l]	**0.39**	**578**	**0.34**	**740**
[ʤ]	0.29	1298	0.33	1424
[ʒ]	0.46	844	0.36	1257
[r]	**0.55**	**639**	**0.55**	**765**
[ɟ]	0.23	1537	0.34	1565
[j]	0.20	1702	0.17	2123
[ɲ]	**0.21**	**1629**	**0.18**	**2123**
[ʎ]	**0.26**	**1387**	**0.37**	**1483**
[g]	0.86	339	0.92	209
[ŋ]	**1.00**	**155**	**0.92**	**301**
GENDER	**Male**		**Female**	

sonants with the values of the other consonants listed in Table 8 and inspecting Figure 12 it can be concluded that [ʣ] and [z] are placed inside the zone for dentals (Figure 12), but the location of [ʤ] and [ʒ] differs from that of [r]. The male pronunciation of [ʒ] (0.46, 844) is the closest to [r] and follows the same pattern. In this case it can be assumed that the vertical boundary



F i g u r e 12. **The placement of the Latvian sonorants and voiced non-sonorants in the plane based on the values determined by locus equations** (the areas limited by the grey dashed ellipses show the distribution zones of the consonants according to the place of articulation, the black symbols represent male pronunciation, the grey symbols represent female pronunciation)

between the dentals and alveolars is at slope value 0.45. The Latvian alveolars [ʤ] and [ʒ] (as well as [ʧ] and [ʃ]) are supposed to be pronounced with palatalization that explains why the loci of these consonants are close to the region of palatal consonants. [ʤ] in the female pronunciation (0.33, 1424) is placed in the zone of palatals, i.e., above the hypothetical horizontal boundary between dental and palatal consonants (1310 Hz), but [ʤ] in the male (0.29, 1298) and [ʒ] in the female (0.36, 1257) pronunciation – in the zone of dentals, i.e., right below this boundary. It is possible that the male pronunciation of [ʒ] (0.46, 844) differs by a smaller degree of palatalization, or there is no palatalization at all.

Conclusions

The results of the present study indicate that the Latvian sonorants can be characterized sufficiently by a set of acoustic parameters including spectral characteristics of the consonants and formant transitions of context vowels. The described acoustic characteristics are indicative; before drawing general conclusions the findings of the present research have to be checked with data obtained on the basis of the pronunciation of a greater number of informants. A parallel palatographic study linking acoustic and articulatory data would be beneficial.

LATVIŲ KALBOS SONANTŲ AKUSTINĖS YPATYBĖS

Santrauka

Šiame straipsnyje, remiantis instrumentinio tyrimo duomenimis, aprašomos latvių bendrinės kalbos sklandžiųjų priebalsių spektrinės charakteristikos. Rūpimų garsų tyrimui pasirinkti simetriški CVC tipo junginiai (C – latvių kalbos sonantai [m], [n], [ɲ], [ŋ], [l], [ʎ], [r], V – latvių kalbos trumpieji monoftongai [i], [e], [æ], [ɑ], [ɔ], [u]), kuriuos po tris kartus įskaitė penki gimtakalbiai, kalbos defektų neturintys informantai (dvi moterys ir trys vyrai). Analizuotas tik pradinio CVC junginio priebalsio spektras, taip pat atsižvelgta į gretimo balsio formančių dinamiką ir struktūrą.

Gauti duomenys rodo, kad latvių kalbos sklandieji [l] ir [ʎ] labiausiai skiriasi antrõsios formantės (F_2) vieta (reikšme) spektre ir formančių energija. Šios spektrinės charakteristikos skiria šoninius sklandžiuosius priebalsius ir nuo kitų latvių kalbos garsų, o antiformantės (arba nulinės formantės) reikšmė ir priebalsio pabaigos bei gretimo balsio pradžios formančių (ypač F_2) dinamika laikytini papildomais skiriamaisiais [l] ir [ʎ] spektro požymiais. Tačiau kaip tik priebalsio pabaigos ir gretimo balsio formančių (ypač F_2) juostų dinamika ir struktūros matavimai bei kitos būdingosios nosinių sonantų spektrinės charakteristikos (kurias lemia papildomo rezonatoriaus įtaka) labiausiai skiria latvių kalbos [m], [n], [ɲ] ir [ŋ] nuo kitų garsų, o priebalsių formančių bei antiformančių reikšmės ir struktūra svarbesnės nustatant pačių nosinių sonantų ir jų alofonų skiriamuosius požymius.

Latvių kalbos virpamųjų sonantų spektrui būdingas periodiškas formančių struktūros ir intensyvumo susilpnėjimas, kuris atitinka artikuliacinius virptelėjimus: tariant [r] dėl praeinančios oro srovės virpa liežuvio galiukas (dažniausiai vieną arba du kartus), atsitrenkdamas į alveoles, todėl spektrinė energija atitinkamai susilpnėja ar dingsta. Spektrinės analizės duomenimis, [r] formančių reikšmės panašios į vidurinės eilės balsių, tačiau priklauso ir nuo gretimo monoftongo kokybės.

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Juris GRIGORJEVS
LU Latviešu valodas institūts
Akadēmijas laukums 1
LV-1050 Rīga
Latvia
[*jugrig@latnet.lv*]