

# (Non-)retroflex Slavic affricates and their motivation: Evidence from Czech and Polish

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The Slavic affricate represented by /č/ is tacitly or explicitly assumed to be  $\widehat{tʃ}$  for all Slavic languages. In this paper we revise the affricate inventories of Polish and Czech, showing that the symbol /č/ stands for two different sounds: the palatoalveolar  $\widehat{tʃ}$  in Czech and the retroflex  $\widehat{ʃ}$  in Polish. This conclusion is supported by acoustic results for Polish and Czech data. The fact that COG (centre of gravity) values of frication are not significantly different for Polish and Czech /č/ appears a bit surprising especially in light of the fact that COG is generally seen as a parameter contributing to the distinction of fricatives (including sibilants, see e.g. Gordon, Barthmaier & Sands 2002). Our results show that other parameters such as duration of the frication phase, F1 and F2 of the following vowel as well as spectral slopes are more reliable cues for distinguishing the small differences between affricates examined here.

## 1 Introduction

What is Slavic /č/ in IPA terms? How is it realized in the individual Slavic languages? The answer to these questions should not be controversial, as several, if not all, studies tacitly or explicitly assume that the Slavic affricate /č/ stands for  $\widehat{tʃ}$  in all Slavic languages (see e.g. de Bray 1951 or various chapters in Comrie & Corbett 1993).

However, /č/ makes a different perceptual impression depending on the language. Thus, for example, replacing the Czech /č/ with the Polish /č/ and vice versa would lead to a striking

non-native pronunciation in both languages. Similar observations can be made with respect to other Slavic ‘cross-splicing’ effects with phonemes such as the Lower Sorbian /č/ and the Russian /č/. The aim of this paper is to show that the affricate in question is a different sound in the two selected Slavic languages: Polish and Czech. It will be shown that, in fact, the two sounds differ considerably from each other with respect to selected parameters.

This difference in the realization of affricates is intriguing if one considers the fact that both sounds, Polish /t͡s/ and Czech /t͡ʃ/, originate from the same Old Slavic ancestor, /t͡ʃ/. Thus, the question arises as to why in some Slavic languages /t͡ʃ/ has changed to /t͡s/, while in others it has remained /t͡ʃ/. In the present study, it is proposed that the change from /t͡ʃ/ to /t͡s/, as in Polish, was not accidental but can be accounted for when perceptual contrast among the affricates in a given system is taken into consideration.

The paper is organized as follows. In Section 2, we provide results of an acoustic experiment of the two selected Slavic languages, Polish and Czech, which differ in their phonemic inventories, i.e. complex vs. simple coronal affricate systems. In Section 3, we discuss some articulatory aspects of the category ‘retroflex’ as employed for the purposes of the present paper and provide articulatory characteristics of the Polish and Czech /č/. Furthermore, in Section 4, we outline perceptual differences between the sounds. Section 5 provides a link between the articulation and perception of retroflex sounds. In Section 6, we put forward a hypothesis that the differences in Polish and Czech inventories are not accidental but follow from the tendency to optimize perceptual contrast. The main conclusions of the study are summarized in Section 7.

## 2 Acoustic study

The aim of this section is twofold. First, it will be determined experimentally whether the Slavic affricates in question are indeed palatoalveolars as commonly assumed in the literature.<sup>1</sup> Second, the affricate in question, /č/, will be compared with other coronal sounds of the same inventory with respect to selected parameters.

We hypothesize that Polish and Czech /č/ are different sounds. In the former case the sound should be denoted as retroflex /t͡ʃ/, in the latter as palatoalveolar /t͡ʃ/.

The coronal inventories of the two languages are presented in (1).

(1) Czech	alveolar	palatoalveolar	palatal <sup>2</sup>
	t    t͡s	t͡ʃ	c
Polish <sup>3</sup>	dental/alveolar	retroflex	alveolo-palatal
	t    t͡s	t͡ʃ	t͡ʃ

<sup>1</sup> In the present study, the term POSTALVEOLARS is used as a cover term for sounds articulated at the following places of articulation: retroflex /ʃ z t͡ʃ d͡ʒ/, palatoalveolar /ʃ ʒ t͡ʃ d͡ʒ/, and alveolo-palatal /ç ʒ t͡ʃ d͡ʒ/. Thus, the IPA postalveolars /ʃ ʒ t͡ʃ d͡ʒ/ are referred to below as PALATOALVEOLARS.

<sup>2</sup> It is a matter of debate if /c/ can be classified as coronal; see Hall (1997b) for arguments in favour of the coronal status of /c/. The classification of /c/ as coronal is, however, of no consequence for the present study.

<sup>3</sup> In a few words of foreign origin, /t͡s/ are pronounced as [t͡ʃ] before /i/, e.g. *op/ti/mum* is pronounced as *op[t͡ʃi]mum* ‘optimum’. However, in a majority cases of adopted words, /i/ changes to [i] after coronals. For instance, the French word *visite* is pronounced in Polish as *wi[zɨ]ta* ‘visit’ (Rubach 1984: 205).

One of the reviewers pointed to [t͡ʃ] as a potential challenge for our claim. Since we are not able to list more than one single word with a voiced variant [d͡ʒ] in ‘gin’ which even can be pronounced with a non-palatalized variant [d͡ʒi]n (Rubach 1984: 205), we do not consider this allophone to be a serious competitor in the theory of contrast advanced in the present paper. Note also that the reason why the retroflex /t͡ʃ/ changes to [t͡ʃ] is based on the fact that retroflexes are not followed by high vowels due to the incompatibility of articulatory gestures (Hamann 2003). Admittedly, detailed articulatory studies are needed in order to (dis)confirm this statement for Polish sibilants.

Polish and Czech have been chosen for the following reasons. First, both languages differ in their affricate inventories: while the Polish sibilant system is deemed complex, the Czech system, with its two sibilant affricates, belongs to the simple systems (see Hall 1997a). Furthermore, the place of articulation of Czech /tʃ/ is by no means clear from the descriptions available in the literature (see Section 3). In a similar vein, the corresponding Polish postalveolar affricate is repeatedly reported to be the palatoalveolar /tʃ/, despite its retroflex features; see Sections 3 and 5 below. Finally, the presence of the palatal stop /c/ in Czech on the one hand and of the alveolo-palatal affricate /tʃ/ in Polish on the other is important because it enables us to postulate the extent to which the sounds might influence the development of postalveolar affricates in these two languages; see Section 6 below.

## 2.1 Experimental design

The material for testing our hypothesis consisted of words containing the consonants listed in (2).

### (2) Phonemic systems

Czech	/t c tʃ ʃ/
Polish	/t tʃ ts ʃ/

The consonants appeared in word-initial /\_a/ and word-medial /a\_a/ positions. The vowel /a/ was chosen in order to avoid palatalization (as in the case of /i/) or rounding effects (as in the case of /u/). The vowel /a/ is a low, central vowel in both languages as shown in acoustic and articulatory studies (e.g. Wierzchowska 1971, 1980 for Polish and Hála 1962, Borovičková & Maláč 1967 for Czech). With one exception due to lexicon restrictions, i.e. the Czech word -t'at-, all words were bisyllabic with stress falling on the first syllable; see tables in Appendix A. It should be noted that two Polish speakers produced *braci* 'brothers, GEN' and not *bracia* 'brothers, NOM'. The words were embedded in the following carrier sentences:

### (3) Carrier sentences

Polish:	<i>Powiedzcie ... jeszcze raz.</i>	'Say (PL) ... once again.'
Czech:	<i>Řekněte ... jednou.</i>	'Say (PL) ... once.'

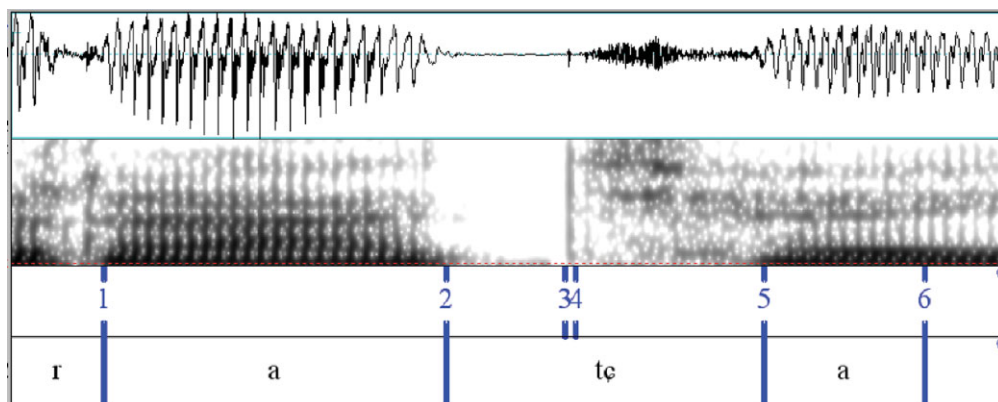
The carrier sentences have the same number of syllables in both languages, i.e. three syllables before the item under investigation and three syllables after it. Ten repetitions of each sentence were randomized and presented in an orthographical form to the speakers; see Appendix A.

Four native speakers of Czech (two females, LS and MK, and two males, NN and KC, aged from 22 to 28 years) and four native speakers of Polish (two females, MN and MZ, and two males, JK and PW, aged from 23 to 43 years) took part in the experiment. All speakers were monolingual and spoke a standard version of their native language. The informants were asked to read the sentences aloud at a normal speech rate. All recordings were conducted in a soundproof lab at the Zentrum für Allgemeine Sprachwissenschaft in Berlin using a Sennheiser MKH20 P48 microphone located 10 cm in front of the mouth. The recordings were made to a DAT-recorder at a sample rate of 22050 Hz; for the formant analysis they were down-sampled to 11025 Hz. The items were further analysed with Praat version 5.2 (Boersma & Weenink 2011) and MATLAB version R2007b.

For the purposes of the present study, six places in the spectrogram of the signal were determined by placing the cursor at the following points:

### (4) Marking points

- Point 1: The beginning of the vowel preceding the consonant (V1).
- Point 2: The end of the vowel preceding the consonant (V1).



**Figure 1** (Colour online) The oscillogram and spectrogram of Polish [brat̪ca].

Point 3: The beginning of the burst.

Point 4: The end of the burst.

Point 5: The beginning of the vowel following the consonant (V2).

Point 6: The end of the vowel following the consonant (V2).

All six places in (4) are exemplified in the oscillogram and spectrogram of Polish [brat̪ca] ‘brothers’ in Figure 1.

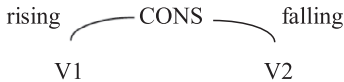
In order to test our hypothesis, the following acoustic parameters were investigated:

(5) *Parameters*

- (i) The closure and frication duration.
- (ii) The formant frequencies F1, F2, and F3 of the vowels preceding and following the consonant (endpoint frequencies).
- (iii) The formant frequency range of F1, F2, and F3 of the vowels preceding and following the consonant.
- (iv) The highest spectral peak frequency of the burst and the following frication.
- (v) Slopes of regression lines (spectral fit) m1 and m2 for both burst and following frication.
- (vi) Spectral moments as proposed by Forrest et al. (1988) for both burst and frication: M1 (mean), M2 (variance), M3 (skewness), and M4 (kurtosis).
- (vii) Centre of gravity (COG), standard deviation, skewness, and kurtosis for both burst and frication based on the formulae given in PRAAT version 5.2 (Boersma & Weenink 2011).

Regarding (5i): The closure was measured from point 2 to point 3, the burst from 3 to 4 and the frication from 4 to 5. Due to measurement limitations of the stop phase in the consonants in the word-initial position, the closure was measured only for word-medial consonants. If the starting point of the closure did not coincide with the offset of the formants of the vowel, an additional point was set at the end of voicing. This point was then considered as the starting point of the closure.

Regarding (5ii): The formant frequencies F1, F2, and F3 were measured at the onset and offset of vowels, i.e. at point 1, 2, 5, and 6. The offset was defined as the end of the stable formant structure. The formants of the vowel segments were measured semi-automatically by means of Linear Predictive Coding (LPC). Prior to formant analysis (and only for the formant analysis) the audio signals were down-sampled to 11025 Hz (to only allow for formant peak picking in the first five formants up to 5500 kHz). The LPC was calculated by using the



**Figure 2** Schematic representation of raising and falling formant frequency values.

following parameters: pre-emphasis frequency 50 Hz, analysis window duration 0.0256 s, time step 0.001 s and a prediction order of 13. Maximally five peaks from the LPC spectrum derived by peak picking were considered as formant candidates. As in some cases a certain formant value could not be detected by the peak-picking algorithm, for every spectrum the three formant candidate values were checked and manually corrected if necessary in order to determine the correct formant values.

Regarding (5iii): The frequency ranges of the F1, F2, and F3 were computed for (a) the preceding vowel by subtracting the frequency values at the formant transition offset (point 2) from those obtained at the midpoint of the vowel, and (b) the following vowel by subtracting the frequency values at the formant transition onset (point 5) from those obtained at the midpoint of the vowel (the midpoint of the vowel was calculated as the equal temporal distance between the onset and offset of the vowel).

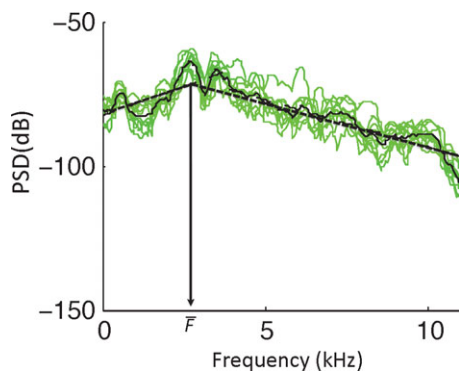
When the formant frequency values obtained were positive, the formant toward the consonant was considered to be rising and in the case of the vowel following the consonant, the formant was considered to be falling. This is schematically shown in Figure 2. When the values were negative, the formant of the preceding vowel was falling and the formant of the following vowel was rising.

Regarding (5iv)–(5vii): All spectral values were calculated by computing multitaper spectra (see below for an explanation of the multitaper method) with a 23 ms window for the frication noise midpoint (512 point Hamming window) or a 11.5 ms window for the burst landmark (256 point Hamming window). The windows were left aligned to the beginning timepoint of the burst (only the burst was completely included in the time window and the following frication noise was excluded) or the acoustic midpoint between the end of the burst and the beginning of the following vowel (points 4 and 5). The power spectral density (PSD) was estimated via the Thomson multitaper method (linear combination with unity weights of individual spectral estimates and the default FFT (Fast Fourier Transform) length) available in the MathWorks Signal Processing Toolbox Version 6.2 (MathWorks 2007: 470–475).

Regarding (5iv): The highest spectral peak was computed in the frequency range from 1000 Hz to 11025 Hz. We excluded the low-frequency region up to 1 kHz since we were primarily interested in the front cavity resonances, which occur between 2000 Hz and 8000 Hz for the fricative part of the signals (see Jesus & Shadle 2002 for further explanation).

Regarding (5v): The regression lines were computed between the spectral limits (i.e. between 500 Hz and 11025 Hz) and the average spectral peak frequency ( $\bar{F}$ ), separately estimated for all recorded Polish and Czech items for burst and frication noise (thus four measures of  $\bar{F}$ ).<sup>4</sup> The frequency  $\bar{F}$  is the mean of all highest spectral peaks per language (Czech, Polish) and landmark (burst or frication noise), rounded to the nearest kHz. In Jesus & Shadle (2002) and Lousada, Jesus & Pape (2012), it was shown that this computation of  $\bar{F}$  and its rounding adapts well to find the endpoint between the two parts of the spectra (low part from 500 Hz to  $\bar{F}$  and high part from  $\bar{F}$  to the Nyquist frequency; see Jesus & Shadle 2002:

<sup>4</sup> The spectral slope measures (m1 and m2) were derived from previous studies of the acoustic mechanisms of fricative production by Shadle (1991), Shadle & Mair (1996) and Jesus & Shadle (2002). Other authors, e.g. Evers, Reetz & Lahiri (1998) have also successfully used spectral slopes to characterize fricatives.



**Figure 3** (Colour online) Multitaper spectra and regression lines used to calculate the low-frequency slope ( $m_1$ ) and high-frequency slope ( $m_2$ ), with the split point at the mean frequency ( $\bar{F}$ ).

447 for further information). In Jesus & Shadle (2002: 447), a value of 4000 Hz was found for postalveolar fricatives of European Portuguese, and in Lousada et al. (2012: 10) a value of 3900 Hz was found for the burst of dental stops. However, in order to apply this measure to our data, we had to adapt it to our Polish and Czech data, assuming (and thus simplifying) that the place of articulation is more or less consistent for corresponding phonemes. In our case we found an  $\bar{F}$  value of 3000 Hz for both Czech and Polish. This value was identical for both burst and frication noise.

Thus,  $m_1$  is the slope of the spectral regression line for the frequency range between 500 Hz and 3000 Hz, and  $m_2$  is the slope of the spectral regression line for the range between 3000 Hz and 11025 kHz. The values  $m_1$  and  $m_2$  were separately computed for the burst and the frication noise. Figure 3 shows an example of 10 different spectra from one speaker, the overlaid mean spectrum and the computation of the regression lines  $m_1$  and  $m_2$ , with the endpoint/startpoint  $\bar{F}$ .

Regarding (5vi): According to Forrest et al. (1988), the power spectrum of a fricative can be seen as a normal statistical distribution, from which the computation of the four spectral moments can help to distinguish between different fricatives or places of articulation. Lousada et al. (2012) used the four moments to distinguish between different stops and places of articulation in burst spectra. For the frequency range from 0 Hz to 11025 Hz, we computed the four moments  $M_1$  (mean),  $M_2$  (variance),  $M_3$  (skewness), and  $M_4$  (kurtosis) for the multitaper spectra for both burst and frication noise.

Regarding (5vii): For the frequency range from 0 Hz to 11025 Hz, we computed four spectral parameters available from Praat version 5.2 (Boersma & Weenink 2011): centre of gravity (COG), standard deviation of the spectrum, skewness, and kurtosis of the spectrum for both burst and frication noise. It should be noted that the standard deviation, skewness, and kurtosis differ from the values in (5vi) due to different weighting and normalization techniques.

The motivation for using multitaper spectra was the following. The existing large variance in fricative parts of the speech signal normally requires a massive variance reduction, but if possible without losing the distinctive properties of the examined phoneme. However, in order for most variance reduction methods to work, they require certain assumptions to be met with respect to the speech signal in question, primarily that the signal is regarded as stationary and ergodic, i.e. the statistical properties of the process are independent of the sample sequence. However, fricative parts of the speech signal are neither stationary



nor ergodic (Blacklock 2004, Lousada et al. 2012), which limits the use of most methods: ensemble-averaging techniques can only be used if the signal is ergodic; time-averaging over the phoneme duration assumes the signal to be stationary and thus not changing from onset to offset, which clearly does not happen during speech production, where articulators are constantly on the move from one phoneme to the other.

Therefore, both time-averaging and ensemble-averaging techniques cannot be used for short – and thus non-stationary – periods of a given burst signal. This leaves out the standard frequency smoothing techniques to reduce the variability. These algorithms use standard windowing techniques to smooth the spectra. As a result, the windows invariably lose important data towards the edges (due to the necessary sidelobe suppression), which in turn leads to an undesirable increase in the variance of the spectral estimate (Blacklock 2004, Lousada et al. 2012).

The problem of losing data at the window edges is solved by the multitaper technique (Blacklock 2004, Lousada et al. 2012), which applies consecutive orthogonal windows (Slepian tapers: prolate spheroidal windows), i.e. the second window is set orthogonally to the first window and so on. This technique guarantees that data are not lost towards the ends of each window. At the end of the process, the resulting smoothed spectrum is obtained by summing all orthogonal estimates. This spectrum exhibits highly reduced variance, which is no longer dependent on the underlying spectral magnitude. Thus, in contrast to standard spectral estimation techniques, multitaper analysis provides an optimal way to reduce the bias of the spectral estimates when calculated over only short intervals of the data, and is thus highly suited to examining stochastic parts of the speech signal (see Blacklock 2004 for further explanations). Thus, the multitaper method – an accurate analysis of a single short time window only – is well suited for the characteristics of the short fricative portion of affricates and the burst part of the signals.

For each multitaper spectrum, we computed two sets of established spectral parameters. It should be noted that with the aim of increasing accuracy and spectral information we calculated all spectral parameters for the fricative and burst spectra on the more accurate multitaper spectra and not (as traditionally done) on the error-prone FFT or LPC spectra.

For the first set of spectral parameters (see (5vi) above), we computed the moments according to Forrest et al. (1988), who propose looking at the fricative spectrum as a standard statistical distribution and thus calculate the first four moments for parameterization of the spectra. The first moment is regarded as the mean, the second moment is the variance, and the third and fourth moments are the skewness and kurtosis, respectively.

For the second set of spectral parameters (see (5vii)), we computed the normalized moments centre of gravity (COG), standard deviation (SD), skewness, and kurtosis using the formulae given in PRAAT version 5.2 (Boersma & Weenink 2011). These measures are widely used in the literature on spectral properties of speech signals, so we calculate these values to allow for comparison with other studies. The centre of gravity is the pairwise weighting of the spectral amplitude with the frequency, thus indicating the average central frequencies for the complete spectrum. The standard deviation (SD) indicates the spreading around the centre of gravity. Skewness shows if the spectrum is skewed towards lower or higher frequencies, while the kurtosis can be seen as a measure of the spectral peakedness or deviance from a normal distribution.

The statistical analyses were conducted in the R environment (R Development Core Team 2010). Linear mixed effects models were employed for the investigated variables (closure duration, frication duration, F1, F2, F3 of the preceding and following vowel, F1, F2 and F3 range of the preceding and following vowel, spectral slopes  $m_1$  and  $m_2$  of the burst and frication, COG, standard deviation, skewness and kurtosis of the burst and frication, as well as M1, M2, M3, M4 of the burst and frication) which were studied as effects of LANGUAGE {Czech, Polish}, PHONEME {t, c/tç, č, ts} and POSITION {word-initial, word-medial}. Whereas LANGUAGE, PHONEME and POSITION were considered fixed effects, SPEAKER was included as a random effect. Besides *t*-values for fixed effect, the output also includes a *p*-value based on

Markov chain Monte Carlo sampling (*pMCMC*), which is a possible alternative to *p*-value in mixed model effects (Baayen 2008: 248).

All mean values and their standard deviation are provided in Appendix B. Appendix C includes *t*- and *pMCMC*-values which pertain to comparisons between /č/ and other phonemes within a given language as well as comparisons of the values of Czech and Polish /č/ (i) independent of the position and (ii) split for the word-initial and word-medial position.

## 2.2 Results

In the following, we present selected results of the examined phonemes for each parameter. The order of the presentation is in accordance with the parameters listed in (5). The discussion of the results will be limited to the most relevant findings regarding the purposes of the present study.

### 2.2.1 Parameter (i): The duration of the closure and of the frication phase

Figures 4 and 5 show the log transformed duration values of the closure and frication phases obtained for Czech and Polish consonants in the word-medial position. We log transformed the duration data because the distribution was skewed and log-transformed data are more resistant to outliers. (Obviously, the word-initial position could not be considered for this measurement due to the impossibility of segmenting the exact beginning of the closure phase.)

The results show a clear difference between the Czech and Polish /č/. While the duration of the closure is significantly shorter for Czech /č/ than for Polish /č/ (log values: 4.14 vs. 4.34,  $t = -2.39$ ,  $pMCMC = .0168$ ), the frication is significantly longer for Czech /č/ than for Polish /č/ (log values: 4.44 vs. 3.93,  $t = 3.89$ ,  $pMCMC = .0002$ ). Importantly, the frication in the Czech /č/ is longer than its closure (4.14 vs. 4.44), whereas the opposite scenario is found in the corresponding Polish sound: the closure is longer than the frication (4.34 vs. 3.93). This is illustrated in Figure 6. The difference between closure and frication duration is highly

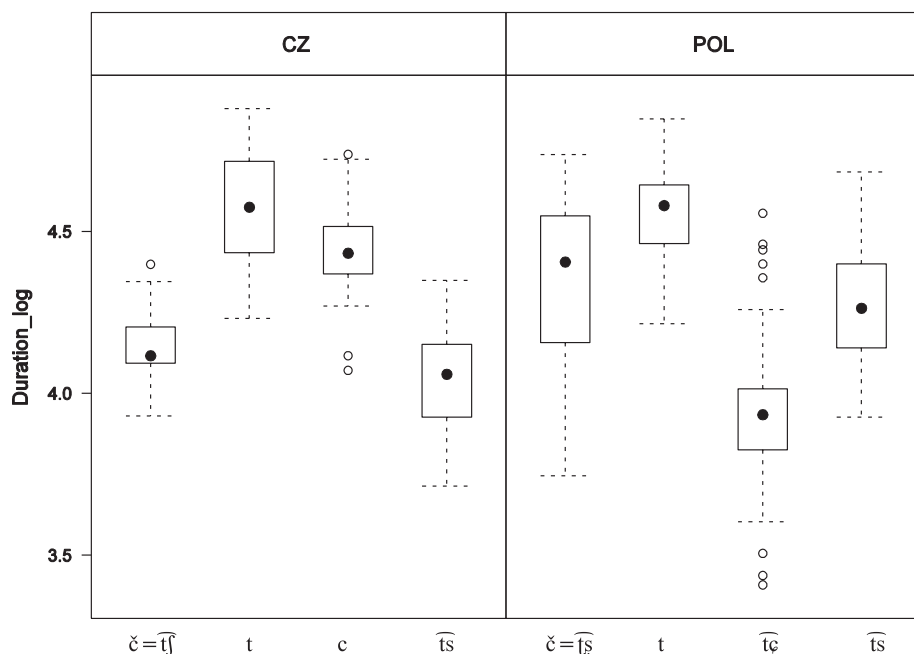


Figure 4 Average duration of closure phase in Czech and Polish consonants.



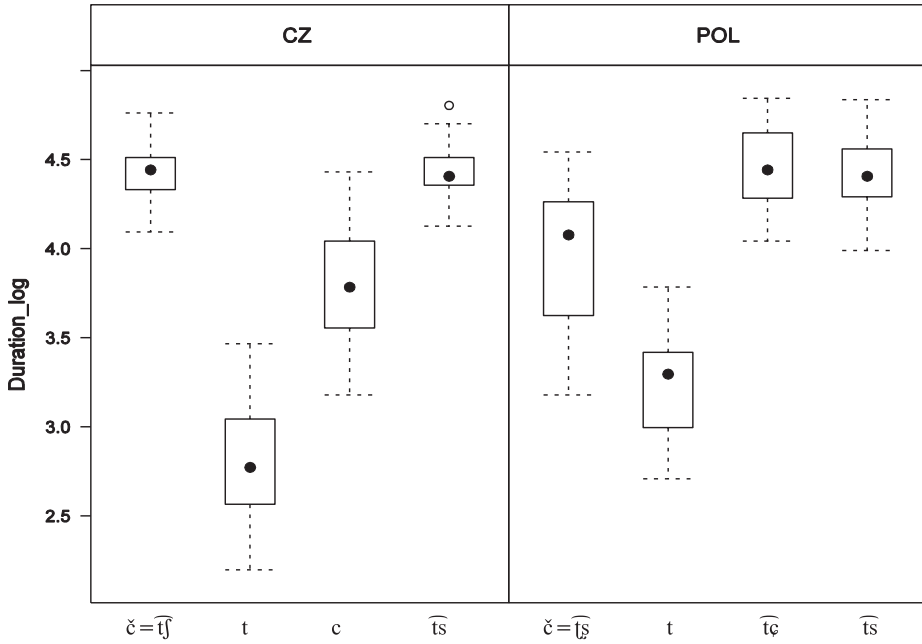


Figure 5 Average duration of frication phase in Czech and Polish consonants.

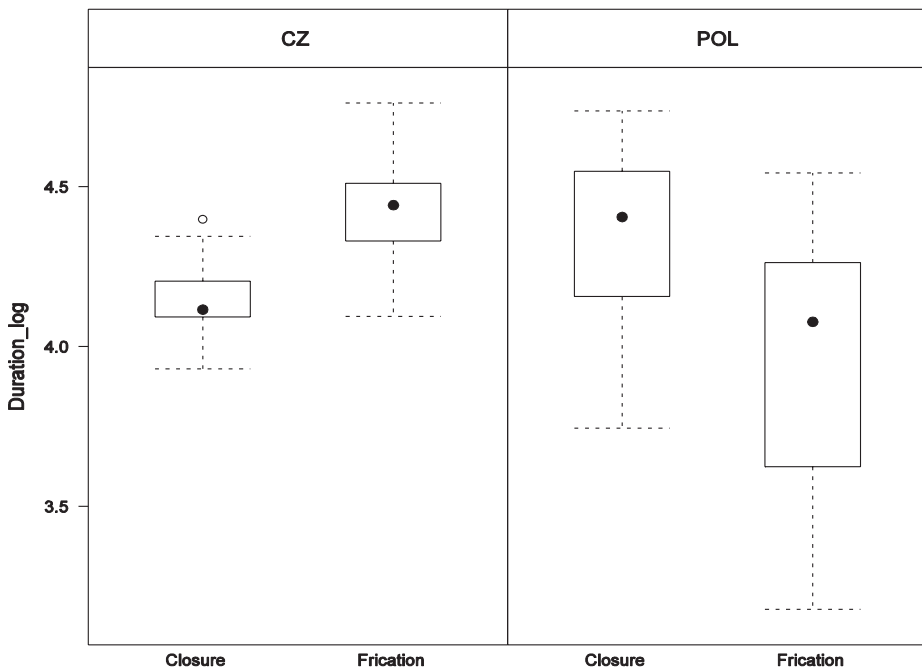


Figure 6 Average duration of closure and friction phase in Czech and Polish /č/.

significant in both languages (Czech /č/:  $t = -7.22$ ,  $pMCMC = .0001$ ; Polish /č/:  $t = 9.61$ ,  $pMCMC = .0001$ ).

Potentially, it could be argued that the Polish /č/ behaves more similarly to a stop, where the closure is typically longer than the frication, and it less resembles an affricate, as e.g. Czech /ts/ and /č/.<sup>5</sup> However, it has been shown that such a characteristic is also typical of retroflex sounds occurring in other languages: the shorter duration of frication in comparison to closure duration has been noted for Serbian retroflex affricates (Miller-Ockhuizen & Zec 2003) and Komi-Permyak retroflex affricates (Kochetov & Lobanova 2007). The results presumably point to an important articulatory difference between the postalveolar affricates. The Czech affricate /č/ is articulated with the tongue blade, while the corresponding Polish sound is articulated with the tongue tip, as is typical for retroflex sounds.

The results presented in Figures 4 and 5 point to another difference between the Czech and Polish affricate inventory which is probably crucial for explaining the differences between the languages. The Czech coronal inventory includes two affricates, /ts/ and /tʃ/, which (i) both show longer frication than closure (/ts/: closure 4.04 vs. frication 4.43,  $t = -9.33$ ,  $pMCMC = .0001$ ; /tʃ/: closure 4.14 vs. frication 4.44,  $t = -7.22$ ,  $pMCMC = .0001$ ), and (ii) do not differ significantly with respect to frication duration (/ts/ 4.43 vs. /tʃ/ 4.44) but only with respect to closure duration which is shorter for /ts/ than for /tʃ/ (/ts/ 4.04 vs. /tʃ/ 4.14,  $t = -2.63$ ,  $pMCMC = .0114$ ). Yet the Polish inventory is more complex as it consists of three affricates, /tɕ/, /ts/ and /tʂ/. In contrast to the Czech affricates, (i) the relation between closure and frication in Polish differs depending on the sound: whereas in /tɕ/ and /ts/ the closure is shorter than the frication (/tɕ/: closure 3.94 vs. frication 4.25,  $t = -11.95$ ,  $pMCMC = .0001$ ; /ts/: closure 4.26 vs. frication 4.41,  $t = -3.45$ ,  $pMCMC = .001$ ) in /tʂ/ the closure is longer than the frication (closure 4.34 vs. frication 3.93,  $t = 9.61$ ,  $pMCMC = .0001$ ). Furthermore, a comparison of the closure and frication duration among the Polish affricates reveals that the closure is shorter in /tɕ/ (3.94) than in /ts/ (4.26) and /tʂ/ (4.34) (/tɕ/ vs. /tʂ/:  $t = -11.52$ ,  $pMCMC = .0001$ ) and the frication is shorter in /tʂ/ (3.93) than in /ts/ (4.41) (/ts/ vs. /tʂ/:  $t = 14.56$ ,  $pMCMC = .0001$ ) and /tɕ/ (4.25) (/tɕ/ vs. /tʂ/:  $t = 15.76$ ,  $pMCMC = .0001$ ). Such differences presumably allow a better perceptual contrast between the affricates of a complex system to be maintained (see Section 6 below for a perceptually-based hypothesis on Polish sibilants).

<sup>5</sup> One of the reviewers pointed out that this difference can be explained by the fact that Polish contrasts the affricate /tʂ/ in e.g. *czy* ‘whether’ with the sequence /ts/ as in *trzy* ‘three’. Although this interpretation is possible, it seems that it is less probable for at least three reasons. First, the contrast appears in a very limited number of words. Second, Polish native speakers often produce the affricate [tʂ] as a pronunciation variant of the underlying /ts/, especially in casual speech; e.g. /tʂ/ *trzeba* ‘there is a need’ is pronounced as [tʂ] *eba* or [ts] *eba* and /dʒ/ *em* ‘jam’ as [dʒ] *em* or [dʒ] *em*. Finally, similar duration differences, i.e. a long stop phase vs. a short frication phase, have been found for retroflex affricates in other languages as well (e.g. Serbian and Komi-Permyak).

It is also worth pointing out that the phonetic difference between the sequence [tʂ] and the affricate [tʂ] is not only their duration (the frication duration in [tʂ] is considerably shorter than in [tʂ]: 74 ms vs. 121 ms as shown by Dogil & Jessen 1989: 230), but also the rise in spectral amplitude, called ‘rise-time’. The sequence [tʂ], being a discontinuant signal, i.e. consisting of two segments, shows a quick change in the amplitude, whereas the amplitude in [tʂ] changes slowly (smoothly). In the case of Polish, Dogil & Jessen (1989) observe that in a word-initial fricative (in [s] *eść* ‘six’) the amplitude rises about 8 dB in 100 ms, while in the corresponding word-initial [tʂ] (in [tʂ] *eść* ‘hello’), the amplitude changes 8.3 dB in 20 ms.

### 2.2.2 Parameter (ii): The formant frequencies F1, F2, and F3 of the vowels preceding and following the consonant

Figure 7 presents the results of F1 and F2 of a vowel following a given consonant (measured at point 5) for Czech and Polish.

As far as /č/ is concerned, a comparison of the formant frequencies of the following vowel reveals differences especially in F1 and F2: F1 frequency of the following vowel is higher in Polish (677 Hz) than in Czech (453 Hz), but the reverse situation is found with respect to F2, which is higher in Czech (1751 Hz) than in Polish (1606 Hz). Statistically, both differences are significant: for F1 of Czech vs. Polish /č/:  $t = -3.612$ ,  $pMCMC = .0001$ ; and for F2,  $t = 1.298$ ,  $pMCMC = .0444$ . The differences in F3 frequency between the two sounds appear to be insignificant. If we compare Polish /č/ to other sounds which are inherently palatalized, such as Czech /c/ or Polish /č̣/, then, as expected, the F2 frequency (1606 Hz) is significantly lower in comparison to the palatal /c/ (2096 Hz,  $t = -3.922$ ,  $pMCMC = .0001$ ) and alveolo-palatal /č̣/ (1938 Hz,  $t = -19.65$ ,  $pMCMC = .0001$ ). Furthermore, the F2 frequency of Czech /č/ (1751 Hz) is lower than the F2 frequency of /č̣/ (1938 Hz,  $t = -1.571$ ,  $pMCMC = .0016$ ). Regarding the F1 frequency of Polish /č/ (677 Hz), a significant difference was found when compared to /č̣/ (543 Hz,  $t = 9.221$ ,  $pMCMC = .0001$ ) and /c/ (383 Hz,  $t = 4.766$ ,  $pMCMC = .0001$ ). Finally, Polish /č/ and /ts/ do not show a significant difference with respect to F1. Finally, Polish /č/ and /ts/ do not show a significant difference with respect to F1.

Figure 8 presents F1 and F2 frequencies of the preceding vowel at the word-medial position in both languages.

The results show that the F1 frequency of the preceding vowel is higher in Polish (666 Hz) than in Czech (510 Hz) and the difference is significant ( $t = 2.643$ ,  $pMCMC = .005$ ). (Please note that the  $t$ -values might differ in terms of  $<+>$  or  $<->$  from the corresponding  $t$ -values provided in Appendix C depending on the order of comparison, e.g. F1 of Polish /a/ vs. Czech /a/:  $t = 2.643$ , but F1 of Czech /a/ vs. Polish /a/:  $t = -2.643$ .) Whereas F2 does not show significant differences in the two languages, F3 appears to be lower in Czech than in Polish /č/ (2610 Hz vs. 2809 Hz,  $t = -1.288$ ,  $pMCMC = .0076$ ).

Regarding F1 frequency, Polish /č/ (666 Hz), but not Czech /č/, significantly differs from /c/ (516 Hz,  $t = 2.874$ ,  $pMCMC = .0048$ ) and /č̣/ (568 Hz,  $t = 5.332$ ,  $pMCMC = .0001$ ). With respect to F2 frequency, Polish /č/ (1645 Hz) shows significantly lower values in comparison to /č̣/ (1793 Hz,  $t = -6.041$ ,  $pMCMC = .0001$ ) and /c/ (1789 Hz,  $t = -1.074$ ,  $pMCMC = .0368$ ). F2 frequency of Czech /č/ (1718 Hz) is lower than F2 of /c/ (1789 Hz,  $t = -3.233$ ,  $pMCMC = .0012$ ) but does not differ with respect to /č̣/.

### 2.2.3 Parameter (iii): The formant frequency range of F1, F2, and F3 of the vowels preceding and following the consonant

As far as the frequency range of the formants is concerned, the main points of interest are the first three formants of vowels which precede and follow the consonant under consideration. While F1 and F2 generally characterize the vertical and the horizontal position of the tongue, F3 is especially important for proving the possible retroflexion of the Polish postalveolar sound in question. If the F1 frequency is rising and the F2 frequency of the following vowel is falling, then this indicates the transition from the palatal position characteristic of palatalized segments or palatals, which are produced with the tongue blade or tongue dorsum (see e.g. Ladefoged & Maddieson 1996: 364). We expect such results in the case of Czech /č/, but not in the case of the corresponding Polish sound.

The retroflex character of a sound can also be substantiated by looking at F3 transitions. It has been found that retroflexes show an F3 frequency lowering from the vowel to the consonant and an F3 frequency rising from the consonant to the vowel due to the more posterior (but still coronal) place of articulation; see, for example, Stevens & Blumstein (1975) and Hamilton (1996).

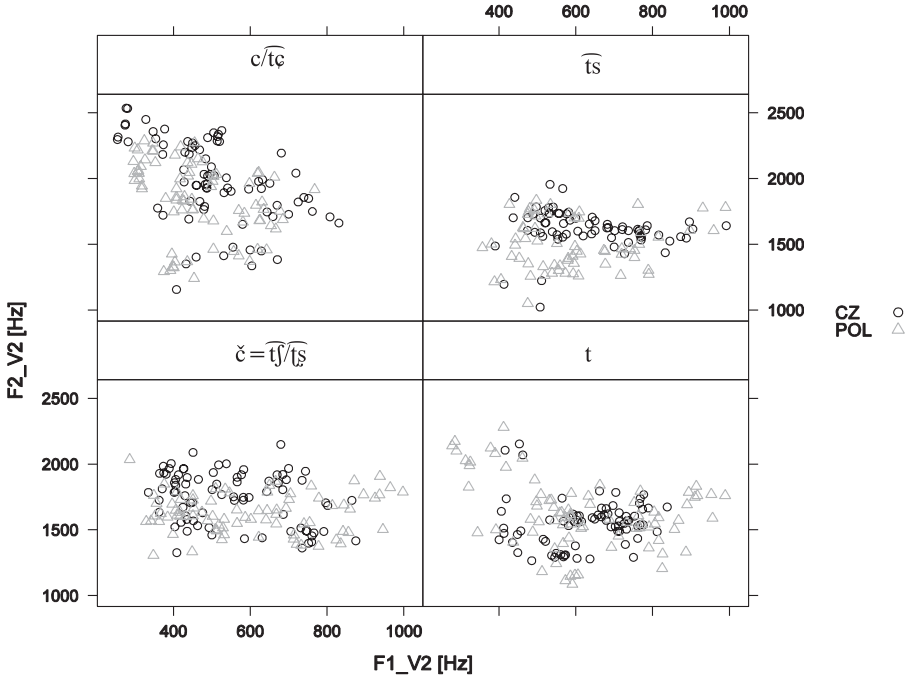


Figure 7 F1 and F2 frequencies of the following vowel in Czech and Polish.

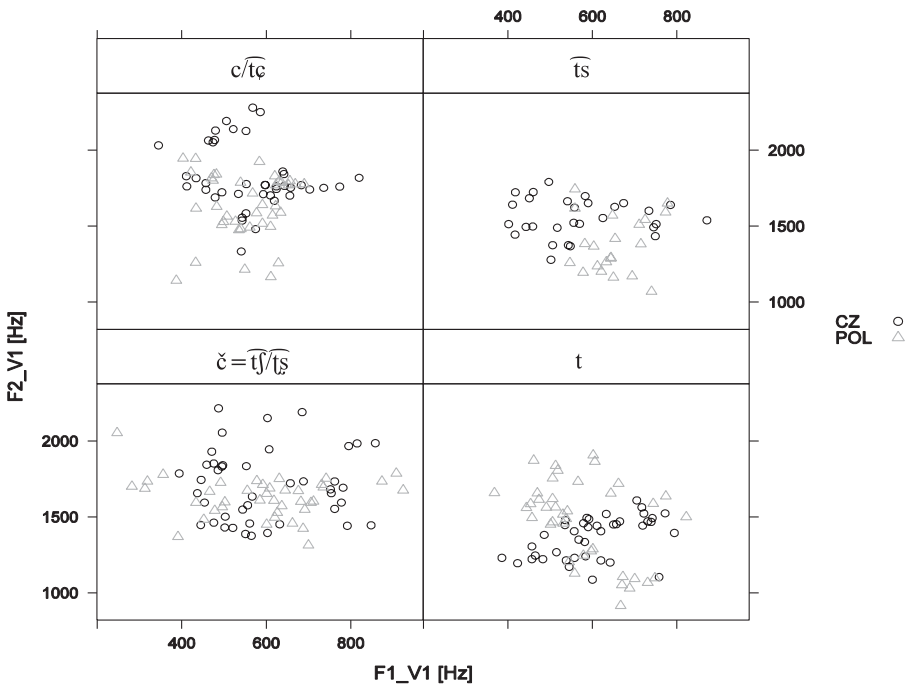


Figure 8 F1 and F2 of the preceding vowel in Czech and Polish.

Regarding formants of the following vowel, the greatest difference between Czech and Polish /č/ is found with respect to the F2 frequency range of the following vowel which is falling in Czech but not in Polish (236 Hz vs. 96 Hz). The difference, however, remains at the level of a statistical tendency ( $t = 2.209$ ,  $pMCMC = .0556$ ). The F1 frequency rises slightly in both languages (Czech – 161 Hz vs. Polish – 100 Hz) and F3 shows a falling effect (Czech 77 Hz vs. Polish 124 Hz), but these differences are not statistically significant.<sup>6</sup>

As expected, Czech /č/ does not show any significant effects in comparison to /c/ and /tʃ/, regarding neither F1 nor F2 frequency range. In contrast, the F1 frequency range of Polish /č/ (–100 Hz) is significantly higher than that of /tʃ/ (–158 Hz,  $t = 3.572$ ,  $pMCMC = .0004$ ) and the F2 frequency range of Polish /č/ (96 Hz) is significantly lower than that of /tʃ/ (340 Hz,  $t = -6.174$ ,  $pMCMC = .0001$ ) and /c/ (247 Hz,  $t = -3.322$ ,  $pMCMC = .0118$ ). Finally, Polish /č/ shows significantly lower F3 frequency range values (124 Hz) than /tʃ/ does (179 Hz,  $t = -2.113$ ,  $pMCMC = .0286$ ). In comparison to /c/ (318 Hz) and /tʃ/, Czech /č/ (77 Hz) does not show significant differences.

As far as the formant frequency range of the preceding vowel is concerned, the F1 frequency is falling in both languages (Czech – 164 Hz vs. Polish – 177 Hz), while F2 and F3 are rising in both languages (F2 range: Czech 356 Hz vs. Polish 290 Hz; F3 range: Czech 268 Hz vs. Polish 308 Hz); the differences are not, however, significant. Therefore, we conclude that the formant frequency ranges of the preceding vowel do not contribute to the acoustic difference between Czech and Polish /č/.

**SPECTRAL PROPERTIES.** Before presenting the results of individual spectral parameters in the following sections, we will provide in this passage a comparison of the multitaper spectra of Polish and Czech /č/. The spectra are obtained at the frication noise of /č/ occurring in the same word, *časý* (Cz.) and *czasý* (Pol.) ‘times’.

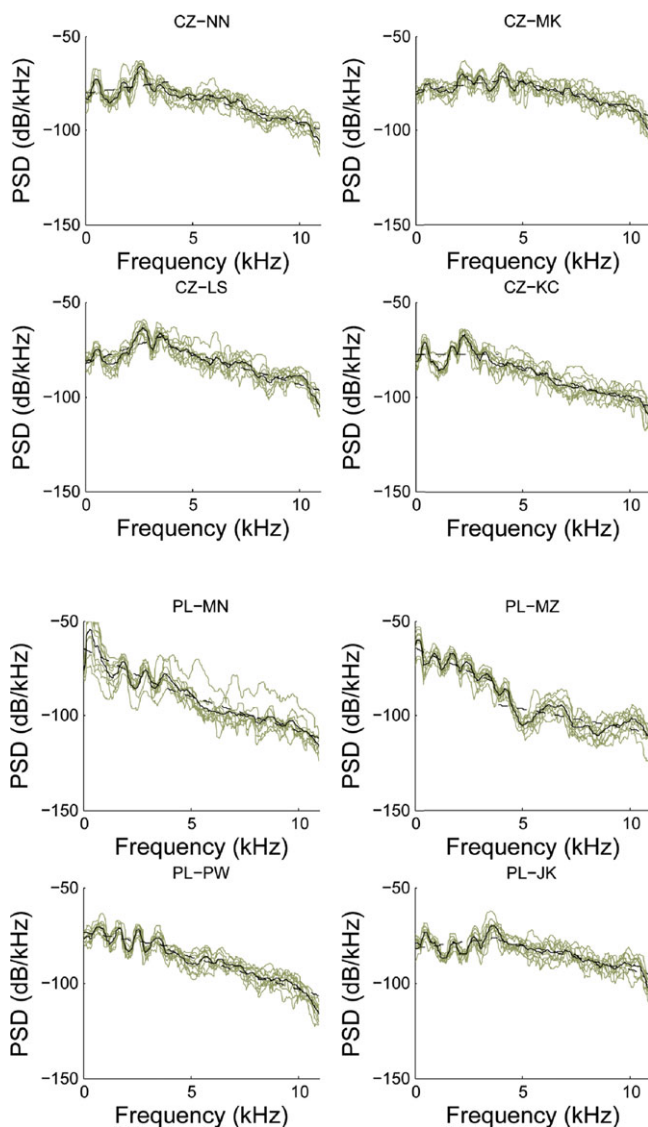
The multitaper spectra for the nine repetitions at the frication noise for each speaker are presented in Figure 9, with the mean spectrum overlaid. As can be seen in Figure 9, the frequency of the highest spectral peak does not seem to differ between the two languages. In contrast, with an endpoint at the highest spectral peak, it can be observed that the spectra for Czech are rising up to the highest spectral peak (reflected in the  $m_1$  value), while there is nearly no rise (or there is even a negative slope) for the Polish spectra. For the higher frequencies, there is no  $m_2$  difference to be noted between the two languages. When comparing the speaker differences for each language, it is apparent that the Polish speaker MZ shows a strong difference in spectral shape as compared to all other speakers. The reasons for the different spectral behaviour of this speaker are not clear. We compared this speaker’s glottal parameters (e.g. Harmonics-to-Noise Ratio HNR) to the other speakers but could not find a difference which would justify the discrepancy.

Following this exploratory spectral comparison of the Czech and Polish /č/, we will now discuss in detail the spectral characteristics of both burst and frication noise.

#### 2.2.4 Parameter (iv): The highest spectral peak frequency of the burst and the following frication

While the mean of the burst highest peak frequency in Czech /č/ is found at 3448 Hz, it appears at 3064 Hz in the corresponding Polish sound. The highest peak frequency of /č/ frication amounts to 3107 Hz in Czech /č/ and to 3252 Hz in Polish /č/. Neither the difference in the highest peak frequency found for the burst nor for the frication part is significant.

<sup>6</sup> Recall that for the preceding vowel, a rise of the formant frequencies is indicated by a positive value of the frequency range. In contrast, for the following vowel, a rise of the formant frequencies is indicated by a negative value of the frequency range (see point (5iii) in Section 2.1 above for further details).



**Figure 9** (Colour online) Multitaper spectra for all repetitions (grey) for Czech (upper half) and Polish (lower half) and the resulting averaged spectrum (overlaid in black). Each panel represents one speaker. The black dashed lines represent the linear line fits from 500 Hz to  $F$  and from  $F$  to the Nyquist frequency.

### 2.2.5 Parameter ( $\nu$ ): Slopes of the regression lines (spectral fit) $m_1$ and $m_2$ of the burst and following frication noise

In Figure 10, the values of the first regression line slope ( $m_1$ ) as compared to the second regression line slope ( $m_2$ ) are plotted for the burst of the Polish and Czech consonants. In Figure 11, the  $m_1$  and  $m_2$  values are plotted for the frication of the same consonants. The endpoint between  $m_1$  and  $m_2$  is 3000 Hz. Note also that there is no frication for /t/ presented since the phoneme is a stop which does not show frication.

The slopes of the regression lines of both burst and frication spectra appear to be very useful in differentiating Polish and Czech /č/. The first regression line slope ( $m_1$ ) of the burst of Polish /č/ ( $2.11 \text{ dB/kHz}^2$ ) is significantly higher than in Czech /č/ ( $-0.27 \text{ dB/kHz}^2$ ,  $t =$

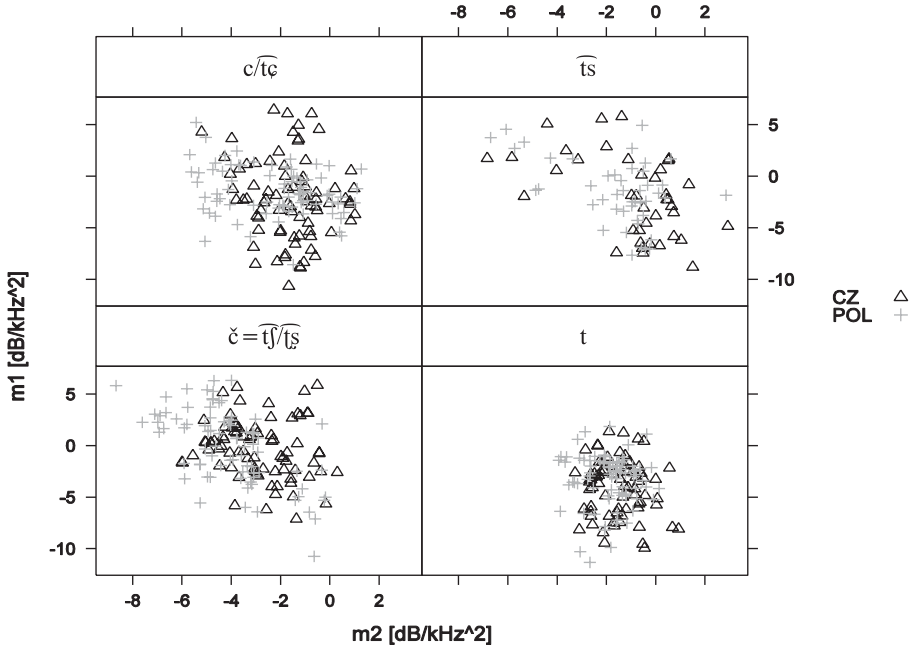


Figure 10 The regression line slopes ( $m1$  and  $m2$ ) of the burst spectra of Czech and Polish consonants.

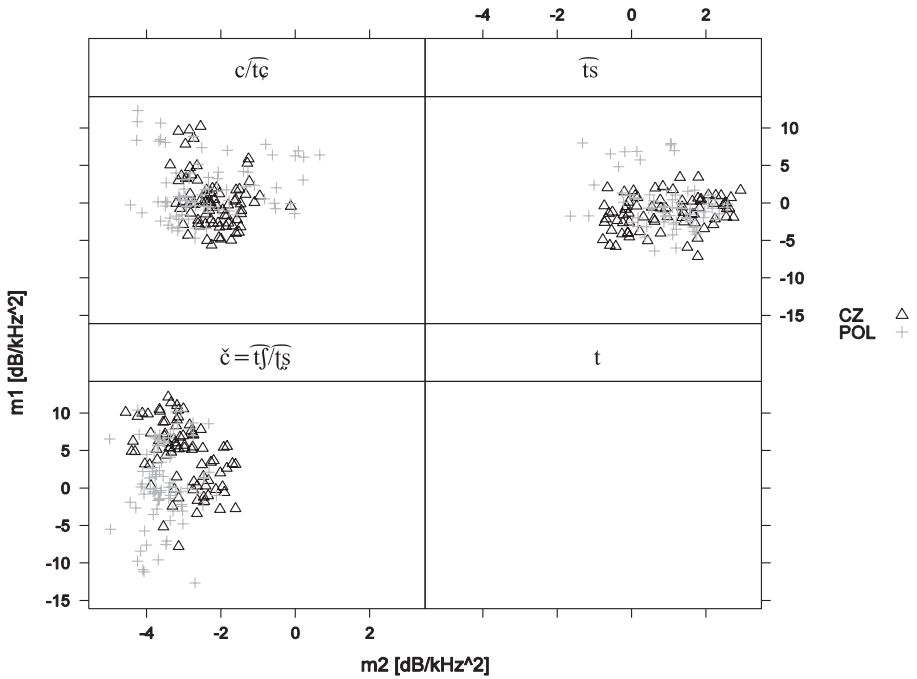
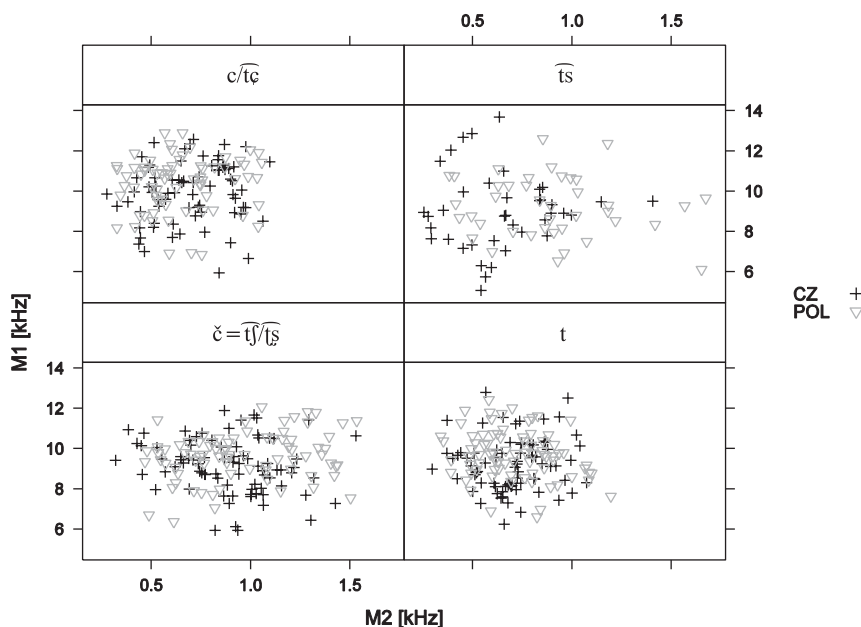


Figure 11 The regression line slopes ( $m1$  and  $m2$ ) of the frication spectra of Czech and Polish consonants.





**Figure 12** The first (M1) and second (M2) spectral moments of the burst spectra of Czech and Polish consonants following Forrest et al. (1988).

2.713,  $pMCMC = .0188$ ). Furthermore,  $m_2$  of the burst spectrum is significantly higher in Czech ( $-2.86$  dB/kHz<sup>2</sup>) than in Polish /č/ ( $-4.69$  dB/kHz<sup>2</sup>,  $t = 3.410$ ,  $pMCMC = .0022$ ).

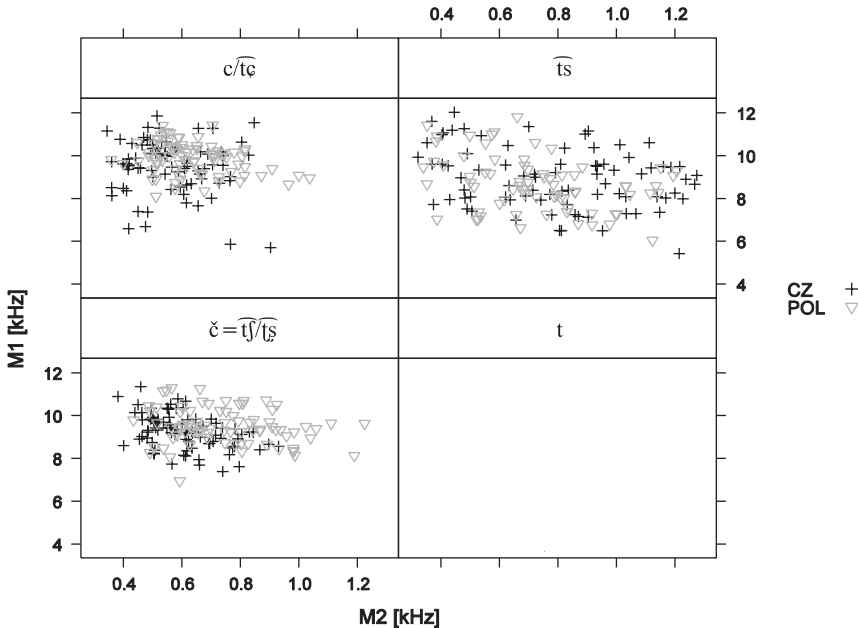
As far as  $m_1$  of the frication noise is concerned, it is higher in Czech ( $6.84$  dB/kHz<sup>2</sup>) than in Polish /č/ ( $0.43$  dB/kHz<sup>2</sup>,  $t = 7.471$ ,  $pMCMC = .0001$ ). Finally,  $m_2$  of frication noise amounts to  $-3.02$  dB/kHz<sup>2</sup> in Czech and to  $-3.52$  dB/kHz<sup>2</sup> in Polish; the difference is not significant.

In sum, the spectral slopes  $m_1$  and  $m_2$  of the burst of the Polish sound /č/ were significantly steeper than the corresponding Czech spectral slopes. For the frication noise, the same effect can be observed for  $m_2$  (although not significant), but there is an opposite trend for  $m_1$  (the Czech rise is significantly steeper than the Polish rise in the spectra).

The  $m_1$  of the burst also appears to be important for distinguishing among the spectra of other sounds. The  $m_1$  of the burst of Polish /č/ shows the steepest rise in comparison to other palatal/palatalized sounds, and the differences are highly significant: /č/ ( $2.11$  dB/kHz<sup>2</sup>) vs. /č̄/ ( $-0.9$  dB/kHz<sup>2</sup>)  $t = 7.033$ ,  $pMCMC = .0001$ ; and /č/ ( $2.11$  dB/kHz<sup>2</sup>) vs. /c/ ( $-3.16$  dB/kHz<sup>2</sup>)  $t = 2.795$ ,  $pMCMC = .0012$ ). In the same vein,  $m_2$  of the burst of Polish /č/ significantly differs from /č̄/ (/č̄/  $-4.69$  dB/kHz<sup>2</sup> vs. /č̄/  $-3.15$  dB/kHz<sup>2</sup>,  $t = -7.765$ ,  $pMCMC = .0001$ ) and /c/ (/c/  $-4.69$  dB/kHz<sup>2</sup> vs. /c/  $-1.4$  dB/kHz<sup>2</sup>,  $t = -5.223$ ,  $pMCMC = .0001$ ). Furthermore,  $m_1$  of the frication of Polish /č/ is different from that of /č̄/ (/č̄/  $0.43$  dB/kHz<sup>2</sup> vs. /č̄/  $4.8$  dB/kHz<sup>2</sup>,  $t = -11.31$ ,  $pMCMC = .0001$ ) but not from /c/ ( $-0.85$  dB/kHz<sup>2</sup>). Finally,  $m_2$  of the frication of Polish /č/ is significantly different from  $m_2$  of both /č̄/ (/č̄/  $-3.52$  dB/kHz<sup>2</sup> vs. /č̄/  $-2.39$  dB/kHz<sup>2</sup>,  $t = -10.035$ ,  $pMCMC = .0001$ ) and /c/ ( $-2.21$  dB/kHz<sup>2</sup>,  $t = -5.105$ ,  $pMCMC = .0001$ ).

## 2.2.6 Parameter (vi): Spectral moments as proposed by Forrest et al. (1988) for burst and frication

Following Forrest et al. (1988) the first and the second spectral moments are plotted for the burst in Figure 12 and for the frication noise in Figure 13.



**Figure 13** The first (M1) and second (M2) spectral moments of the frication spectra of Czech and Polish consonants following Forrest et al. (1988).

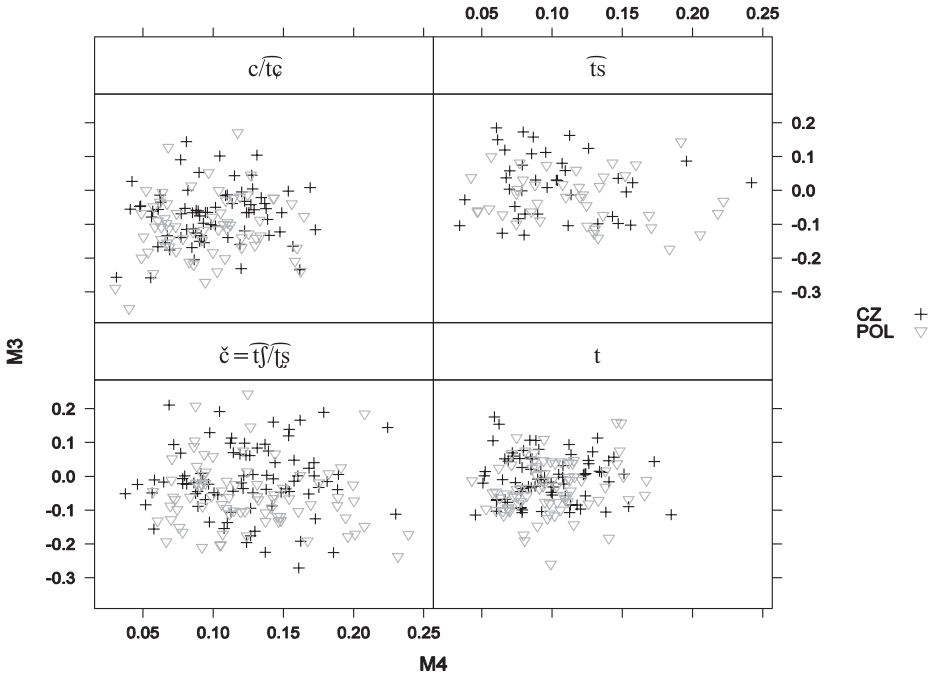
The burst spectra of Polish and Czech /č/ do not significantly differ with respect to the first moment M1 (Polish /č/ 9.31 kHz vs. Czech /č/ 9.35 kHz), but they show a significant effect with respect to the second moment M2 (Polish /č/ 1.12 kHz vs. Czech /č/ 0.86 kHz,  $t = 3.247$ ,  $pMCMC = .004$ ). The fricative spectra are not significantly different with respect to M1 (Polish /č/ 9.49 kHz vs. Czech /č/ 9.25 kHz), but they do differ with respect to M2 (Polish /č/ 0.75 kHz vs. Czech /č/ 0.61 kHz,  $t = 2.962$ ,  $pMCMC = .0182$ ).

Furthermore, Polish /č/ is significantly different from /č/ (Polish /č/ 9.31 kHz vs. /č/ 10.87 kHz,  $t = -7.07$ ,  $pMCMC = .0001$ ) regarding M1 of the burst spectrum as well as from the same sound /č/ (Polish /č/ 1.12 kHz vs. /č/ 0.71 kHz,  $t = 11.918$ ,  $pMCMC = .0001$ ) and /c/ (Polish /č/ 1.12 kHz vs. /c/ 0.65 kHz,  $t = 4.797$ ,  $pMCMC = .0006$ ) regarding M2. Finally, the frication of Polish /č/ significantly differs from the frication of /č/ (Polish /č/ 9.49 kHz vs. /č/ 9.98 kHz,  $t = -2.57$ ,  $pMCMC = .009$ ) regarding M1 but not from that of /c/ (9.48 kHz); however, it shows a significant difference for M2 of /č/ (Polish /č/ 0.75 kHz vs. /č/ 0.63 kHz,  $t = 4.361$ ,  $pMCMC = .0001$ ) and /c/ (Polish /č/ 0.75 kHz vs. /c/ 0.55 kHz,  $t = 2.574$ ,  $pMCMC = .0048$ ).

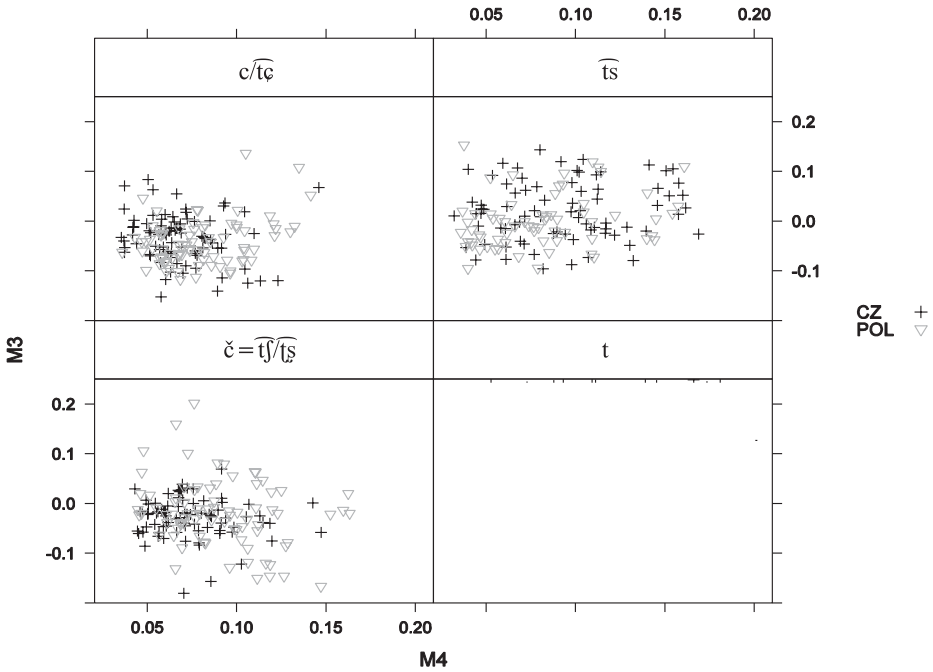
The third and fourth moments of the burst and frication spectra are shown for Polish and Czech consonants in Figures 14 and 15.

Regarding M3, neither the burst nor frication spectra are significantly different for Czech and Polish /č/ (burst: Czech /č/  $-0.04$  vs. Polish /č/  $-0.04$ , frication: Czech /č/  $-0.02$  vs. Polish /č/  $-0.03$ ). With respect to M4, the burst spectrum of Polish /č/ shows significantly higher values than that of Czech /č/ (Polish /č/ 0.15 vs. Czech /č/ 0.13,  $t = 3.509$ ,  $pMCMC = .0032$ ) and the fricative spectrum of Polish /č/ is characterized by significantly higher values than that of Czech /č/ (Polish /č/ 0.09 vs. Czech /č/ 0.07,  $t = 3.088$ ,  $pMCMC = .0146$ ).

If we compare the two sounds to other palatal/palatalized segments, then the following results are obtained: the values of M3 of the burst distinguish between the Polish /č/ and /č/ (Polish /č/  $-0.04$  vs. /č/  $-0.13$ ,  $t = 6.764$ ,  $pMCMC = .0001$ ) as well as between Czech /č/ and



**Figure 14** The third (M3) and fourth (M4) moments of the burst spectra of Czech and Polish consonants following Forrest et al. (1988).



**Figure 15** The third (M3) and fourth (M4) moments of the frication spectra of Czech and Polish consonants following Forrest et al. (1988).

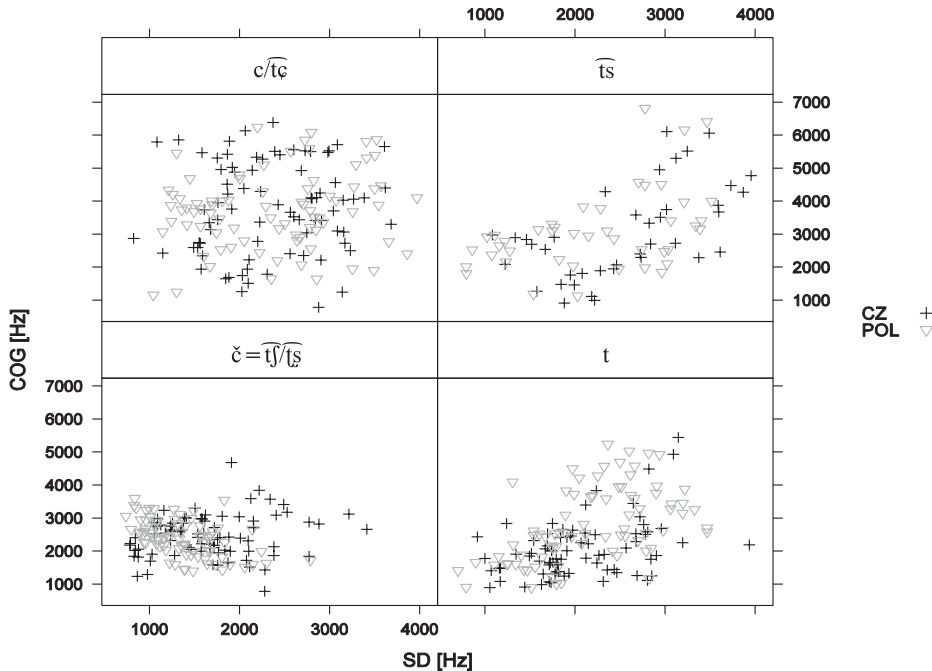


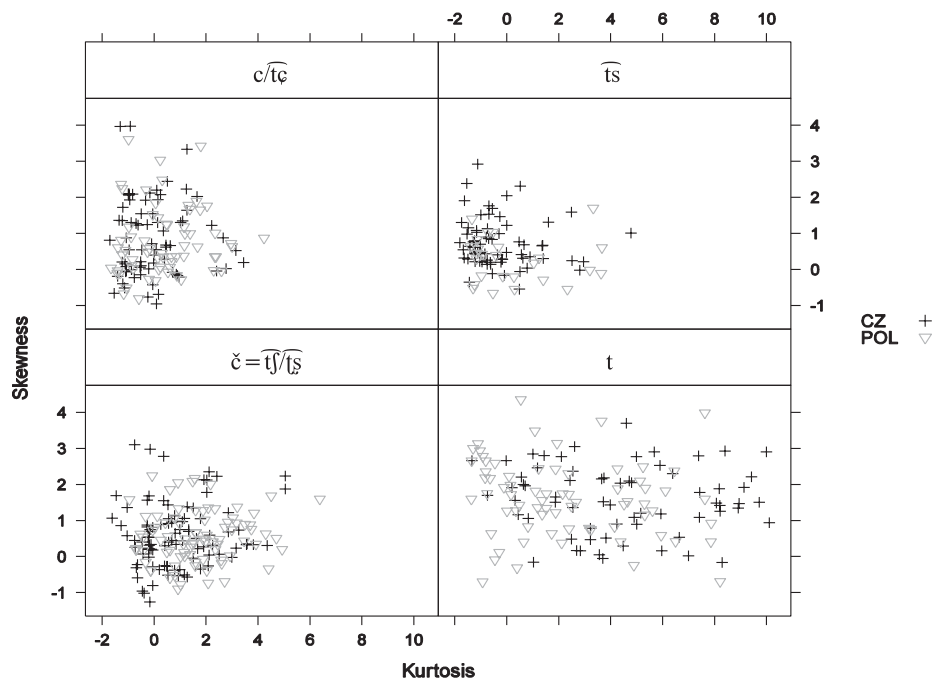
Figure 16 Centre of gravity (COG) and spectral standard deviation (SD) of the burst of Czech and Polish consonants.

$\sqrt{t\check{c}}$  ( $/\check{c}/ -0.04$  vs.  $\sqrt{t\check{c}}$   $-0.13$ ,  $t = 2.003$ ,  $pMCMC = .0232$ ). M4 appears to be distinctive for the burst spectra of Polish  $/\check{c}/$  in comparison to  $\sqrt{t\check{c}}$  ( $/\check{c}/ 0.15$  vs.  $\sqrt{t\check{c}}$   $0.11$ ,  $t = 6.806$ ,  $pMCMC = .001$ ) and  $/c/$  ( $/\check{c}/ 0.15$  vs.  $/c/ 0.1$ ,  $t = 4.987$ ,  $pMCMC = .001$ ) as well as for the spectra of Czech  $/\check{c}/$  in comparison to  $/c/$  ( $/\check{c}/ 0.13$  vs.  $/c/ 0.1$ ,  $t = 5.535$ ,  $pMCMC = .0001$ ). Furthermore, the M3 of the frication spectra of Polish  $/\check{c}/$  is statistically different from the M3 of the frication spectra of  $\sqrt{t\check{c}}$  ( $/\check{c}/ -0.03$  vs.  $\sqrt{t\check{c}}$   $-0.05$ ,  $t = 2.727$ ,  $pMCMC = .0054$ ) but not of  $/c/$  ( $-0.02$ ). Finally, M4 of the frication is statistically different for the Polish  $/\check{c}/$  and  $\sqrt{t\check{c}}$  ( $/\check{c}/ 0.09$  vs.  $\sqrt{t\check{c}}$   $0.07$ ,  $t = 3.954$ ,  $pMCMC = .0002$ ) as well as the Polish  $/\check{c}/$  and  $/c/$  of frication spectra ( $/\check{c}/ 0.09$  and  $/c/ 0.07$ ,  $t = 2.146$ ,  $pMCMC = .0280$ ).

### 2.2.7 Parameter (vii): Centre of gravity, standard deviation, skewness and kurtosis of burst and frication noise spectra

Figure 16 presents centre of gravity and standard deviation calculated according to Praat version 5.2 (Boersma & Weenink 2011) formulae. It should be noted that the values obtained differ from those obtained by applying Forrest et al.'s (1988) method.

The centre of gravity values of the burst are not significantly distinctive for Polish and Czech  $/\check{c}/$ : the average burst COG values of Polish and Czech  $/\check{c}/$  are 2563 Hz and 2648 Hz, respectively. Although the COG value at the frication noise is lower for Polish  $/\check{c}/$  (3064 Hz) than for Czech  $/\check{c}/$  (3466 Hz), the difference is statistically not significant. The results are in contrast to the spectral standard deviation, which is significantly different for the burst: 1145 Hz for Polish  $/\check{c}/$  vs. 1587 Hz for Czech  $/\check{c}/$  ( $t = -2.835$ ,  $pMCMC = .0032$ ). However, the same parameter applied to the frication landmark results in values, which are not statistically significant if comparing Polish  $/\check{c}/$  (1464 Hz) and Czech  $/\check{c}/$  (1357 Hz).



**Figure 17** Kurtosis and skewness of the burst of Czech and Polish consonants.

With respect to the COG, the burst spectra of the palatalized/palatal sounds  $\widehat{t\check{c}}$  and  $/c/$  are significantly different from the burst of Polish  $/\check{c}/$  ( $\widehat{t\check{c}}$ / 3396 Hz vs.  $/\check{c}/$  2563 Hz,  $t = 5.457$ ,  $pMCMC = .0001$ ;  $/c/$  4164 vs.  $/\check{c}/$  2563 Hz,  $t = 3.146$ ,  $pMCMC = .0012$ ) and Czech  $/\check{c}/$  ( $/\check{c}/$  2648 Hz vs.  $\widehat{t\check{c}}$ / 3396 Hz,  $t = -2.237$ ,  $pMCMC = .0278$ ; and  $/\check{c}/$  2648 Hz vs.  $/c/$  4164,  $t = -10.622$ ,  $pMCMC = .0001$ ). The average COG values of the  $/c/$  frication spectra are significantly higher than the COG of Czech  $/\check{c}/$  ( $/c/$  3755 Hz vs.  $/\check{c}/$  3466 Hz,  $t = 2.529$ ,  $pMCMC = .016$ ) but similarly high with respect to Polish  $/\check{c}/$  (3064 Hz). This is in contrast to the average COG values of  $\widehat{t\check{c}}$  frication spectra, which are significantly higher than those obtained for both Polish  $/\check{c}/$  ( $\widehat{t\check{c}}$ / 4738 Hz vs.  $/\check{c}/$  3064 Hz,  $t = 12.553$ ,  $pMCMC = 0.0001$ ) and Czech  $/\check{c}/$  ( $\widehat{t\check{c}}$ / 4738 Hz vs.  $/\check{c}/$  3466 Hz,  $t = 1.906$ ,  $pMCMC = 0.0002$ ).

With respect to the SD of burst spectra, Polish  $/\check{c}/$  shows significantly lower values regarding  $\widehat{t\check{c}}$  ( $/\check{c}/$  1145 Hz vs.  $\widehat{t\check{c}}$ / 2026 Hz,  $t = -10.490$ ,  $pMCMC = .0001$ ), contrary to Czech  $/\check{c}/$  (1587 Hz) which does not significantly differ with respect to the SD obtained for  $\widehat{t\check{c}}$  (2026 Hz). However, both Polish and Czech  $/\check{c}/$  have significantly lower SD values with respect to  $/c/$  (Polish  $/\check{c}/$  1145 Hz vs.  $/c/$  2268 Hz,  $t = -5.285$ ,  $pMCMC = .0001$ ; Czech  $/\check{c}/$  1578 Hz vs.  $/c/$  2268 Hz,  $t = -6.945$ ,  $pMCMC = .0001$ ). The SD of the frication spectra of Czech  $/\check{c}/$  shows significantly lower values with respect to  $/c/$  ( $/\check{c}/$  1357 Hz vs.  $/c/$  2213 Hz,  $t = -15.03$ ,  $pMCMC = .0001$ ) and  $\widehat{t\check{c}}$  ( $/\check{c}/$  1357 Hz vs.  $\widehat{t\check{c}}$ / 1765 Hz,  $t = -2.44$ ,  $pMCMC = .0046$ ). Finally, the SD of the frication spectra of Polish  $/\check{c}/$  is significantly lower than that of  $/c/$  ( $/\check{c}/$  1464 Hz vs.  $/c/$  2213 Hz,  $t = -4.694$ ,  $pMCMC = .0001$ ) and  $\widehat{t\check{c}}$  ( $/\check{c}/$  1464 Hz vs.  $\widehat{t\check{c}}$ / 1765 Hz,  $t = -5.275$ ,  $pMCMC = .0001$ ).

Kurtosis and skewness values are plotted for the burst of Polish and Czech consonants in Figure 17. The values were obtained according to Praat version 5.2 (Boersma & Weenink 2011) formulae.

Regarding skewness, the values are positive for both burst and frication spectra of /č/, but significantly lower when comparing Polish to Czech (burst: Polish /č/ 0.20 vs. Czech /č/ 0.81,  $t = -2.561$ ,  $pMCMC = .0274$ ; frication: Polish /č/ 0.69 vs. Czech /č/ 1.47,  $t = -2.17$ ,  $pMCMC = .0394$ ). Kurtosis is significantly different in the case of frication but not for the burst spectra (burst: Polish /č/ 1.84 vs. Czech /č/ 0.93; frication: Polish /č/ 2.0 vs. Czech /č/ 5.19,  $t = -2.49$ ,  $pMCMC = .0264$ ).

Skewness of the burst of Polish /č/ (0.2) does not show any significant effect when compared to /t͡ʃ/ (0.35) and /c/ (0.3) in contrast to skewness of the burst of Czech /č/ which is significantly higher when compared to /c/ (/č/ 0.81 vs. /c/ 0.3,  $t = 4.424$ ,  $pMCMC = .0001$ ). Furthermore, the skewness of the frication spectra of Czech but not Polish /č/ is significantly different from the skewness of /c/ (/č/ 1.47 vs. /c/ 0.29,  $t = 8.87$ ,  $pMCMC = .0001$ ) and of /t͡ʃ/ (/č/ 1.47 vs. /t͡ʃ/ 0.44,  $t = 2.244$ ,  $pMCMC = .0054$ ).

If we compare the kurtosis of /č/ to palatalized/palatal sounds, the burst spectra of both Polish and Czech /č/ are significantly higher than those of /c/ (Polish /č/ 1.84 vs. /c/ -0.029,  $t = 4.229$ ,  $pMCMC = .0014$ ; Czech /č/ 1.84 vs. /c/ -0.029,  $t = 3.294$ ,  $pMCMC = .0008$ ) but only Polish /č/ shows significantly higher values than /t͡ʃ/ (/č/ 1.84 vs. /t͡ʃ/ 0.39,  $t = 4.598$ ,  $pMCMC = .0001$ ). Finally, in contrast to frication spectra of Polish /č/, the kurtosis values of Czech /č/ are different from the corresponding values of /c/ and /t͡ʃ/ (Czech /č/ 5.19 vs. /t͡ʃ/ 0.72,  $t = 2.856$ ,  $pMCMC = .0046$ ; /č/ 5.19 vs. /c/ 0.72  $t = 3.68$ ,  $pMCMC = .0001$ ).

### 3 Articulatory characteristics

Before taking a closer look at the articulation of Polish and Czech postalveolar sounds, we will review the main articulatory facts about retroflex sounds.

Retroflex sounds are well known for their articulatory variation (Ladefoged & Wu 1984, Ladefoged & Maddieson 1996). Typical retroflex stops are articulated with a raised tongue tip placed at the postalveolar region (as in e.g. Hindi) or with the underside of the tongue tip touching the palatal place of articulation (as in e.g. Tamil). Between these two articulatory extremes other realizations of retroflex stops are also found, for example, in Pekingesese sibilants (see Ladefoged & Bhaskararao 1983). Retroflex fricatives are typically produced with the tongue tip raised to the postalveolar place of articulation (Keating 1991: 35). This is in contrast to palatoalveolar sibilants, which are produced with the tongue blade touching the postalveolar area. While in the case of retroflexes the tongue dorsum is usually flat, in the case of palatoalveolars it is domed. Such observations lead to the classification of several sibilant fricatives often assumed to be palatoalveolars as retroflexes, e.g. Mandarin sibilants (Ladefoged & Wu 1984), some Slavic sibilants (Žygis 2003, 2006; Hamann 2004), and Komi-Permyak sibilants (Kochetov & Lobanova 2007).

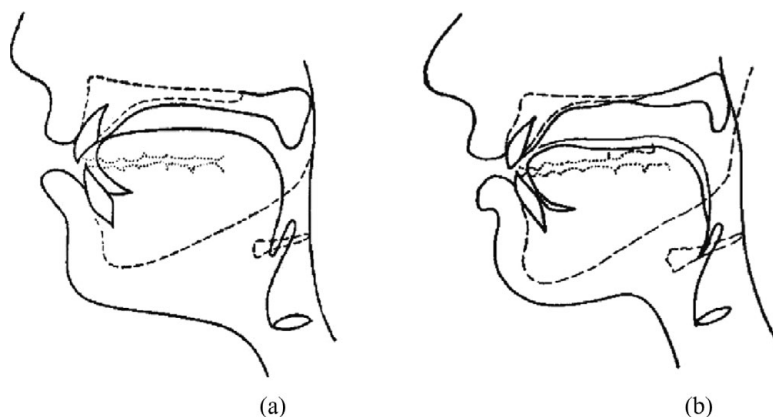
#### 3.1 Polish

Biedrzycki (1974) provides an x-ray tracing of the stop component of Polish /č/ (the sound he transcribes as /t͡ʃ/) which leaves no doubt that the stop component also has features characteristic of typical retroflex stops: it is produced with the tongue tip, which is extended and raised. It touches the alveolar ridge or even the area behind it. In addition, the posterodorsum is raised and the sound is velarized; see Figure 18 (an equivalent x-ray tracing of the fricative component is not provided by Biedrzycki 1974). A very similar x-ray tracing of the stop component is provided by Ostaszewska & Tambor (2001: 40), who transcribe the affricate as /č/.

Wierzchowska (1971: 163) provides another x-ray tracing of the stop component of the postalveolar affricate. It is shown in Figure 19a, while the fricative component is presented in Figure 19b. Note that Wierzchowska also transcribes the affricate as /č/.



**Figure 18** Stop component of Polish /č/ based on Biedrzycki (1974: 22).

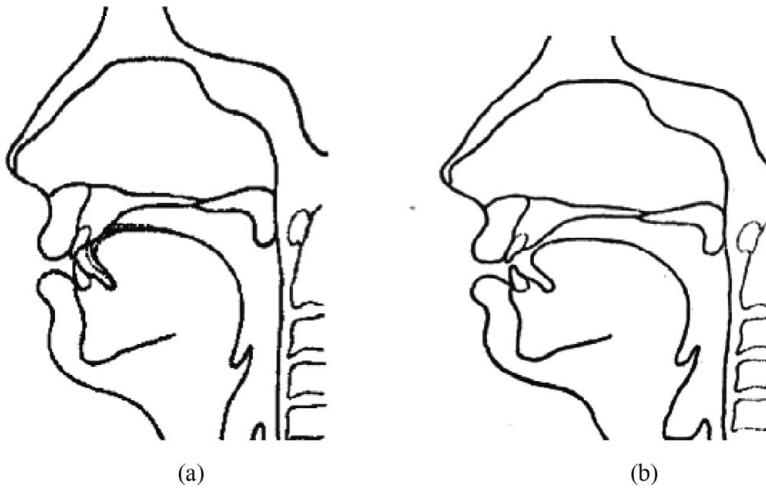


**Figure 19** (a) Stop component of Polish /č/ based on Wierchowska (1971: 163). (b) Fricative component of Polish /č/ based on Wierchowska (1980: 64).

Although the tongue tip is not curled up in Figure 19a, Wierchowska (1971: 163) observes that the difference between the Polish coronal stop /t/ and the stop component of /č/ is that the tongue tip is positioned higher in the latter sound than in the former one. As shown in Figure 19a, the tongue tip touches the alveolar ridge, whereas in the case of /t/ the tongue tip is positioned behind the teeth.<sup>7</sup> Wierchowska explicitly states that the sound is articulated with the tongue tip behind the alveolar ridge. The affricate /č/ is pronounced

<sup>7</sup> Wierchowska (1971: 164) also notes that the stop component as shown in Figure 19a also occurs in sequences before the fricatives /ʂ z/ (i.e. /ʂ/ /z/ in her terms) which do not create an affricate, see Footnote 5.





**Figure 20** (a) Stop component of Czech /tʃ/ (Palková 1994: 229). (b) Czech /ʃ/ (Palková 1994: 235).

with a flat tongue dorsum, and it also displays a sublingual cavity, which is characteristic of retroflexes.

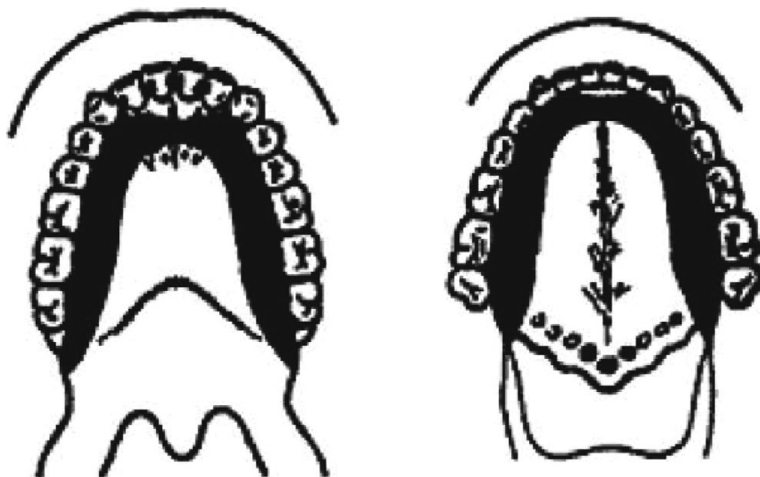
As far as the fricative part of /č/ is concerned, Wierzchowska (1980) provides the same x-ray tracing as for the corresponding fricative /š/. Regarding the definition of retroflexes adopted for the present study, according to which retroflexes are apical and produced at a postalveolar place of articulation, the fricative part of the Polish sound can also be classified as retroflex, which leads to the conclusion that /tʃ/ (and not /tʃ/) reflects the articulatory characteristics of the Polish sound in a more optimal way.

It is also worth noting that in the Slavic tradition the postalveolar sounds in question are denoted as /č/, /ž/ (e.g. Benni 1931, Wierzchowska 1971, Rubach 1984, Ostaszewska & Tambor 2001); /č/, /dž/ (e.g. Gussmann 1980, Szpyra 1995); /tʃ/, /dʒ/ (Biedrzycki 1974); or as IPA /tʃ/, /dʒ/ (e.g. Jassem 1979, 2003; Dukiewicz & Sawicka 1995). However, in the non-Slavic tradition researchers have already pointed out the retroflex character of the Polish sibilant fricatives; see Keating (1993), Ladefoged & Maddieson (1996), Hall (1997b), Rochoń [Żygis] & Pompino-Marschall (1999), Hamann (2003, 2004), and Żygis (2003, 2006). Only one study, to the best of our knowledge, namely Stevens & Blumstein (1975), treats the Polish affricate /dʒ/ as a retroflex sound, although its properties are not discussed there in detail.

### 3.2 Czech

An x-ray tracing of the stop component of Czech /č/ is shown in Figure 20a. It shows that in the release phase of the closure, a constriction similar to that of /ʃ/ is created. The lips are protruded. The tongue dorsum is rather domed. Figure 20b provides an x-ray tracing of the fricative /ʃ/. (These and the images in Figure 21 are taken from Palková (1994) by permission.)

Palková (1994: 235) states that in the closure phase the tongue tip is situated at the rear of the alveolar ridge. This is confirmed by both the palatogram and the linguagram of /tʃ/ provided in Figure 21.



**Figure 21** Palatogram and linguagram of the closure of Czech /č/ (Palková 1994: 235).

In our view, the articulatory data do not provide clear evidence in favour of  $/\text{t}\check{\text{c}}/$ , which is typically produced with the tongue blade touching the postalveolar place of articulation and a raised tongue dorsum. The data are based on an investigation of only one speaker, and we conclude that further study is needed in order to gain more insight into the articulation of Czech /č/; see also a description of the Czech phonemic inventory by Dankovičová (1997) who also used the symbol  $/\text{t}\check{\text{c}}/$ .

#### 4 Impressionistic perception of Polish and Czech /č/

In the Slavic literature, it is common to use terms such as SOFT vs. HARD to differentiate between palatalized and non-palatalized sounds; see de Bray (1951). Occasionally, the term SEMI-SOFT is used to distinguish sounds which are perceived as less soft than palatalized sounds. In other words, palatalized sounds are called SOFT, non-palatalized sounds are perceived as HARD and sounds whose percept lies between palatalized and non-palatalized, presumably slightly palatalized, are interpreted as SEMI-SOFT. It should also be stressed that although these terms are perceptually (impressionistically) oriented, no exact perceptual definition is given.<sup>8</sup>

From a perceptual point of view, Polish affricates are unanimously considered to be of low sibilant tonality (Żygis 2006), or HARD in traditional terms, especially when compared with affricates of other Slavic languages, e.g. Russian (de Bray 1951). The ‘hardness’ of these sounds is acoustically mirrored by prominent lower frequencies, which are characteristic of retroflexes.

Lehr-Spławiński & Stieber (1957: 40) maintain that the pronunciation of the FRICATIVES /š ž/ in Czech can be as ‘hard’ as the corresponding Polish sounds, but it often happens that the sounds are articulated in a ‘semi-soft’ way. This is especially noticeable – as Lehr-Spławiński

<sup>8</sup> Potentially, we could make use of the already existing diacritics for tone levels and transcribe sibilants of low tonality with the additional symbol [j], of mid tonality with [ɨ], and of high tonality with [ɨ̄] (as well as their refinements). This proposal needs to be analysed from a broader perceptual perspective by taking into consideration all sibilants. We leave this topic for further study.

& Stieber (1957) observe – when Czechs speak Polish. With respect to the corresponding affricate /č/, the situation is different in that there is no option: the affricate is always semi-soft and differs from Polish /t͡ʃ/ (i.e. /č/ in Lehr-Splawiński & Stieber's terms).

As far as the present study is concerned, all four Czech speakers produced a 'semi-soft' affricate which makes a strikingly different perceptual impression in comparison to the 'hard' Polish affricate pronounced by all four Polish speakers. This was especially evident when both Polish and Czech informants produced the same word, *časy* 'times', in both languages.

## 5 Articulation, perception, and the retroflex puzzle

Before we share some thoughts on the motivation for the appearance of retroflexes in Polish (in Section 6 below), let us look at some articulatory variants of retroflex fricatives in Polish.

Styczek (1973) provides x-ray data of Polish sibilants as pronounced by thirteen Polish speakers. Styczek (1973) shows that her speakers produced Polish /ʂ/ in four different ways, as listed in (6) below. Note that not every pronunciation variant can be classified as retroflex in our terms as the sibilants are also produced at the alveolar ridge (6c) and sometimes even with the tongue blade (6d).

- (6) *Production of Polish /ʂ/ based on x-ray data of 13 speakers (Styczek 1973)*
- a. With a slightly raised tongue tip accompanied by lip rounding.
  - b. With a curled up tongue tip without lip rounding.
  - c. With a tongue tip touching the alveolar ridge accompanied by lip rounding.
  - d. With a slightly raised tongue blade without lip rounding.

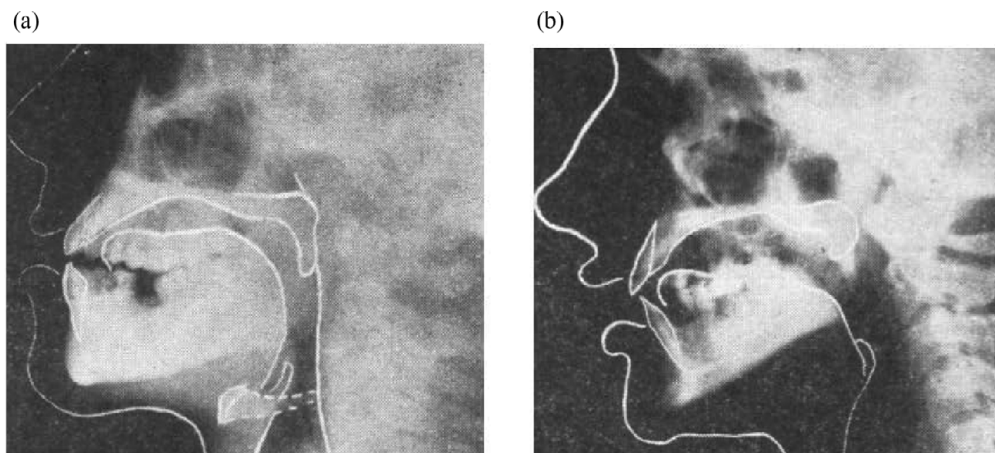
How can we explain such variation? In fact, the varying gestures in (6a–d) are not arbitrary but they regulate the size of the front cavity (Stevens 1998). Speakers use different strategies to form the large cavity and thereby achieve the lowering of resonances (see below). They can either raise the tongue tip higher (sometimes even curling it up), or, alternatively, they can protrude their lips. In fact, speakers use these two gestures in various ways: they round the lips if the tongue tip is closer to the alveolar ridge, but they do not necessarily round their lips if the tongue tip is placed high behind the alveolar ridge. Between the two extremes other configurations are possible since they all lead to a similar perceptual output.

Two possible articulatory configurations are illustrated by the x-ray tracings in Figure 22; they illustrate the pronunciation of /ʂ/ by two native speakers of Polish (Styczek 1973 uses the symbol /ʂ/ to denote this sound).

The speaker whose pronunciation is shown in the x-ray tracing in Figure 22a raises his tongue tip almost without protruding his lips. Different articulatory gestures are found in the pronunciation of the second speaker (Figure 22b): the tongue tip is not raised, while the lips are protruded.

Varying degrees of lip protrusion are not only characteristic for Polish sibilants. Koneczna & Zawadowski (1956: 77) also observe a similar variation in the pronunciation of Russian /ʂ/ by their two speakers. One speaker produced /ʂ/ by placing the tongue tip further back at the postalveolar place of articulation than the other. At the same time, the latter speaker protruded his lips, whereas the former did not. Again, the explanation provided by Koneczna & Zawadowski (1956) is straightforward: the first speaker did not need to protrude his lips as the front cavity was already large enough to achieve the resonances required; see also Toda, Maeda & Honda (2010).

In light of the articulatory variation found not only in retroflexes but also in all sibilants, it appears that sibilants can be better captured as a natural class in perceptual terms than in articulatory terms. Ladefoged (1997: 614) notes that in the case of sibilants their perceptual characteristics prove to be better for grouping all sibilants into one class than the articulatory features:



**Figure 22** Polish /š/ as produced by two speakers (Styczek 1973). (a) Large front cavity without lip protrusion. (b) Small front cavity with lip protrusion.

What is at stake is whether the auditory definition provides a better explanation for the grouping than a definition in terms of the articulatory attributes. Until there is some evidence for the shared articulatory properties being the reason for this grouping, it seems preferable to continue to maintain that the well attested salient auditory characteristics are the basis for the natural class. (Ladefoged 1997: 614)

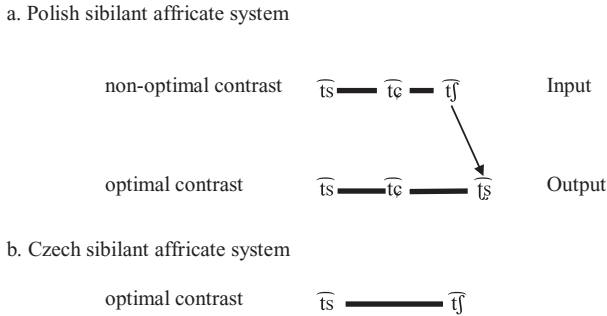
Returning to sibilant affricates, it seems that like sibilant fricatives they show articulatory variation on the one hand and a stable percept on the other (see Section 4). For this reason we would prefer to use a detailed perceptually-based transcription and not an articulatorily-based one. Since such transcriptions do not exist, we have chosen transcriptions which cover most articulatory variation and which are closer to these sounds from a perceptual point of view. The Polish affricates are typically pronounced with the tongue tip touching the postalveolar place of articulation, but a great deal of variation is found among speakers (see (6) above). For these cases we decided to use the traditional IPA notation of retroflex affricates  $\text{ʃ̌}$ ,  $\text{ʧ̌}$  to describe these sounds since the retroflexes are generally produced with the tongue tip and the term retroflex covers several places of (postalveolar) articulation. Furthermore, in our view these affricates are perceptually closer to the retroflexes  $\text{ʃ̌}$ ,  $\text{ʧ̌}$  than to the palatoalveolars  $\text{tʃ}$ ,  $\text{dʒ}$ . Finally, a possible candidate for transcribing the Polish affricate, i.e. the palatoalveolar affricate produced with the tongue tip  $\text{tʃ}$ , does not reflect the articulation with the curled-up tongue tip, which is a possible articulation attested in the affricate realization.

## 6 Why retroflexes in Polish?

In light of our conclusions, an intriguing question arises as to why the Polish inventory contains the retroflex sound at all while the corresponding sound in its neighbouring language Czech is a palatoalveolar  $\text{tʃ}$ . This question is even more intriguing if one considers the fact that both sounds originate from the same Protoslavic ancestor  $\text{č}$ .<sup>9</sup>

<sup>9</sup> The emergence of  $\text{tʃ}$  goes back to the Protoslavic First Velar Palatalization (1stVP), according to which /k/, /g/, and /x/ changed to  $\text{tʃ}$ ,  $\text{ʒ}$ , and  $\text{ʃ}$  before front vowels:  $\text{ĩ}$   $\text{ĩ}$   $\text{ě}$   $\text{ē}$  (Stieber 1969: 66). Note that the symbols  $\text{ĩ}$   $\text{ē}$  stand for long /i e/, while  $\text{ĩ}$   $\text{ě}$  denote their short counterparts.

Since the process of the 1stVP occurred in Protoslavic, palatoalveolar  $\text{tʃ}$  is also an ancestor of the



**Figure 23** Schematic representation of perceptual relations in affricate systems.

Our hypothesis concerning this question invokes perceptual relations among the sibilants in a given inventory since – as stated in the previous section – perception plays an indispensable role in determining sibilant systems. The hypothesis is also based on a phonological principle originally proposed by Hall (1997a) for describing sibilant fricative systems. According to this principle, in complex sibilant systems, i.e. those consisting of at least two postalveolar fricative sibilants, one of them is retroflex. The present study extends this principle to affricates as shown in (7). Note that the principle refers only to postalveolar sibilants but does not exclude the presence of dental or alveolar /s/ in a given inventory.

(7) *Markedness statement* (see Hall 1997a for a statement on sibilant fricatives)

If the inventory is complex, i.e. consists of at least two postalveolar sibilant affricates, then one of the postalveolar affricates is retroflex.

Hall (1997a) argues that the palatoalveolar fricative /ʃ/ and the alveolo-palatal /ç/ do not co-occur in phonemic inventories because both fricatives are identical with regard to their features, i.e. [+coronal, –anterior, +distributed]. Therefore, /ʃ/ converts to /ʃ̣/ changing its feature specification to [+coronal, –anterior, –distributed].

In contrast to Hall (1997a), we advance the hypothesis that perception rather than articulation is responsible for changes in sibilant systems. In particular, changes from palatoalveolar to retroflex sibilants are claimed to be perceptually-based:  $\widehat{ʃ̣}$  and  $\widehat{tʃ̣}$  form a better perceptual contrast than  $\widehat{tʃ}$  and  $\widehat{tʃ̣}$ ; therefore,  $\widehat{tʃ}$  changed to  $\widehat{ʃ}$  in those systems which already contained the alveolo-palatal, as was the case in Polish.

The relevant change is schematically shown in Figure 23. The arrow indicates the change and the horizontal lines indicate the perceptual distance.

Polish affricate /č/. Around the fifteenth century, the ‘hardening processes’ started with the consequence that the affricate  $\widehat{tʃ}$  originating from the 1stVP converted to the perceptually hard variant of /č/ (i.e. the retroflex  $\widehat{ʃ̣}$  in our terms). This process is well documented in the orthography, where ⟨i⟩ signaling the softness of the preceding consonant changed to ⟨y⟩, i.e. the high back vowel [ɯ] in IPA terms, e.g. *čisto* vs. *czysto* ‘clean’ or *šija* vs. *szyja* ‘neck’ (Rospond 1971: 113).

In simple sibilant systems, i.e. those consisting of one postalveolar affricate as in Czech (see Figure 23), the postalveolar affricate is almost always a palatoalveolar  $\widehat{tʃ}$  because the perceptual distance between the two sounds is sufficient and an optimal contrast already exists.<sup>10,11</sup>

An important though indirect piece of evidence supporting this view is provided by Żygis & Padgett's (2010) acoustic and perceptual study of Polish fricatives. They analyse the relative distances between the Polish fricatives in the form of a multidimensional scaling which is in line with the corresponding affricates in the Figure 23. Their results show that the pair /s/ and /ç/ is better discriminated than the pair /ʃ/ and /ç/ by both English and Polish listeners. In an acoustic space whose dimensions are created by F2 and COG, the distance between /s/ and /ç/ is greater than between /ʃ/ and /ç/ (Padgett & Żygis 2007, Żygis & Padgett 2010).

The results of the present study show, however, that COG does not contribute to the distinction of the frication part of the affricates. This appeared a bit surprising especially in light of the fact that COG is generally seen as a parameter contributing to the distinction of fricatives including sibilants. We hypothesise that other parameters such as e.g. temporal cues and formants have greater impact on distinguishing small differences between the affricates. In addition, spectral slopes may play a more important role in the perception of rather small perceptual differences in affricates than COG does. Therefore, it remains to be seen which parameters are decisive for the perception of the affricates, a topic which we leave open for further study.

## 7 Conclusions

The results of the experimental study have revealed a clear difference between the Czech and Polish affricates /č/, which are consistently assumed to be the same palatoalveolar  $\widehat{tʃ}$  in both languages. Whereas the Czech affricate is indeed a palatoalveolar  $\widehat{tʃ}$ , the Polish postalveolar affricate has been classified as a retroflex according to the results of the present study.

Czech and Polish /č/ differ with respect to several parameters. While in Czech  $\widehat{tʃ}$ , the frication is significantly longer than the closure, the Polish affricate  $\widehat{tʃ}$  shows the reverse

<sup>10</sup> Again, diachronic data give us some insight into the development of the sibilant affricates. It seems that the development of the Proto-Slavic /tʃ/ was crucial for shaping the inventories. In Polish, the Proto-Slavic /tʃ/, originating from /tj/, was converted to alveolo-palatal  $\widehat{tʃ}$  around the thirteenth century; for instance, *i[d̪]e[tʃ]e* ( *i[d̪z̪]e[tʃ]e* (Stieber 1962: 63). Subsequently,  $\widehat{tʃ}$  was phonemicized, and since then it has formed an integral part of the Polish consonantal inventory. Hence, until the fifteenth century,  $\widehat{tʃ}$  was found alongside  $\widehat{tʃ}$  in the Polish phonemic inventory, and then the latter changed to  $\widehat{tʃ}$  and was phonemicized.

In contrast to Polish, /tʃ/ did not convert to an affricate in Czech. Instead, it gradually changed to the palatal stop [c], and then around the end of the fourteenth century it entered the phonemic inventory of Czech (Lamprecht, Šlosar & Bauer 1977). Since then it has co-occurred with  $\widehat{tʃ}$ .

In summary, since  $\widehat{tʃ}$  and not /c/ was perceptually close to  $\widehat{tʃ}$ , the latter sound changed to  $\widehat{tʃ}$  in order to create more perceptual distance from  $\widehat{tʃ}$ . In the Czech system, this change was not required, because the perceptual distance between the already existing affricates had not been changed by the introduction of the new phoneme /c/.

<sup>11</sup> Flemming (1995/2002) also offers a perceptually-based account of the Polish sibilant inventory. He argues that the lip rounding of the Polish retroflex is motivated perceptually as the lip gesture lowers the resonance of the front cavity and creates a more optimal perceptual contrast to other sibilants. However, as the data provided by Styczek (1973) show, the lip rounding is only one of the possible gestures used by speakers to enlarge the front cavity (recall the discussion in Section 5 above). But our hypothesis is in line with Flemming's (1995/2002) general idea that the presence of /s/ is needed in order to create a more optimal contrast to another postalveolar sound, namely /ç/ (see also Stevens et al. 2004, Boersma & Hamann 2008).



pattern: a long closure followed by a short frication. This result points to an important articulatory difference between the postalveolar affricates. In the case of the Czech /tʃ/, the fricative part is considerably longer presumably because the tongue blade takes longer to separate from the prepalate. The corresponding Polish sound is articulated with the tongue tip, which is typical for retroflex sounds (see also Miller-Ockhuizen & Zec 2003, Kochetov & Lobanova 2007).

The results also show crucial differences in formants of the vowel [a] following /č/: F1 frequency is higher in Polish (677 Hz) than in Czech (453 Hz), and F2 frequency is higher in Czech (1751 Hz) than in Polish (1606 Hz). Furthermore, F1 of the preceding vowel [a] is higher in Polish (666 Hz) than in Czech (510 Hz) and F3 frequency appears to be lower in Czech than in Polish /č/ (2610 Hz vs. 2809 Hz).

Further differences were found when comparing spectral characteristics of the sound /č/. Both the lower frequency spectral slope value  $m_1$  (from 500 Hz to 3000 Hz) and the higher frequency value  $m_2$  (from 500 Hz to the Nyquist frequency) differ significantly between Polish and Czech /č/: the burst spectral slope of the Polish sound /č/ is steeper than the Czech spectral slope up to the peak mean frequency  $\bar{F}$ . Towards higher frequencies above  $\bar{F}$ , the Polish spectral slope is steeper than the Czech spectral slope. For the frication part, the same trend (though not significant) is observed for  $m_2$ . In contrast,  $m_1$  is significantly steeper for Czech than for Polish.

The burst spectra of Polish and Czech /č/ do not significantly differ with respect to the first moment M1 (Polish /č/ 9.31 kHz vs. Czech /č/ 9.35 kHz) but they do differ with respect to the second moment M2, which is lower for Czech /č/ (0.86 kHz) than for Polish /č/ (1.12 kHz). In the same vein, only the fricative spectra are different with respect to M2 (Polish /č/ 0.75 kHz vs. Czech /č/ 0.61 kHz). While M3 is approximately the same for the two sounds (burst: Czech /č/ -0.04 vs. Polish /č/ -0.04, frication: Czech /č/ -0.02 vs. Polish /č/ -0.03), M4 is significantly different for (i) the burst spectra of Polish, which shows significantly higher M4 values for Polish (0.15) than for Czech /č/ (0.13), and (ii) the fricative spectra, with the M4 being higher for Polish /č/ (0.09) than for Czech /č/ (0.07).

For both the burst and the frication landmarks, the centre of gravity does not significantly distinguish Polish and Czech /č/ (Polish /č/ 3064 Hz vs. Czech /č/ 3466 Hz). The spectral standard deviation values appear to be significantly different for the burst: 1145 Hz for Polish /č/ vs. 1587 Hz for Czech /č/. In contrast, skewness significantly differs for the frication (Polish /č/ 0.69 vs. Czech /č/ 1.47) and the burst landmark (Polish /č/ 0.20 vs. Czech /č/ 0.81). Kurtosis is significantly different in the case of frication (Polish /č/ 2.0 vs. Czech /č/ 5.19) but not burst spectra (Polish /č/ 1.84 vs. Czech /č/ 0.93).

Thus, the results show that Polish and Czech affricates differ more in the overall spectral shape (as indicated by the spectral slope measures and – with some restrictions – also skewness and kurtosis) than in the location of the spectral peaks and maxima. Apparently other aerodynamic factors such as source strength plays a more important role than do differences in place of articulation ( $\bar{F}$ , COG, spectral maxima) when distinguishing the spectral properties of the affricates in the two languages (see also Jesus & Shadle 2002, who have shown that  $m_2$  is related to noise source strength, with less negative values indicating higher flow velocity).

Furthermore, it has been hypothesized that the choice of /tʃ/ or /tʃ̺/ in phonemic inventories is not accidental: /tʃ̺/ is attested in complex sibilant systems, i.e. those containing at least two postalveolar affricates (Polish), whereas /tʃ/ is found in simple affricate systems, i.e. those containing one postalveolar affricate (Czech). This systematic difference is presumably motivated perceptually by the need to optimize the contrast between sibilants: since the Czech /tʃ/ creates a sufficient perceptual contrast to /tʃ̺/ (the only other affricate present in this inventory), there is no need for /tʃ̺/ to be converted into a retroflex, in contrast to the situation in complex inventories such as that of Polish. This hypothesis should be perceptually tested, a topic which we leave open for further study.



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## Appendix A. Material

### 1. Czech data

Position	/t/	/c/	/ts/	/tʃ/
Word-initial	[t]abak <i>tabák</i> ‘tabak’	[c]at <i>t’at</i> ‘gashed’	[ts]andát <i>candát</i> ‘zander’	[tʃ]asy <i>časy</i> ‘times’
Word-medial	cha[t]a <i>chata</i> ‘cottage’	ta[c]i <i>tati</i> ‘father’	ra[ts]ek <i>racek</i> ‘gull’	ba[tʃ]a <i>bača</i> ‘shepherd’

### 2. Polish data

Position	/t/	/ts/	/tɕ/	/ʦ/
Word-initial	[t]ata <i>tata</i> ‘father’	[ts]ała <i>cała</i> ‘whole’	[tɕ]ało <i>ciało</i> ‘body’	[ʦ]asy <i>czasy</i> ‘times’
Word-medial	cha[t]a <i>chata</i> ‘cottage’	ta[ts]a <i>taca</i> ‘platter’	bra[tɕ]a <i>bracia</i> ‘brothers’	ma[ʦ]a <i>macza</i> ‘he dunks’

## Appendix B. Average values and standard deviations (SDs)

For each consonant we provide average values (left column) and their standard deviations (right column). The SDs are given in italics.

### 1. Duration (log values)

#### 1.1 Closure duration

Polish	/t/		/tɕ/		/ts/		/ʦ/	
	4.552	<i>0.140</i>	3.939	<i>0.269</i>	4.264	<i>0.193</i>	4.341	<i>0.245</i>
Czech	/t/		/c/		/ts/		/tʃ/	
	4.571	<i>0.168</i>	4.439	<i>0.139</i>	4.043	<i>0.152</i>	4.140	<i>0.102</i>

## 1.2 Frication duration

Polish	/t/		$\widehat{/t\text{c}/}$		$\widehat{/ts/}$		$\widehat{/t\text{s}/}$	
	3.158	0.284	4.250	0.317	4.412	0.152	3.93	0.447
Czech	/t/		/c/		$\widehat{/ts/}$		$\widehat{/t\text{j}/}$	
	2.805	0.301	3.784	0.294	4.431	0.122	4.437	0.145

## 2. Formant values (all values in Hz)

## 2.1 F1 of the following vowel

Polish	/t/		$\widehat{/t\text{c}/}$		$\widehat{/ts/}$		$\widehat{/t\text{s}/}$	
	739	116	543	112	679	128	677	677
Czech	/t/		/c/		$\widehat{/ts/}$		$\widehat{/t\text{j}/}$	
	589	81	383	81	526	105	453	105

## 2.2 F2 of the following vowel

Polish	/t/		$\widehat{/t\text{c}/}$		$\widehat{/ts/}$		$\widehat{/t\text{s}/}$	
	1614	121	1938	166	1560	138	1606	167
Czech	/t/		/c/		$\widehat{/ts/}$		$\widehat{/t\text{j}/}$	
	1451	154	2096	227	1521	211	1751	182

## 2.3 F3 of the following vowel

Polish	/t/		$\widehat{/t\text{c}/}$		$\widehat{/ts/}$		$\widehat{/t\text{s}/}$	
	2737	155	2692	184	2734	151	2668	169
Czech	/t/		/c/		$\widehat{/ts/}$		$\widehat{/t\text{j}/}$	
	2686	155	3047	205	2695	195	2555	230

## 2.4 F1 of the preceding vowel

Polish	/t/		$\widehat{/t\text{c}/}$		$\widehat{/ts/}$		$\widehat{/t\text{s}/}$	
	652	79	568	85	605	83	666	126
Czech	/t/		/c/		$\widehat{/ts/}$		$\widehat{/t\text{j}/}$	
	553	99	516	94	584	118	510	141

## 2.5 F2 of the preceding vowel

Polish	/t/		$\overline{/t\text{ç}/}$		$\overline{/ts/}$		$\overline{/tʃ/}$	
	1453	153	1793	85	1483	173	1645	131
Czech	/t/		/c/		$\overline{/ts/}$		$\overline{/tʃ/}$	
	1295	172	1789	238	1394	176	1718	227

## 2.6 F3 of the preceding vowel

Polish	/t/		$\overline{/t\text{ç}/}$		$\overline{/ts/}$		$\overline{/tʃ/}$	
	2647	156	2716	163	2684	160	2809	156
Czech	/t/		/c/		$\overline{/ts/}$		$\overline{/tʃ/}$	
	2576	163	2779	249	2607	232	2610	310

## 3. Formant frequency range (all values in Hz)

## 3.1 F1 range of the following vowel

Polish	/t/		$\overline{/t\text{ç}/}$		$\overline{/ts/}$		$\overline{/tʃ/}$	
	-22	87	-158	156	84	113	-100	124
Czech	/t/		/c/		$\overline{/ts/}$		$\overline{/tʃ/}$	
	-85	72	-168	93	-71	87	-161	92

## 3.3 F2 range of the following vowel

Polish	/t/		$\overline{/t\text{ç}/}$		$\overline{/ts/}$		$\overline{/tʃ/}$	
	77	240	340	330	67	232	96	211
Czech	/t/		/c/		$\overline{/ts/}$		$\overline{/tʃ/}$	
	3	237	247	343	-89	237	236	151

## 3.3 F3 range of the following vowel

Polish	/t/		$\overline{/t\text{ç}/}$		$\overline{/ts/}$		$\overline{/tʃ/}$	
	148	154	179	185	169	172	124	174
Czech	/t/		/c/		$\overline{/ts/}$		$\overline{/tʃ/}$	
	94	157	318	160	86	150	77	119

## 3.4 F1 range of the preceding vowel

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	-200	81	-257	96	-213	94	-177	161
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	-126	82	-171	95	-93	116	-164	127

## 3.5 F2 range of the preceding vowel

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	108	175	226	134	24	148	290	126
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	-98	102	233	114	-69	119	356	141

## 3.6 F3 range of the preceding vowel

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	322	407	221	156	113	194	308	442
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	103	218	150	133	147	156	268	289

## 4. Spectral properties

## 4.1 Highest peak frequency – burst (all values in Hz)

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	2554	715	4232	833	2765	1194	3064	405
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	2323	456	4961	717	5360	922	3448	624

## 4.2 Highest peak frequency – frication noise midpoint (all values in Hz)

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	2686	717	4013	1193	7859	1453	3251	605
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	2680	660	4373	978	7323	1520	3107	795

4.3 Spectral slope  $m_1$  (Jesus & Shadle 2002) – burst (all values in dB/kHz<sup>2</sup>)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	-2.90	2.29	-0.9	2.23	-3.74	2.73	2.11	2.09
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	-4.5	2.24	-3.16	4.38	-2.64	2.29	-0.27	2.55

4.4 Spectral slope  $m_1$  (Jesus & Shadle 2002) – frication (all values in dB/kHz<sup>2</sup>)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	-7.53	2.24	4.8	3.6	-1.57	2.22	0.43	3.02
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	-9.61	2.23	-0.85	2.35	-0.86	1.73	6.84	2.35

4.5 Spectral slope  $m_2$  (Jesus & Shadle 2002) – burst (all values in dB/kHz<sup>2</sup>)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	-2.05	1.0	-3.15	1.55	-0.72	1.26	-4.69	1.33
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	-1.52	0.9	-1.4	0.76	-0.33	1.18	-2.86	1.6

4.6 Spectral slope  $m_2$  (Jesus & Shadle 2002) – frication (all values in dB/kHz<sup>2</sup>)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	-1.72	0.60	-2.39	1.20	0.78	1.03	-3.52	0.56
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	-1.17	0.62	-2.21	0.62	0.85	1.10	-3.02	0.7

4.7 First moment  $M_1$  (Forrest et al. 1988) – burst (all values in kHz)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	9.78	1.13	10.87	1.1	9.46	1.86	9.31	0.96
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	9.0	1.25	9.9	1.25	8.91	1.62	9.35	1.50

## 4.8 First moment M1 (Forrest et al. 1988) – frication (all values in kHz)

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	7.55	0.87	9.98	0.73	8.68	1.3	9.49	0.84
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	6.42	1.13	9.48	1.24	8.96	1.37	9.25	0.80

## 4.9 Second moment M2 (Forrest et al. 1988) – burst (all values in kHz)

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	0.74	0.19	0.71	0.19	0.58	0.21	1.12	0.26
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	0.73	0.17	0.65	0.20	0.64	0.19	0.86	0.23

## 4.10 Second moment M2 (Forrest et al. 1988) – frication (all values in kHz)

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	0.66	0.13	0.63	0.13	0.73	0.22	0.75	0.17
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	0.65	0.12	0.55	0.12	0.78	0.28	0.61	0.12

## 4.11 Third moment M3 (Forrest et al. 1988) – burst

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	-0.03	0.07	-0.13	0.07	0.004	0.08	-0.04	0.08
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	0.02	0.07	-0.05	0.06	-0.0002	0.08	-0.04	0.10

## 4.12 Third moment M3 (Forrest et al. 1988) – frication

Polish	/t/		$\widehat{t\check{c}}/$		$\widehat{ts}/$		$\widehat{t\text{ʂ}}/$	
	0.08	0.04	-0.05	0.03	0.01	0.05	-0.03	0.05
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tj}/$	
	0.16	0.06	-0.02	0.04	0.004	0.05	-0.02	0.03

## 4.13 Fourth moment M4 (Forrest et al. 1988) – burst

Polish	/t/		$\widehat{tc}/$		$\widehat{ts}/$		$\widehat{tʃ}/$	
	0.1	0.02	0.11	0.03	0.09	0.03	0.15	0.04
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tʃ}/$	
	0.96	0.02	0.1	0.03	0.09	0.03	0.13	0.03

## 4.14 Fourth moment M4 (Forrest et al. 1988) – frication

Polish	/t/		$\widehat{tc}/$		$\widehat{ts}/$		$\widehat{tʃ}/$	
	0.09	0.24	0.07	0.02	0.09	0.03	0.09	0.03
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tʃ}/$	
	0.12	0.04	0.07	0.03	0.09	0.04	0.07	0.01

## 4.15 Centre of gravity (Praat) – burst (all values in Hz)

Polish	/t/		$\widehat{tc}/$		$\widehat{ts}/$		$\widehat{tʃ}/$	
	2263	805	3396	870	3027	1391	2563	465
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tʃ}/$	
	1783	517	4164	1271	3552	1494	2648	616

## 4.16 Centre of gravity (Praat) – frication noise midpoint (all values in Hz)

Polish	/t/		$\widehat{tc}/$		$\widehat{ts}/$		$\widehat{tʃ}/$	
	833	546	4738	1035	6990	1360	3064	1072
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tʃ}/$	
	522	222	3755	1151	6996	1167	3466	813

## 4.17 Standard deviation (Praat) – burst (all values in Hz)

Polish	/t/		$\widehat{tc}/$		$\widehat{ts}/$		$\widehat{tʃ}/$	
	1990	688	2026	615	2656	683	1145	280
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{tʃ}/$	
	1980	557	2268	641	2894	689	1587	542

## 4.18 Standard deviation (Praat) – frication (all values in Hz)

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	932	388	1765	270	2289	470	1464	344
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	648	313	2213	291	2008	471	1357	339

## 4.19 Skewness (Praat) – burst

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	1.57	0.8	0.35	0.51	1.07	1.0	0.20	0.67
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	2.22	0.76	0.3	0.61	0.7	0.79	0.81	0.7

## 4.20 Skewness (Praat) – frication

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	4.87	1.46	0.44	0.72	-1.13	0.82	0.69	0.55
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	8.92	1.52	0.29	0.75	-0.98	0.85	1.47	0.81

## 4.21 Kurtosis (Praat) – burst

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	2.27	2.72	0.39	1.33	0.22	1.69	1.84	1.51
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	4.41	3.02	-0.029	1.16	-0.28	1.3	0.93	1.46

## 4.22 Kurtosis (Praat) – frication

Polish	/t/		$\widehat{t\text{c}}/$		$\widehat{ts}/$		$\widehat{t\text{s}}/$	
	38.7	18.89	0.72	1.46	1.89	2.58	2.0	2.25
Czech	/t/		/c/		$\widehat{ts}/$		$\widehat{t\text{j}}/$	
	124.14	18.82	0.72	3.28	2.68	4.82	5.19	4.57



## Appendix C. Statistical results

In the tables in this appendix, ini = initial, med = medial, and bold is used to emphasize a comparison between Czech and Polish /č/.

### 1. Duration

#### 1.1. Closure duration (log)\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	12.00	.0001	Polish t vs. č	5.99	.0001
ts vs. č	-2.63	.0094	ts vs. č	-2.12	.0332
c vs. č	8.61	.0001	tc vs. č	-11.52	.0001
<b>Czech č vs. Polish č</b>	-2.39	.0168			

\* no comparison regarding position

#### 1.2. Frication duration (log)

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-50.03	.0001	Polish t vs. č	-21.62	.0001
ts vs. č	-0.16	.8690	ts vs. č	14.56	.0001
c vs. č	-19.85	.0001	tc vs. č	15.76	.0001
<b>Czech č vs. Polish č</b>	3.89	.0002			
Cz. ini. vs. med. č	1.81	.0774	Pol. ini. vs. med. č	0.29	.7772
Cz. vs. Pol. ini. č	-3.55	.0004	Pol. vs. Cz. med č	-4.04	.0002

### 2. Formant frequency values

#### 2.1 F1 of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	9.852	.0001	Polish t vs. č	4.526	.0001
ts vs. č	5.340	.0001	ts vs. č	-0.452	.6588
c vs. č	-5.148	.0001	tc vs. č	-9.221	.0001
<b>Czech č vs. Polish č</b>	-3.612	.0001			
Cz. ini. vs. med. č	1.725	.0952	Pol. ini. vs. med. č	3.748	.0002
Cz. vs. Pol. ini. č	-3.748	.0002	Pol. vs. Cz. med č	3.192	.00029

#### 2.2 F2 of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-16.876	.0001	Polish t vs. č	0.289	.7816
ts vs. č	-12.929	.0001	ts vs. č	-2.298	.0222
c vs. č	19.653	.0001	tc vs. č	18.312	.0001
<b>Czech č vs. Polish č</b>	1.298	.0444			
Cz. ini. vs. med. č	-2.643	.0110	Pol. ini. vs. med. č	6.312	.0001
Cz. vs. Pol. ini. č	0.345	.5522	Pol. vs. Cz. med č	-2.046	.0006

## 2.3 F3 of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	7.362	.0001	Polish t vs. č	0.289	.7794
ts vs. č	8.573	.0001	ts vs. č	-2.298	.0238
c vs. č	27.706	.0001	tc vs. č	18.312	.0001
<b>Czech č vs. Polish č</b>	1.298	.0568			
Cz. ini. vs. med. č	-2.643	.0084	Pol. ini. vs. med. č	6.312	.0001
Cz. vs. Pol. ini. č	0.345	.5324	Pol. vs. Cz. med č	-2.046	.0412

## 2.4 F1 of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	1.638	.1118	Polish t vs. č	-0.930	.3748
ts vs. č	3.689	.0002	ts vs. č	-3.429	.0008
c vs. č	0.126	.9030	tc vs. č	-5.332	.0001
<b>Czech č vs. Polish č</b>	-2.643	.0036			

\* no initial position

## 2.5 F2 of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-17.999	.0001	Polish t vs. č	-8.209	.0001
ts vs. č	-13.197	.0001	ts vs. č	-6.394	.0001
c vs. č	3.233	.0022	tc vs. č	6.041	.0001
<b>Czech č vs. Polish č</b>	0.615	.3022			

\* no initial position

## 2.6 F3 of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-2.736	.0100	Polish t vs. č	-7.519	.0001
ts vs. č	-0.234	.8274	ts vs. č	-5.283	.0001
c vs. č	7.185	.0001	tc vs. č	-4.006	.0001
<b>Czech č vs. Polish č</b>	-1.288	.0076			

\* no initial position

## 3. Formant frequency range

## 3.1 F1 range of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	4.787	.0001	Polish t vs. č	5.300	.0001
ts vs. č	5.907	.0001	ts vs. č	0.975	.3322
c vs. č	−0.496	.6092	tc vs. č	−3.572	.0004
<b>Czech č vs. Polish č</b>	−1.439	.1422			
Cz. ini. vs. med. č	1.277	.2148	Pol. ini. vs. med. č	−2.172	.0332
Cz. vs. Pol. ini. č	−0.682	.4732	Pol. vs. Cz. med č	2.224	.0294

## 3.2 F2 range of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	−5.786	.0001	Polish t vs. č	−0.536	.5876
ts vs. č	−8.180	.0001	ts vs. č	−0.686	.4916
c vs. č	0.227	.8106	tc vs. č	6.174	.0001
<b>Czech č vs. Polish č</b>	2.209	.0556			
Cz. ini. vs. med. č	6.017	.0001	Pol. ini. vs. med. č	9.925	.0001
Cz. vs. Pol. ini. č	1.172	.2398	Pol. vs. Cz. med č	−3.060	.0076

## 3.3 F3 range of the following vowel

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	0.636	.5226	Polish t vs. č	1.008	.3140
ts vs. č	0.435	.0001	ts vs. č	1.860	.0628
c vs. č	9.121	.6630	tc vs. č	2.113	.0364
<b>Czech č vs. Polish č</b>	−0.997	.3552			
Cz. ini. vs. med. č	−2.891	.0042	Pol. ini. vs. med. č	3.178	.2464
Cz. vs. Pol. ini. č	−2.878	.0114	Pol. vs. Cz. med č	−1.238	.2556

## 3.4 F1 range of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	1.520	.1254	Polish t vs. č	−0.903	.3534
ts vs. č	3.056	.0028	ts vs. č	−1.659	.0956
c vs. č	−0.354	.7276	tc vs. č	−3.409	.0004
<b>Czech č vs. Polish č</b>	0.389	.6906			

\* no initial position

## 3.5 F2 range of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-6.103	.0001	Polish t vs. č	-14.706	.0001
ts vs. č	-8.771	.0001	ts vs. č	-14.480	.0001
c vs. č	-2.236	.0190	tc vs. č	-4.047	.0001
<b>Czech č vs. Polish č</b>	1.528	.1702			

\* no initial position

## 3.6 F3 range of the preceding vowel\*

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-2.788	.0044	Polish t vs. č	0.193	.8612
ts vs. č	-2.131	.0356	ts vs. č	-3.484	.0008
c vs. č	-1.979	.0478	tc vs. č	-1.708	.0868
<b>Czech č vs. Polish č</b>	-0.453	.6478			

\* no initial position

## 4. Spectral properties

## 4.1 Highest peak frequency – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-11.184	.0001	Polish t vs. č	-5.075	.0001
ts vs. č	13.918	.0001	ts vs. č	-1.542	.1188
c vs. č	14.327	.0001	tc vs. č	11.449	.0001
<b>Czech č vs. Polish č</b>	1.460	.1482			
Cz. ini. vs. med. č	-1.959	.0508	Pol. ini. vs. med. č	1.887	.0592
Cz. vs. Pol. ini. č	0.519	.6040	Pol. vs. Cz. med č	-2.074	.0387

## 4.2 Highest peak frequency – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-3.264	.0014	Polish t vs. č	-4.21	.0001
ts vs. č	31.130	.0001	ts vs. č	33.27	.0001
c vs. č	9.819	.0001	tc vs. č	5.72	.0001
<b>Czech č vs. Polish č</b>	-0.29	.7356			
Cz. ini. vs. med. č	-0.268	.7889	Pol. ini. vs. med. č	-0.003	.9977
Cz. vs. Pol. ini. č	-0.329	.7420	Pol. vs. Cz. med č	0.236	.8137

## 4.3 Spectral slope m1 (Jesus &amp; Shadle 2002) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	-10.045	.0001	Polish t vs. ě	-12.538	.0001
ts vs. ě	-5.874	.0001	ts vs. ě	-10.647	.0001
c vs. ě	-7.201	.0001	tc vs. ě	-7.033	.0001
<b>Czech ě vs. Polish ě</b>	-2.713	.0220			
Cz. ini. vs. med. ě	-0.108	.9116	Pol. ini. vs. med. ě	0.860	.3918
Cz. vs. Pol. ini. ě	-2.764	.0186	Pol. vs. Cz. med ě	2.164	.0522

## 4.4 Spectral slope m1 (Jesus &amp; Shadle 2002) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	-43.54	.0001	Polish t vs. ě	-21.515	.0001
ts vs. ě	-20.79	.0001	ts vs. ě	-5.327	.0001
c vs. ě	-43.54	.0001	tc vs. ě	11.306	.0001
<b>Czech ě vs. Polish ě</b>	7.471	.0001			
Cz. ini. vs. med. ě	1.159	.2586	Pol. ini. vs. med. ě	-0.215	.8422
Cz. vs. Pol. ini. ě	7.662	.0001	Pol. vs. Cz. med ě	-6.805	.0001

## 4.5 Spectral slope m2 (Jesus &amp; Shadle 2002) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	7.558	.0001	Polish t vs. ě	15.385	.0001
ts vs. ě	14.638	.0001	ts vs. ě	16.190	.0001
c vs. ě	8.439	.0001	tc vs. ě	7.765	.0001
<b>Czech ě vs. Polish ě</b>	3.410	.0022			
Cz. ini. vs. med. ě	-4.079	.0001	Pol. ini. vs. med. ě	-2.443	.0128
Cz. vs. Pol. ini. ě	2.971	.0048	Pol. vs. Cz. med ě	-3.659	.0008

## 4.6 Spectral slope m2 (Jesus &amp; Shadle 2002) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	16.14	.0001	Polish t vs. ě	15.93	.0001
ts vs. ě	34.86	.0001	ts vs. ě	38.16	.0001
c vs. ě	7.47	.0001	tc vs. ě	10.04	.0001
<b>Czech ě vs. Polish ě</b>	1.26	.1442			
Cz. ini. vs. med. ě	-0.070	.9566	Pol. ini. vs. med. ě	0.511	.6228
Cz. vs. Pol. ini. ě	1.145	.1896	Pol. vs. Cz. med ě	-1.359	.1330

## 4.7 First moment M1 (Forrest et al. 1988) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-1.66	.0912	Polish t vs. č	2.23	.0248
ts vs. č	-2.11	.0352	ts vs. č	0.32	.7294
c vs. č	2.58	.0102	tc vs. č	7.07	.0001
<b>Czech č vs. Polish č</b>	0.16	.8668			
Cz. ini. vs. med. č	-0.25	.7874	Pol. ini. vs. med. č	0.51	.6212
Cz. vs. Pol. ini. č	-0.22	.8178	Pol. vs. Cz. med č	-0.47	.6446

## 4.8 First moment M1 (Forrest et al. 1988) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-17.33	.0001	Polish t vs. č	-12.07	.0001
ts vs. č	-1.76	.0804	ts vs. č	-5.02	.0001
c vs. č	1.44	.1514	tc vs. č	2.57	.0128
<b>Czech č vs. Polish č</b>	-0.76	.4552			
Cz. ini. vs. med. č	-0.06	.9510	Pol. ini. vs. med. č	0.69	.4909
Cz. vs. Pol. ini. č	-0.93	.3628	Pol. vs. Cz. med č	0.44	.6570

## 4.9 Second moment M2 (Forrest et al. 1988) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	-3.843	.0001	Polish t vs. č	-3.843	.0002
ts vs. č	-6.739	.0001	ts vs. č	-6.739	.0001
c vs. č	-6.469	.0001	tc vs. č	-11.918	.0001
<b>Czech č vs. Polish č</b>	-3.247	.0066			
Cz. ini. vs. med. č	4.495	.0001	Pol. ini. vs. med. č	-0.204	.8474
Cz. vs. Pol. ini. č	-1.780	.0690	Pol. vs. Cz. med č	4.257	.0006

## 4.10 Second moment M2 (Forrest et al. 1988) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	1.582	.1120	Polish t vs. č	-3.205	.0018
ts vs. č	6.764	.0001	ts vs. č	-0.574	.5794
c vs. č	-2.104	.0394	tc vs. č	-4.361	.0001
<b>Czech č vs. Polish č</b>	-2.962	.0176			
Cz. ini. vs. med. č	1.127	.2492	Pol. ini. vs. med. č	-0.937	.3526
Cz. vs. Pol. ini. č	-1.890	.0868	Pol. vs. Cz. med č	3.269	.0064

## 4.11 Third moment M3 (Forrest et al. 1988) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	4.810	.0001	Polish t vs. ě	0.568	.5594
ts vs. ě	3.162	.4822	ts vs. ě	2.987	.0030
c vs. ě	−0.713	.0016	tc vs. ě	−6.764	.0001
<b>Czech ě vs. Polish ě</b>	0.258	.7956			
Cz. ini. vs. med. ě	−0.639	.5280	Pol. ini. vs. med. ě	−1.261	.2106
Cz. vs. Pol. ini. ě	0.490	.6490	Pol. vs. Cz. med ě	0.028	.9806

## 4.12 Third moment M3 (Forrest et al. 1988) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	24.218	.0001	Polish t vs. ě	15.934	.0001
ts vs. ě	3.384	.0008	ts vs. ě	7.122	.0001
c vs. ě	−0.875	.3760	tc vs. ě	−2.727	.0062
<b>Czech ě vs. Polish ě</b>	0.863	.4074			
Cz. ini. vs. med. ě	−0.038	.9550	Pol. ini. vs. med. ě	−0.095	.9356
Cz. vs. Pol. ini. ě	0.813	.4328	Pol. vs. Cz. med ě	−0.770	.4434

## 4.13 Fourth moment M4 (Forrest et al. 1988) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	−4.369	.0001	Polish t vs. ě	−10.231	.0001
ts vs. ě	−6.169	.0001	ts vs. ě	−8.446	.0001
c vs. ě	−5.535	.0001	tc vs. ě	−6.806	.0001
<b>Czech ě vs. Polish ě</b>	−3.509	.0078			
Cz. ini. vs. med. ě	2.939	.0032	Pol. ini. vs. med. ě	−0.756	.4486
Cz. vs. Pol. ini. ě	−2.059	.0630	Pol. vs. Cz. med ě	4.314	.0012

## 4.14 Fourth moment M4 (Forrest et al. 1988) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. ě	10.471	.0001	Polish t vs. ě	0.138	.8770
ts vs. ě	4.154	.0001	ts vs. ě	−1.051	.2932
c vs. ě	−0.549	.5820	tc vs. ě	−3.971	.0001
<b>Czech ě vs. Polish ě</b>	−3.088	.0152			
Cz. ini. vs. med. ě	0.957	.3394	Pol. ini. vs. med. ě	−0.610	.5454
Cz. vs. Pol. ini. ě	−1.988	.0718	Pol. vs. Cz. med ě	3.151	.0104



## 4.15 Centre of gravity (Praat) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	−6.170	.0001	Polish t vs. č	−2.350	.0160
ts vs. č	6.360	.0001	ts vs. č	1.682	.0966
c vs. č	10.622	.0001	tc vs. č	5.457	.0001
<b>Czech č vs. Polish č</b>	0.242	.7964			
Cz. ini. vs. med. č	−0.988	.3292	Pol. ini. vs. med. č	1.483	.1420
Cz. vs. Pol. ini. č	−0.375	.6870	Pol. vs. Cz. med č	−0.866	.3684

## 4.16 Centre of gravity (Praat) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	−22.329	.0001	Polish t vs. č	−17.243	.0001
ts vs. č	26.986	.0001	ts vs. č	29.115	.0001
c vs. č	2.529	.0160	tc vs. č	12.553	.0001
<b>Czech č vs. Polish č</b>	0.864	.3168			
Cz. ini. vs. med. č	0.549	.5830	Pol. ini. vs. med. č	1.168	.2410
Cz. vs. Pol. ini. č	0.718	.4008	Pol. vs. Cz. med č	−0.962	.3363

## 4.17 Standard deviation (Praat) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	0.234	.7896	Polish t vs. č	10.923	.0001
ts vs. č	12.803	.0001	ts vs. č	13.398	.0001
c vs. č	6.945	.0001	tc vs. č	10.490	.0001
<b>Czech č vs. Polish č</b>	2.835	.0066			
Cz. ini. vs. med. č	−3.705	.0004	Pol. ini. vs. med. č	0.264	.7902
Cz. vs. Pol. ini. č	1.900	.7896	Pol. vs. Cz. med č	−3.519	.001

## 4.18 Standard deviation (Praat) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	−12.349	.0001	Polish t vs. č	−9.226	.0001
ts vs. č	11.294	.0001	ts vs. č	14.169	.0001
c vs. č	15.029	.0001	tc vs. č	5.275	.0001
<b>Czech č vs. Polish č</b>	−1.214	.2630			
Cz. ini. vs. med. č	1.387	.1696	Pol. ini. vs. med. č	0.293	.7640
Cz. vs. Pol. ini. č	−0.615	.5532	Pol. vs. Cz. med č	1.427	.1944

## 4.19 Skewness (Praat) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	12.706	.0001	Polish t vs. č	12.816	.0001
ts vs. č	-0.764	.4598	ts vs. č	6.189	.0001
c vs. č	-4.424	.0001	tc vs. č	1.080	.2790
<b>Czech č vs. Polish č</b>	2.561	.0226			
Cz. ini. vs. med. č	-2.088	.0340	Pol. ini. vs. med. č	-0.816	.4150
Cz. vs. Pol. ini. č	2.803	.4266	Pol. vs. Cz. med č	-2.803	.0148

## 4.20 Skewness (Praat) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	47.73	.0001	Polish t vs. č	28.531	.0001
ts vs. č	-18.30	.0001	ts vs. č	-13.397	.0001
c vs. č	-8.87	.0001	tc vs. č	-1.758	.0714
<b>Czech č vs. Polish č</b>	2.174	.0398			
Cz. ini. vs. med. č	-0.75	.4660	Pol. ini. vs. med. č	-1.375	.1612
Cz. vs. Pol. ini. č	2.412	.0292	Pol. vs. Cz. med č	-2.05	.0600

## 4.21 Kurtosis (Praat) – burst

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	11.167	.0001	Polish t vs. č	1.764	.0778
ts vs. č	-3.982	.0001	ts vs. č	-3.013	.0028
c vs. č	-3.294	.0006	tc vs. č	-4.598	.0001
<b>Czech č vs. Polish č</b>	-1.469	.1640			
Cz. ini. vs. med. č	-0.025	.9760	Pol. ini. vs. med. č	-0.265	.7928
Cz. vs. Pol. ini. č	-1.312	.2266	Pol. vs. Cz. med č	1.420	.1868

## 4.22 Kurtosis (Praat) – frication

Comparisons	<i>t</i> -value	<i>pMCMC</i>	Comparisons	<i>t</i> -value	<i>pMCMC</i>
Czech t vs. č	62.77	.0001	Polish t vs. č	27.45	.0001
ts vs. č	-2.09	.0382	ts vs. č	-0.09	.9180
c vs. č	-3.68	.0006	tc vs. č	-1.06	.2914
<b>Czech č vs. Polish č</b>	2.49	.0260			
Cz. ini. vs. med. č	-0.82	.4320	Pol. ini. vs. med. č	-0.003	.9946
Cz. vs. Pol. ini. č	1.411	.1742	Pol. vs. Cz. med č	-2.12	.0458

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