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LOCUS EQUATIONS FOR LATVIAN CONSONANTS

1. Introduction

It has been commonly said that not only the consonant spectrum itself but also the spectral properties of adjacent vowels provide relevant information on the quality of a consonant. One of the approaches that have been used to describe the transition between a consonant and a vowel is locus equation analysis–the method introduced by Lindblom (1963) and employed widely by other scholars (see Section 2.1 and References).

In Latvian phonetics, locus equations have been used extensively for analysing obstruents (Čeirane 2006; 2007; 2011; Čeirane, Indričāne 2012; Indričāne 2013; Markus, Čeirane 2013). In some recent studies, locus equations for sonorants have been investigated (Grigorjevs 2012a; 2012b; Taperte 2013; 2014). The aim of the present paper is to examine whether locus equations can be considered efficient descriptors of consonantal place of articulation across different manner classes in Standard Latvian. This study differs from the previous ones in the fact that a unified recording and measuring procedure was used to obtain locus equation data for the whole consonant inventory of Standard Latvian.

2. Background

2.1. Locus theory

It has long been assumed that formant transitions seen in spectrogram "reflect the changes in cavity size and shape caused by the movements of the articulators", and second formant (F2 henceforth) transitions "rather directly represent the articulatory movements from the place of production of the consonant to the position for the following vowel" (Delattre et al. 1955, 769).

The concept of F2 locus, earlier defined as an abstract and fixed frequency value approximately 50 ms before consonant release and treated as the hypothetic starting point of the F2 of the following vowel (Delattre et al. 1955), was revived by Lindblom (op cit). He was the first investigator to point out that the frequency of *F2* measured at the first glottal pulse of the vowel following the release of a voiced stop plosive ($F2_{onset}$) is a linear function of *F2* as measured in the vowel nucleus (approximately at the middle of the vowel; $F2_{middle}$): $F2_{onset} = slope \cdot F2_{middle} + y\text{-}intercept$. Lindblom found that the slopes of regression lines for the Swedish stops [b; d; g] in CVC syllables with eight different vowels varied along with place of articulation, and thus could be used for distinguishing between these consonants. Based on this idea, the F2 locus can be defined as "the frequency of the formant at the first pulse of the vowel after consonant release" (Krull 1987, 44), which varies systematically under the influence of contextual vowels. The so-termed locus equations therefore enable one to calculate an ideal locus pattern for each consonant using data on formant transitions in CV sequences with several different vowels (Ladefoged 2003, 163).

Krull (1987; 1988; 1989) was the first researcher who used locus equations (slopes in particular) to quantify consonant-to-vowel coarticulatory effects. She pointed out the following regularity:

- Higher slopes (accompanied by lower y-intercepts) indicate variable consonantal locus and a high degree of coarticulation between the vowel and the consonant (i. e., the vowel markedly affects the consonant). In case of maximal degree of coarticulation, slope value is expected to be 1.
- Lower slopes (accompanied by higher y-intercepts) indicate stable locus and a low degree of coarticulation between the vowel and the consonant (i. e., the vowel scarcely affects the consonant). Hypothetically, if there is no coarticulation at all, the slope value should be 0.

Krull demonstrated changes in C-to-V coarticulation caused by consonantal place (labial *vs.* dental *vs.* velar) and speaking style (reading *vs.* spontaneous speech). Since then, locus equations have been used extensively as an approach to study coarticulation patterns in CV sequences (see, for example, Duez 1989; Everett 2008; Fruchter, Sussman 1997; Iskarous et al. 2010; Sussman 1994; Sussman et al. 1991; 1997; Sussman, Shore 1996).

The relation between slope and the degree of coarticulation can be explained by the simple fact that greater slope suggests greater similarity between F2 frequencies at the onset and at the steady state of a vowel, which in turn indicates minimal changes in size and shape of oral cavity during the production of C-to-V transition. Y-intercept is considered to be "a complex measure, affected by several different articulatory phenomena: coarticulation resistance, C-to-V carryover coarticulation, and the average position of the tongue back and lips at the consonant release" (Iskarous et al. 2010, 2023).

Originally, locus equation indices were considered to be universal and invariant descriptors of place distinction across varied manner classes (Sussman 1994; Sussman, Shore 1996), and reasonable distinction between labials, dentals/alveolars and velars was observed. However, it should be noted that locus equations provide information for place indirectly, only insofar as variation in place contributes to variation in coarticulatory resistance, "the extent to which a phonetic segment blocks the coarticulatory influence of adjacent phonetic segments" (Recasens, Espinosa 2009, 2288), since the latter has been also exposed to factors other than place of articulation–manner of articulation, syllable and/or phrasal position, speaking style and rate to name a few (Fowler 1994). All in all, consonantal place effects on vowel F2 loci provide information on coarticulation patterns as indexed by locus equations.

2.2. Consonant inventory of Standard Latvian

In Table 1, the inventory of Latvian consonants arranged by place and manner of articulation is presented. The lateral /l/ is described both as dental (Laua 1997, 63) and alveolar (Grigorjevs 2012, 275) in different studies.

Table 1. The consonant phonemes of Standard Latvian, in IPA

Place / Manner	**Labial**	**Dental**	**Alveolar**	**Palatal**	**Velar**
Stop	/p/ /b/	/t/ /d/		/c/ /ɟ/	/k/ /g/
Fricative	/f/ /v/	/s/ /z/	/ʃ/ /ʒ/	/j̣/	/x/
Affricate		/ʦ/ /ʣ/	/ʧ/ /ʤ/		
Nasal	/m/	/n/		/ɲ/	
Lateral		/l/		/ʎ/	
Trill			/r/		

3. Method

3.1. Speakers, material and recording procedure

Speech recordings from ten native speakers of Standard Latvian, five men and five women aged 19–39, without any disorders or dialectal traces in their pronunciation, were used for the analysis. The speakers were recorded using an AKG C520 head-mounted condenser microphone and an Edirol UA-25 or a Roland UA-55 sound capture device attached to a computer. The recording was performed at 44.1 kHz sample rate and 16 bit quantization using WavePad Sound Editor v5.40 (NCH Software 2013) or Audacity v2.0.3 (Audacity Team 2013) software.[1]

The material consists of isolated CVC syllables, where V is one of the vowels [i(ː); e(ː); æ(ː); ɑ(ː); ɔ(ː); u(ː)], for example, [pip], [pɑp], [pup], [piːp], [pɑːp], [puːp]. The CV parts of the syllables were used for the analysis. For the results to be sufficiently credible, each utterance was recorded in three repetitions by every speaker, thus 9360 items were analysed in total.

3.2. Measurements

Vowel F2 frequencies were tracked using Praat v5.3.35 software (Boersma, Weenink 2012). Measurements were made using wideband spectrograms: the first measurement ($F2_{onset}$) was taken at the CV transition starting point, and the second measurement ($F2_{middle}$) was taken at the steady state (i. e., approximately at the middle) of a vowel (Figure 1).

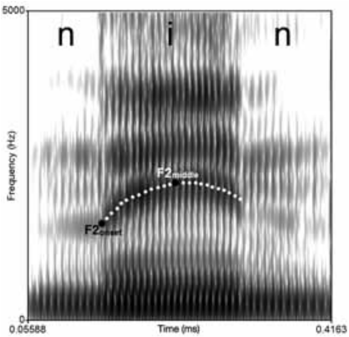

Figure 1. The dynamic spectrogram of [nin] produced by a male speaker of Standard Latvian (white dotted line indicates the trajectory of the vowel's F2; black dots indicate the onset and the middle of the vowel's F2)

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[1] The material was recorded within the research project "Acoustic characteristics of the sound system of Standard Latvian by age groups (5–15, 16–39, 40–59, 60–80)" (No. 148/2012, funded by the Latvian Council of Science) being held at the Latvian Language Institute of the University of Latvia, Riga.

Scattergrams were created to estimate a locus equation for every consonant in question: $F2_{middle}$ values were plotted along the x-axis, $F2_{onset}$ values were plotted along the y-axis, and a linear regression line was generated for each set of points. Finally, slope and y-intercept values were derived from the regression equations generated, and the coefficient of determination (R^2) was estimated for each equation. The charts were created using Microsoft Excel v14.0.4760 software (Microsoft Corporation 2010).

4. Results and discussion

In Appendix A, values of slope, y-intercept and the coefficient of determination (R^2) are presented. In Appendix B, charts with linear regression lines for each consonantal place category are shown.

A. Gender differences

The gender effects observed in the data concern both slope and y-intercept values (see Table 2 and Charts 1 and 2 in Appendix B), while gender induced differences in R^2 values do not shape any consistent pattern (Table 2).

Female data exhibit significantly higher y-intercepts, although the discrepancy between gender groups differs across place categories: it is small for labials (c = 308 Hz for males, c = 375 Hz for females) and velars (c = 156 Hz for males, c = 185 Hz for females), medium for coronals (c = 941 Hz for males, c = 1199 Hz for females) and the most pronounced for palatals (c = 1475 Hz for males, c = 1866 Hz for females). Gender effects in y-intercepts are considered to be a matter of physiology, since this index is directly associated with absolute formant frequency values that are known to be generally higher in female than in male productions due to differences in vocal tract length. The results indicate generally steeper slopes for male pronunciation as compared to female data, although some exceptions were detected as well (i. e., [t], [r], [c], [ʎ], [k] and [x]; consult Table 2 for figures). It can be observed that gender related differences in slopes are more pronounced within the group of voiced consonants as compared to voiceless ones (Charts 1 and 2). The results suggest distinct coarticulation patterns for the same consonant across genders, namely male data indicate a higher degree of anticipatory C-to-V coarticulation than female data. Although similar results were reported in some other studies ealing with voiced stops (Herrmann et al. 2014; Löfqvist 1999; McLeod et al. 2001), this trend was not evident in the locus equation data acquired in previous research on Latvian obstruents (Čeirane 2011; Indričāne 2013). Despite the distinctions mentioned here the relations between the locus patterns of different place and voicing categories remain relatively consistent across gender groups; therefore male and female locus equation data will be examined jointly hereinafter (see the common data column in Table 2 and Charts 3–8 in Appendix B).

B. Place of articulation results

Latvian consonants can be said to comprise three major groups: (1) labials and velars; (2) dentals and alveolars (coronals); (3) palatals.

The labial and velar consonants are characterized by the highest value of slope and the lowest value of y-intercept, as well as the highest rate of R^2 (Charts 3 and 7). In Latvian, velars usually have greater slopes and lower y-intercepts, while in English the steepest regression lines for bilabials are generally observed (Reetz, Jongman 2009, 206).

The highest slope values for labials and velars indicate the weakest coarticulatory resistance to vowel effects for these place categories. However, similar locus equations for labials and velars, as Fowler (1994, 600) and Everett (2008, 194) note, are motivated by distinct factors. The tongue is not involved in the production of labials, therefore it has freedom to adjust to the articulation of an adjacent vowel. Consonantal place is not affected by the vowel, since there is actually no coarticulatory overlap between the main gestures needed for the production of these two segments due to distinct active articulators (lips and tongue). In case of velars, the position of their active articulator, i. e., tongue dorsum, changes under the influence of an adjacent vowel, and this triggers the shift of consonantal place from velar in the context of back vowels to palatovelar in the context of front vowels.

It is worth noting that the considerable place assimilation caused by vowel context (which may manifest itself in a bilinear pattern of data points that seem to be approximated best with either a curve or two straight lines) also distinguishes [g] from the other lingual consonants, since there is no significant vowel-triggered place change in coronals and palatals. Therefore velar consonants tend to be described by two separate regression lines for back and front vowel contexts in some studies (see, for instance, Krull 1988; Lindblom, Sussman 2004; Sussman et al. 1991; 1995; 1997; 1998). The validity of such a differentiation in languages without a phonological opposition between the velar and the palatovelar consonant of the same manner of articulation is rather contradictory. Fowler, in particular, comes up with several arguments against it: (1) slopes for the velar allophone of [g] overlap with those for [b]; (2) the fit of data points to separate regression lines (indexed by R^2) for front and back vowel contexts is worse than the one to a single line for all contexts[2]; (3) listeners do not perceive the two allophones of [g] as distinct consonants (Fowler 1994, 603). Since in Latvian there is no phonological opposition between velar and palatovelar consonants, velar consonants are described by one linear regression line in this paper.

The results show that slope values increase in the following order:

- for **labials**: [m] (0.59) < [v] (0.64) < [b] (0.66) < [f] (0.72) < [p] (0.78);
- for **velars**: [k] (0.94) < [x] (0.96) < [g] (0.98).

Y-intercept values (Hz) increase in the following order:

- for **labials**: [p] (260) < [f] (349) < [m] (350) < [b] (352) < [v] (379);
- for **velars**: [x] (124) < [g] (171) < [k] (188).

Dental and alveolar consonants cannot be distinguished by locus equations, since there is too much overlap between the values of slope and y-intercept (Charts 4 and 5). Due to this, they are combined in one group–coronal consonants. As it was mentioned before, [l] can be pronounced both with dental and alveolar articulation, therefore its data are included in both charts. It can be observed that the locus equation of [l] differs a lot from those of other consonants within the group of dentals and alveolars because of the combination of considerably lower y-intercept and low slope. It should be noted, though, that the given locus pattern and the locus equation indices estimated (Table 2) is the result of highly variable individual data (slope values between 0.14 and 0.44, y-intercept values between 567 Hz and 985 Hz). All in

[2] In the present study, the same trend is observed: R^2 values for the single locus equation for [g] are 0.896 and 0.888 for male and female data, respectively (Table 2); those for back vowel contexts are 0.827 and 0.817, respectively, while R^2's for front vowel contexts are only 0.631 and 0.624, respectively.

all, three kinds of patterns were observed across speakers: (1) relatively low y-intercept and flat regression line (darker [l] in all vowel contexts); (2) relatively high y-intercept and flat regression line (lighter [l] in all vowel contexts); (3) relatively low y-intercept and steep regression line (variable amount of velarization depending on back/front vowel context).

The results show that slope values for **coronals** increase in the following order:

- [ʥ] (0.27) < [ʤ] (0.31) < [z] = [l] (0.33) < [ʒ] = [n] (0.38) < [d] (0.40) < [r] (0.41) < [s] (0.47) < [ʦ] (0.50) < [ʧ] = [ʃ] (0.56) < [t] (0.59).

Y-intercept values (Hz) increase in the following order:

- [l] (743) < [t] (747) < [ʃ] (819) < [ʦ] (882) < [ʧ] (896) < [s] (914) < [r] (950) < [n] (1018) < [d] (1069) < [z] (1148) < [ʒ] (1153) < [ʥ] (1276) < [ʤ] (1407).

Palatals are characterized by the lowest values of slope and the highest values of y-intercept (Chart 6). This pattern is caused by the specific character of the production of these consonants, which requires greater stability in articulation; vowel quality therefore is exposed to the influence of the consonant, while the latter remains relatively the same. Consonant resistance to vowel effects results in very flat regression lines, and the overall increase of F2 values from vowel nuclei towards CV boundaries contributes to high y-intercept values. Slope values for **palatals** increase in the following order:

- [ɲ] (0.25) < [ɟ] (0.29) < [j̥] (0.31) < [ʎ] (0.36) < [c] (0.55).

Y-intercept values increase in the following order:

- [c] (1074) < [ʎ] (1436) < [ɟ] (1650) < [j̥] (1674) < [ɲ] (1823).

It can be observed that [ʎ] and [c] (especially the latter) differ considerably from the rest of the palatal consonants in terms of slope, y-intercept and R^2 rate (higher, lower, higher, respectively). The data for [c] are probably caused by the lack of voicing (discussed further in respect of the entire groups of voiced and voiceless consonants). The locus equation data indicating weaker coarticulatory resistance for [ʎ] in comparison with [ɲ], [ɟ] and [j̥] accord with the findings of Daniel Recasens for the same consonant in Catalan. By comparing the acoustic and EPG data for [j; ɲ; ʎ; n] he inferred that the amount of coarticulatory resistance was positively related to the amount of dorsopalatal contact, which was found to be less for [ʎ] than for [j] or [ɲ] (Recasens 1984, 72).

C. Other differences

As mentioned before, place of articulation is not the only factor affecting locus equations, since they primarily reflect the coarticulatory relations between a consonant and a vowel, which are normally exposed to other influences apart from consonantal place. Also, the variability of locus equation indices within the same place group may be caused by the spectral pattern of CV transition.

Results suggest that there are differences depending on voicing. It can be observed (Chart 8) that the voiced consonants are distributed in a wider range, while the distance between the voiceless ones is considerably reduced, resulting in degraded separability of place categories. Voiced consonants are characterized by lower slopes and higher y-intercepts in comparison with voiceless, with the difference being the most pronounced in coronals and palatals. The only exception here is the group of velars, where the voiced stop [g] has slightly greater slope value (0.98) than its voiceless counterpart [k] (0.94) and the fricative [x] (0.96). The changes in slopes and y-intercepts are accompanied by a notable increase of linearity as indexed by greater R^2 values (Table 2). These voicing-induced differences can be explained by the specifics of spectral pattern rather than differences in the degree of coarticulation. The reason for that, apparently, is greater burst duration typical of voiceless stops as compared with voiced ones (Everett 2008, 195). The F2 transition therefore is usually more noticeable for vowels in the context of voiced rather than voiceless consonants, "since the values can be collected further apart, allowing for greater transition between them" (Ibid.), which in turn may lead to greater difference between F2 middle and onset and, consequently, lower slopes for voiced stops than for voiceless ones of the same place category.

Although most place categories of Latvian consonants can be separated using locus equation data, still there are some differences caused by manner within the place groups. According to Recasens (1989), fricative and stop manners are likely to have distinct degrees of coarticulatory resistance. As Fowler suggests (1994, 600), locus equation indices for stops and fricatives of different place categories might overlap due to manner effects, since "the articulatory requirements for producing fricatives are considerably more delicate than they are for producing stops", and this might lead to shallower slopes for the former as compared with those for the stops of the same place and voicing type. Manner-induced differences of this kind are observed within the groups of Latvian labials and coronals: it can be seen (Table 2, Chart 8) that fricatives and stops of the same place and voicing type have lower slope values. In the group of coronals, [ʣ], [ʤ] and [z] have the flattest regression lines causing an overlap between the zones of coronals and palatals.

5. Conclusion

The data obtained in this study correspond to those of previous research on Standard Latvian (Čeirane, Indričāne 2012). According to the results, Latvian consonants with different places of articulation can be separated to a large extent by locus equation constants. Labials and velars can be separated from coronals and palatals using both locus equation indices. By slope alone, it is possible to distinguish between labials and velars; when using the y-intercept index only, it is possible to discriminate between palatals and coronals (except for [c]).

Locus patterns for labials and velars remain fairly consistent across different manner and voicing categories, while within the groups of palatals and coronals greater variability caused by manner and voicing is observed.

In general, place of articulation appears to be the ruling factor in determining CV coarticulatory effects when other possible influences are excluded, therefore locus equations are efficient for distinguishing between different place categories in certain conditions. Further research on the variability of locus equations as affected by syllable and/or phrasal position, stress, speaking style and other aspects should be carried out to evaluate their effect on the coarticulatory patterns observed across place categories. Parallel study of articulation would be beneficial to link acoustic data with articulation processes.

Locus Equations for Latvian Consonants

Summary

In the article, the consonants of Standard Latvian are analysed using locus equations. The aim of the paper is to examine whether locus equation indices can be considered as efficient descriptors of consonantal place of articulation across different manner classes in Standard Latvian. This study differs from the previous ones in the fact that a unified recording and measuring procedure was used to obtain locus equation data for the whole consonant inventory of Standard Latvian.

The material consists of isolated CVC syllables, where V is one of [i(ː); e(ː); æ(ː); ɑ(ː); ɔ(ː); u(ː)], for example, [pip], [pɑp], [pup], [piːp], [pɑːp], [puːp]. The CV parts of the syllables were used for the analysis. For the results to be sufficiently credible, each utterance was recorded in three repetitions by every speaker, thus 9360 items were analysed in total.

According to the results, Latvian consonants with different places of articulation can be separated to a large extent by locus equation constants. The results suggest that velar and labial consonants can be separated from dental, alveolar and palatal consonants using both locus equation indices. By slope alone, it is possible to distinguish between velar and labial consonants; when using y-intercept index only, palatals can be distinguished from coronals (except for [c]).

Apart from consonantal place, voicing- and manner-induced effects were observed as well. Place of articulation appears to be the ruling factor in determining CV coarticulatory effects when other possible influences are excluded, therefore locus equations are efficient for distinguishing between different place categories in certain conditions.

Keywords: Standard Latvian, consonants, locus equations, coarticulation, place of articulation.

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Appendix A

Table 2. Values of slope, y-intercept and coefficient of determination (R^2) calculated for the consonants of Standard Latvian

C	Males			Females			Common		
	Slope	Inter-cept (Hz)	R^2	Slope	Inter-cept (Hz)	R^2	Slope	Inter-cept (Hz)	R^2
[p]	0.79	243	0.959	0.77	266	0.949	0.78	260	0.954
[b]	0.65	338	0.905	0.64	394	0.941	0.66	352	0.930
[f]	0.72	312	0.953	0.69	427	0.919	0.72	349	0.930
[v]	0.67	325	0.919	0.62	427	0.895	0.64	379	0.909
[m]	0.62	320	0.868	0.58	359	0.877	0.59	350	0.875
[t]	0.54	759	0.824	0.56	865	0.895	0.59	747	0.850
[d]	0.40	982	0.721	0.34	1262	0.773	0.40	1069	0.676
[s]	0.44	877	0.749	0.40	1141	0.783	0.47	914	0.725
[z]	0.29	1090	0.599	0.25	1401	0.620	0.33	1148	0.527
[ts]	0.48	834	0.779	0.43	1080	0.819	0.50	882	0.763
[dz]	0.25	1204	0.542	0.20	1490	0.542	0.27	1276	0.469
[n]	0.37	941	0.702	0.34	1187	0.731	0.38	1018	0.662
[l]	0.34	684	0.698	0.30	854	0.653	0.33	743	0.656
[ʃ]	0.57	720	0.799	0.47	1053	0.710	0.56	819	0.727
[ʒ]	0.38	1101	0.643	0.32	1303	0.648	0.38	1153	0.658
[tʃ]	0.53	835	0.744	0.47	1160	0.808	0.56	896	0.734
[dʒ]	0.30	1281	0.463	0.20	1737	0.490	0.31	1407	0.389
[r]	0.38	926	0.792	0.38	1055	0.748	0.41	950	0.746
[c]	0.46	1095	0.750	0.47	1335	0.651	0.55	1074	0.656
[ɟ]	0.21	1612	0.435	0.20	1961	0.377	0.29	1650	0.346
[j]	0.24	1584	0.396	0.18	2122	0.417	0.31	1674	0.314
[ɲ]	0.22	1671	0.496	0.15	2198	0.371	0.25	1823	0.292
[ʎ]	0.28	1414	0.664	0.29	1714	0.670	0.36	1436	0.528
[k]	0.93	190	0.928	0.93	204	0.958	0.94	188	0.950
[g]	1.00	140	0.896	0.97	197	0.888	0.98	171	0.895
[x]	0.94	137	0.973	0.96	155	0.975	0.96	124	0.974

Appendix B

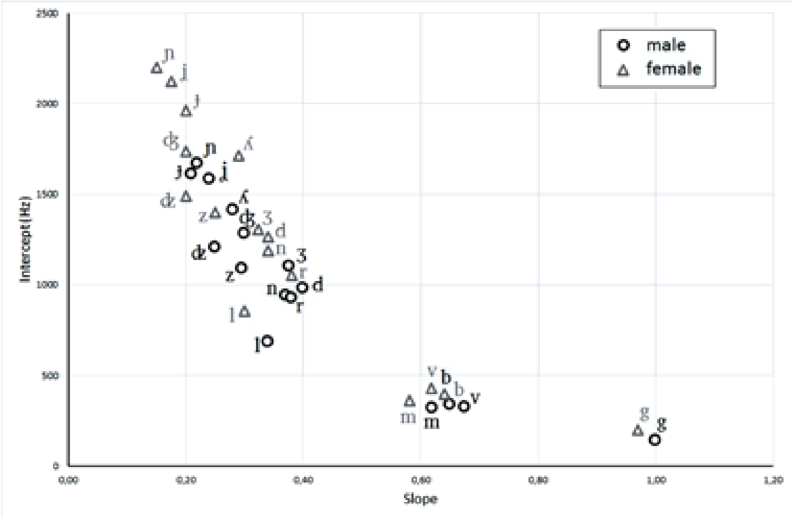

Chart 1. F2 loci for voiced consonants (male vs. female)

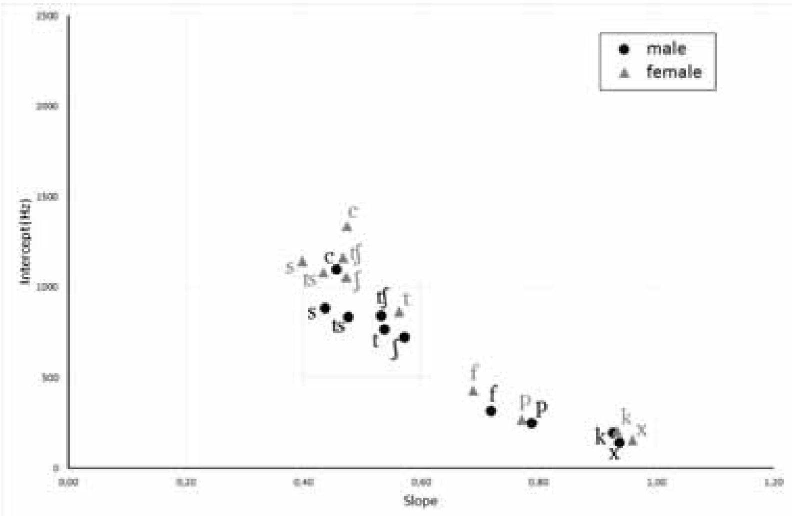

Chart 2. F2 loci for voiceless consonants (male vs. female)

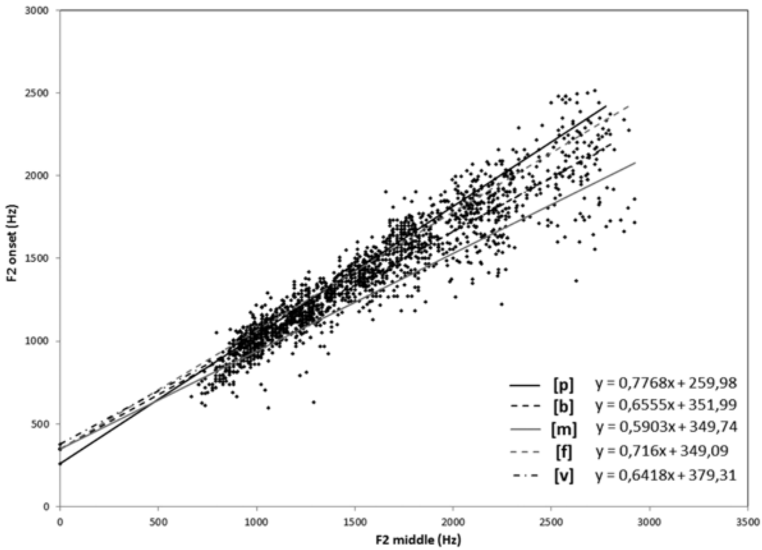

Chart 3. Linear regression lines for labials

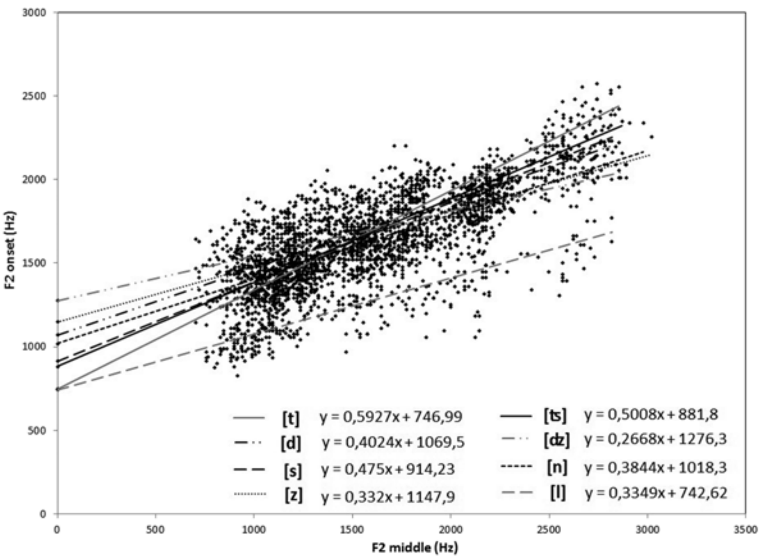

Chart 4. Linear regression lines for dentals

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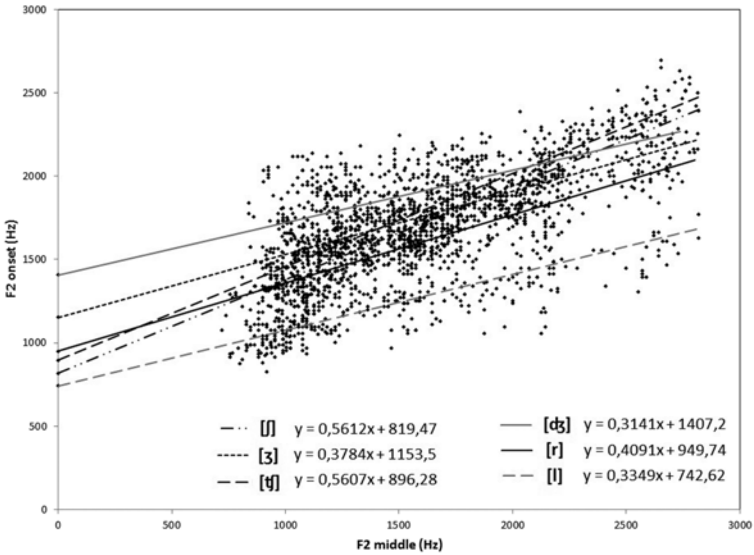

Chart 5. Linear regression lines for alveolars

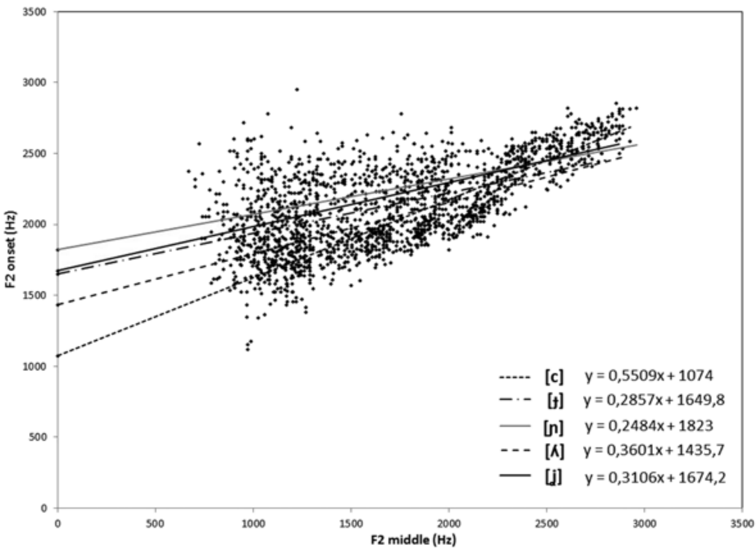

Chart 6. Linear regression lines for palatals

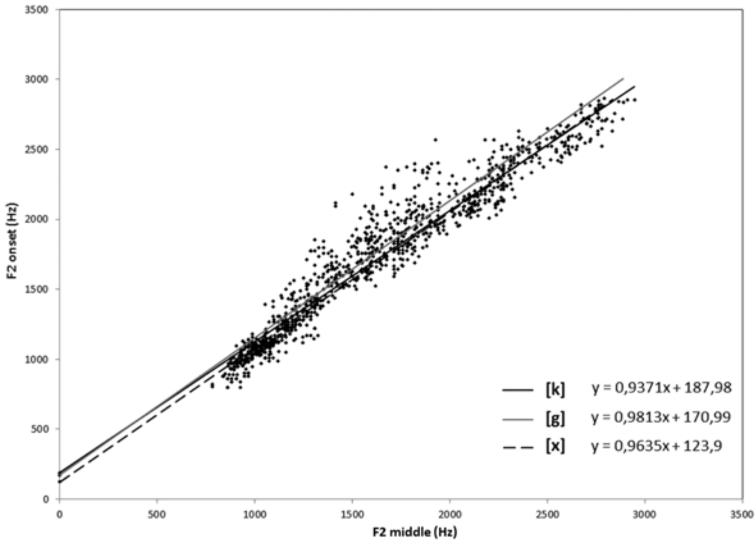

Chart 7. Linear regression lines for velars

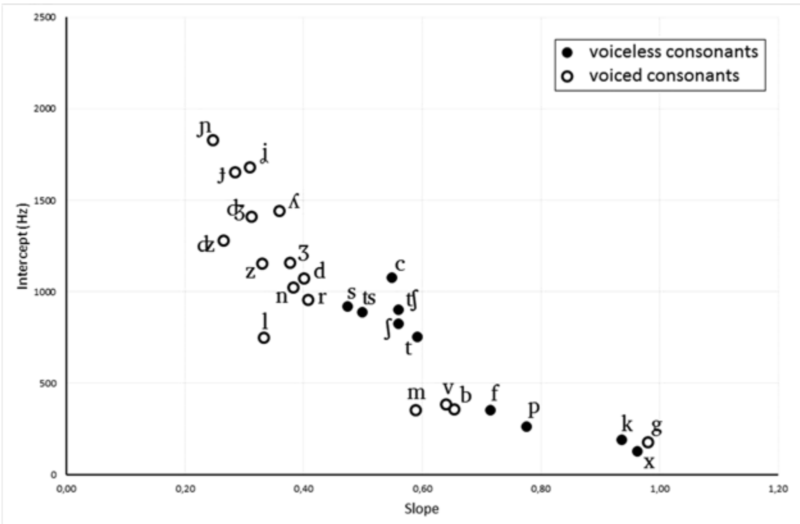

Chart 8. F2 loci for all consonants (common data)