# (Non)Retroflexivity of Slavic Affricates and Its Motivation. Evidence from Polish and Czech <č>.

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The goal of this paper is two-fold. First, it revises the common assumption that the affricate <č> denotes /t͡ʃ/ for all Slavic languages. On the basis of experimental results it is shown that Slavic <č> stands for two sounds: /t͡ʃ/ as e.g. in Czech and /ʈʂ/ as in Polish.

The second goal of the paper is to show that this difference is not accidental but it is motivated by perceptual relations among sibilants. In Polish, /t͡ʃ/ changed to /ʈʂ/ thus lowering its sibilant tonality and creating a better perceptual distance to /t͡ɕ/, whereas in Czech /t͡ʃ/ did not turn to /ʈʂ/, as the former displayed sufficient perceptual distance to the only affricate present in the inventory, namely, the alveolar /t͡s/. Finally, an analysis of Czech and Polish affricate inventories is offered.

## 1 Introduction

In the Slavic tradition, the affricate <č> is tacitly or explicitly assumed to be /t͡ʃ/ for all Slavic languages. (see e.g. de Bray 1951, Comrie & Corbett 1993). In this paper I revise the affricate inventories of Polish and Czech showing that the symbol <č> stands for the palatoalveolar /t͡ʃ/ in Czech and the retroflex /ʈʂ/ in Polish. This conclusion is based on the experimental results presented in the paper.

Second, it will be explained *why* the two languages Polish and Czech, which belong to the same Slavic family, differ in the quality of the affricates. It will be argued that the arrangement of affricates in individual Slavic languages is not accidental but is rather dependent on perceptual relations between the affricates. Slavic inventories clearly show a tendency to optimize perceptual contrast among the sibilants. If the inventory is complex, i.e., consisting of at least one (denti-)alveolar and two postalveolar affricates, then one of the postalveolar affricates is of low sibilant tonality. This is motivated by the principle of contrast optimization: the retroflex affricate displays more perceptual distance to other affricates than, for example, a palatoalveolar affricate, see also Zygis (2003a).

In simple sibilant systems, i.e., consisting of one (denti-)alveolar and one postalveolar affricate, the latter is almost always a palatoalveolar [t͡ʃ] because the perceptual distance between the two sounds is sufficient and an optimal contrast already exists. In fact, this is the case in Czech.

Furthermore, it will be shown that perception played the underlying role in forming affricate systems. The otherwise unexplainable context-free rules, as e.g. /t͡ʃ/ → [ʈ͡ʂ] are straightforwardly accounted for if perceptual relations among phonemes are taken into consideration. This will be shown by analyzing Polish and Czech inventories from a diachronic point of view.

The study is organised as follows. In section 2 the assumptions made for the purposes of the present study are outlined. In section 3 coronal stop inventories, including affricates of Polish and Czech, are analyzed. Section 4 analyses a diachronic development of these two languages. The experimental results presented in section 5 reveal a clear difference between Czech and Polish postalveolar affricates and provide an explanation for these results. A Dispersion-Theory-account of the experimental findings is proposed in section 6. Finally, in section 7, the main conclusions are summarised.

## 2 Necessary assumptions and comments

For the purposes of the present study the following assumptions have been made.

1) First of all, it has been assumed that affricates of a low sibilant quality are denoted as retroflexes [ʈ͡ʂ]. This symbol is, however, not entirely adequate as the sound shows great articulatory variability in terms of place of articulation and the shape of the tongue, see Zygis (2005). The only stable characteristic of this sound is the involvement of the tongue tip as the main articulator. This fact, together with the 'postalveolarity' of this sound, induced classification as the retroflex from an articulatory point of view; see Keating (1991) and Hamann (2003) for more discussion on this point.
2) The crucial point for the present study is the fact that sibilants display a different perceptual quality in terms of their sibilant tonality. It is assumed that specifications of the feature [sibilant tonality], as given below, express the contrast between the sibilants. The specifications are mainly based on perceptual impressions and acoustic results, as presented in the experimental part of the study:

| | [t͡ʂ] | [t͡ʃʲ] | [t͡ʃ] | [t͡ɕ] | [t͡s] |
|---|---|---|---|---|---|
| sibilant tonality: | [low] | [low raising] | [middle] | [middle-high] | [high] |

These affricates exhibit different perceptual distances with each other. This point is discussed in section 6.

3) There is also a phonological piece of evidence which could potentially help in the identification of retroflexes. It has been argued that retroflexes avoid the following high front vocoides (Bhat 1973), or even that they are not followed by high vocoids due to the incompatibility of two articulatory gestures: the curled-up tongue tip is in conflict with the high and raised tongue tip of the front vowels (Hamann 2003). Consequently, a test demonstrating that the sounds under question are not followed by a high vowel /i/ would provide evidence in favor of their retroflex character. In fact, such a test has been used for various languages (see examples provided in Hall 1997b :48) including Slavic languages, see also Hamann (2004). In the present study, I will not apply the test for the purposes of the retroflex identification. My decision is based on the following arguments:
   (i) As already mentioned, there is a lot of articulatory variation in the production of postalveolar sounds, and the prevailing majority of x-rays of the potential retroflexes does not demonstrate a typical curled-up tongue tip. Instead, the tongue tip is often placed at the alveolar ridge and the tongue blade together with the tongue dorsum is flat. Consequently, the incompatibility of the articulatory gestures does not hold for these group of sounds.
   (ii) in some Slavic languages the sounds in question are indeed followed by [ɨ] and not by [i], see, for example, the rule called Retraction in Polish (Rubach 1984). However, this rule also affects other coronal sounds including dental stops, fricatives, and the trill [r].
   (iii) from a diachronic perspective, the [ɨ] vs. [i] distribution goes back to depalatalisation processes which affected all *palatalised* sounds, including labials, and in some Slavic languages velar sounds. Thus, the process cannot be explained by the incompatibility of the articulatory gestures of the curled tongue tip and the raised tongue blade of [i], but deserves a more general explanation.

4) Following Rubach (1994), LaCharité (1993), Kim (1997), Clements (1999), and Kehrein (2002), I assume that affricates are phonologically

strident stops. They form a natural class with other coronal stops, which are also included as a subject of the present investigation. It is shown that the coronal stops, despite forming a natural class with affricates, are not directly influential on sibilant systems. This is due to their different acoustic/perceptual properties, which do not directly compete with the properties of the sibilant frication, as discussed in the experimental part of the present study.

5) Finally, it should be noted that the present account considerably differs from articulatory-based accounts of sibilant systems, as e.g. Hume (1994) or Hall (1997a). Both approaches are discussed in Zygis (2005) in detail.

## 3 Affricates in Slavic languages

For the purposes of the present study fourteen present-day Slavic languages have been investigated. Besides Czech and Polish, recordings from Belorussian, Bulgarian, Croatian, Kashubian, Russian, Macedonian, Serbian, Slovak, Slovenian, Upper and Lower Sorbian and Ukrainian were taken (between 2 and 5 speakers of each language). The data were investigated acoustically and perceptually. In addition, articulatory descriptions of the affricates, including x-ray tracings available in the literature, were considered.

The investigation showed that affricate systems underlie the perceptually based principle in (1):

(1)

If the inventory is complex, i.e., consisting of at least one (denti-)alveolar and two postalveolar affricates or a strongly palatalized /$t^j$/, then one of the postalveolar affricates displays a low sibilant tonality.

Perceptual relations are also responsible for shaping simple sibilant systems. It is argued that:

(2)

In simple sibilant systems, i.e., consisting of one (denti-)alveolar and one postalveolar affricate, the latter is often a palatoalveolar [t͡ʃ].

Note that the if-principle in (1) applies to complex systems only, in which one of the postalveolar affricates must be of low tonality. However, this principle does not exclude the possibility that, in simple systems, the postalveolar sibilant *can* also be of low sibilant tonality. This is because the perceptual distance between the affricates can be extended. In simple systems, more perceptual space is available, see Zygis (2005) for more discussion.

In the following I will focus on Polish and Czech sibilant affricate inventories including coronal stops.

### *3.1 Standard Polish and its dialects*

Polish shows a complex contrast in coronal inventories, as depicted in (3).[1]

(3) Standard Polish[2]

| | denti-alveolar | retroflex | alveolo-palatal |
|---|---|---|---|
| stop | t d | | |
| affricate | t͡s d͡z | ʈ͡ʂ ɖ͡ʐ | t͡ɕ d͡ʑ |
| fricative | s z | ʂ ʐ | ɕ ʑ |

The retroflex status of the Polish postalveolar affricates /ʈ͡ʂ/ /ɖ͡ʐ/, as is argued in the present study, has not been investigated according to the best of my knowledge. In Slavic tradition these affricates are either transcribed as [č] [ǯ] (see Benni 1931, Wierzchowska 1971, Rubach 1984), [č], [dž] (see Gussmann 1980, Szpyra 1995), or [t͡ʃ], [d͡ʒ] in IPA terms (see Dukiewicz & Sawicka 1995, Jassem 2003).

By way of contrast, in a non-Slavic tradition researchers have pointed out the retroflex character of the Polish sibilants; but their studies were limited to fricatives; cf. Keating (1993), Ladefoged & Maddieson (1996), Hall (1997a), and Hamann (2003). Only one study by Stevens & Blumstein (1975) considers the Polish affricate [ɖ͡ʐ] as an example of a retroflex sound, albeit even there its properties are not discussed in detail.

In the following I provide articulatory and perceptual evidence showing that the Polish affricate under consideration is not a palatoalveolar [t͡ʃ] , but that it exhibits some characteristics of the retroflex [ʈ͡ʂ]. While the articulatory and perceptual aspects will be discussed in the present section, the acoustic arguments are provided in section 5 in which the experimental results are discussed.

As far as the articulatory aspect of the Polish postalveolar affricate is concerned, its stop and fricative components display retroflex characteristics.

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1 It should be noticed that Polish contrasts retroflex affricates and sequences of stops followed by fricatives, e.g., [ʈʂɨ] 'three' vs. [ʈ͡ʂɨ] 'whether.'

2 It should be stressed that some scholars also assume that Polish has palatalized dentals /$t^j$/ /$d^j$/ in its phonemic inventory, see, e.g., Bethin (1992). Others maintain that palatalized stops occurring on the surface are underlying sequences of stops followed by /j/ e.g. /tj/, /dj/; see Rubach (1984). As it will be shown by the experimental results, this difference bears no effect on the present investigation.

Biedrzycki (1974) provides an x-ray tracing of the Polish stop component of [t͡ʂ], which leaves no doubt that the stop component also shares features characteristic of typical retroflex stops: the tongue tip is extended out from the tongue body and raised. It touches the alveolar ridge or even the area behind it. In addition the tongue body is raised and thus the sound is velarized; see Figure 1. The fricative component is not provided by Biedrzycki (1974).

A very similar x-ray tracing to the one presented in Figure 1 is provided by Ostaszewska & Tambor (2001:40), although it is not said explicitly which affricate component is presented by the frame.

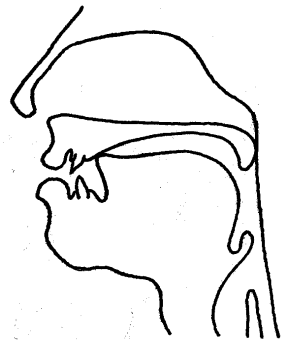


**Figure 1:** Stop component of Polish [t͡ʂ] (Biedrzycki 1974: 22).

Wierzchowska (1971:163) provides another x-ray tracing of the stop component of the postalveolar affricate. It is shown in Figure 2a whereas in Figure 2b the fricative component is presented; see Wierzchowska (1980:64).

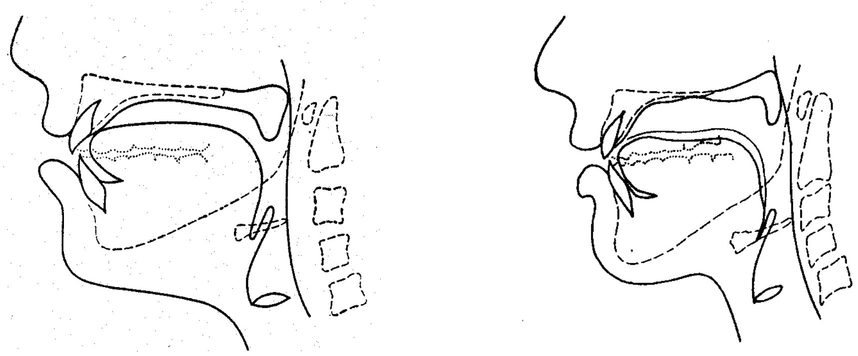


**Figure 2:** a. Stop component of Polish [t͡ʂ] b. Fricative component of Polish [t͡ʂ]

Although the tip is not curled up in Figure 2a Wierzchowska (1971:163) notices that the difference between Polish coronal stop, [t] and the stop component of [t͡ʂ], is that the tongue tip is positioned higher in the latter than in the former case. As displayed in Figure 2a the tongue tip touches the alveolar ridge, whereas in the case of [t] the tongue tip is positioned behind the teeth.[3] Note, however, that it cannot be maintained, on the basis of the x-ray frames in Figure 2 that the affricate [t͡ʂ] is articulated at a posterior place of articulation (as typically occurs with retroflexes), but rather it is articulated at the alveolar place. It also displays a sublingual cavity which is characteristic of retroflexes. As far as the fricative part is concerned, Wierzchowska provides the same x-ray tracing as for the corresponding fricative, which is described as apical and produced at the (denti-) alveolar place of articulation. According to the definition of retroflexes adopted for the present study the fricative part of the Polish [t͡ʂ] can also be classified as retroflex.

Benni (1931) provides a palatogram of the stop component of Polish [t͡ʂ], showing that the tongue tip is positioned farther back at the rear of the alveoli, see Figure 3.

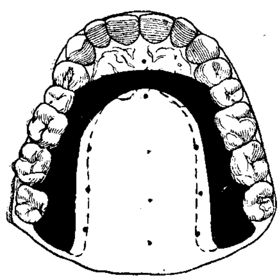


**Figure 3:** Stop component of Polish [t͡ʂ] (Benni 1931:14)

From an impressionistic perceptual point of view, Polish affricates denoted as [t͡ʂ] in the present study, are considered without exception to be hard, especially when they are compared with affricates of other Slavic languages like e.g. Russian; see for example, de Bray (1951). The hardness of these sounds is acoustically mirrored by prominent lower frequencies which are characteristic for retroflexes. This point will be experimentally analyzed in section 5 in great detail.

3 Wierzchowska (1971:164) also notices that the stop component as shown in Figure 2a occurs in sequences before fricatives [ʂ] [ʐ] which do not create an affricate, e.g. [tʂ]y ‘three.’

### *3.2 Czech*

Czech belongs to languages having a simple affricate contrast: /t͡s/ vs. /t͡ʃ/. The two affricates form a natural class with the alveolar /t/ and the palatal /c/. The inventory is shown in (4).[4]

(4) Czech

| | alveolar | | palatoalveolar | | palatal | |
|---|---|---|---|---|---|---|
| stop | t | d | | | c | ɟ |
| affricate | t͡s | | t͡ʃ | (d͡ʒ) | | |
| fricative | s | z | ʃ | ʒ | | |

From the articulatory evidence, it is however far from obvious whether the postalveolar affricates are indeed palatoalveolars. In Figure 4a an x-ray tracing of the plosive component of [t͡ʃ] and in Figure 4b an x-ray tracing of the fricative [ʃ] is shown.

**Figure 4:** a. Czech [t͡ʃ] (Palková 1994: 235) b. Czech [ʃ] (Palkovà 1994:229)

Palková (1994:235) states that in the closure phase the tongue tip is situated at the rear of the alveolar ridge. This is confirmed both by a palatogram and a linguagram provided in Figure 5.

[4] However, there are differences in describing the particular places of articulation. With respect to /t/ and /d/, Short (1993:535) assumes the dento-alveolar place of articulation, while de Bray (1951:439) and Stadnik (1998:387) the dental. There is also no consensus with respect to /c/ and /ɟ/: Whereas Stadnik (1998) and Short (1993) assume that they are palatal sounds, others consider them to be palatalized alveolars /$t^j$/, /$d^j$/; see de Bray (1951), Palková (1994). In the present study, they will be presented as palatals following the experimental study by Machač & Skarnitzl (2004).

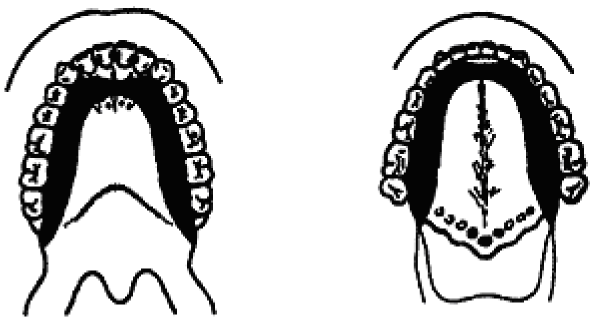


**Figure 5:** Palatogram and linguagram of the closure of Czech [t͡ʃ] (Palková 1994:235)

In the release phase of the closure, a constriction similar to that of [ʃ] is created. The lips are protruded. Palková (1994:235) also observes that the affricate is hard from a perceptual point of view. However, the low spectral prominency between 1.4 and 2 kHz which would suggest the low sibilant tonality refer only to the corresponding fricative. This point is not confirmed by the experiment results presented 5, where it is shown that the COGs of the palatoavleoar [t͡ʃ] are higher (above 3 kHz on average).

As far as the perceptual aspect of Czech [t͡ʃ] is concerned, Lehr-Spławiński & Stieber (1957:40) maintain that the pronunciation of the fricatives [š] [ž] can be as hard as the Polish corresponding sounds, but it often happens that the sounds are articulated in a semi-soft way. This is especially noticeable – as Lehr-Spławiński & Stieber (1957) observe – when Czechs speak Polish. With respect to the corresponding affricate [č] the situation is different as far there is a no option: the affricate is always semi-soft and differs from the Polish [t͡ʂ]. The experimental results presented in section 5 indicate that the Czech postalveolar affricate considerably differs from Polish [t͡ʂ] and should be classified as [t͡ʃ].

In conclusion, Czech postalveolar affricates correspond to the IPA palatoalveolar [t͡ʃ]. It also appears that other stops such as /t/, and especially the palatal /c/, do not have a direct influence on creating affricate inventories, albeit creating a natural class with them. This point is confirmed by experimental results, presented in section 5.

## 4 Czech and Polish affricates from a diachronic point of view

This section deals with the emergence of affricates and their development in two selected Slavic languages, Czech and Polish. The choice of these two neighbouring languages is motivated by the fact that they have developed different affricate contrasts: a two-way contrast in Czech and a three-way contrast in Polish. The inventories, together with coronal stops, are repeated in

(5) for convenience. Note that in Polish the retroflex /t͡ʂ/ is proposed according to the assumptions made in the present study.

| | | | | | | |
|---|---|---|---|---|---|---|
| (5) | Czech | t | c | t͡s | t͡ʃ | |
| | Polish | t | | t͡s | t͡ʂ | t͡ɕ |

In the following it will be shown that the Polish postalveolar affricate <č> was /t͡ʃ/ and later changed to /t͡ʂ/ in order to create a more optimized contrast to /t͡ɕ/. Furthermore, it will be argued that the emergence of the palatal /c/ in Czech did not have a significant impact on its affricate system: /t͡ʃ/ did not change to the retroflex /t͡ʂ/ because the perceptual contrast to the already existing affricate /t͡s/, as well as other stops, was sufficient.

From a diachronic point of view the issues listed in (6) are the main points of interests for the present study. They have been listed chronologically.

(6) Development of affricate system:
- (i) The emergence and development of /t͡ʃ/ in Czech,
- (ii) The emergence and development of /t͡ʂ/ in Polish
- (iii) The emergence of /c/ in Czech and /t͡ɕ/ in Polish

As far as (i) is concerned, the emergence of /t͡ʃ/ goes back to the Protoslavic First Velar Palatalization (1stVP) according to which /k/, /g/, and /x/ changed to [t͡ʃ], [ʒ], and [ʃ] before front vowels; see the rule presented in (7). The process would have been accomplished in or about the 6th or 7th century (Stieber 1969:67)

(7) 1st Velar Palatalisation (Stieber 1969:66)
/k, g, x/ → [t͡ʃ , ʒ, ʃ]/_ ī, ĭ, ē, ě[5]

Stieber (1957: 93) observes that <č> of present-day Czech is not as soft as the Protoslavic [t͡ʃ], but still softer that the corresponding Polish sound. A similar observation is made by Carlton (1991). Therefore, I assume that in terms of IPA the 1st Velar Palatalization of /k/ produced palatalized palatoalveolar [t͡ʃʲ].

Since the process of the 1stVP occurred in Protoslavic, palatoalveolar /t͡ʃʲ/ was also an ancestor of Polish retroflex affricate /t͡ʂ/, see (6iii). However, around the 16th century, the palatalized /t͡ʃʲ/ originating from 1st Velar Palatalization was hardened and converted to the retroflex /t͡ʂ/, e.g. *[t͡ʃʲi]sto* vs. *[t͡ʂɨ]sto* 'clean' (Rospond 1971:91).

[5] The symbols /ī ē/ stand for short /i, e/, while /ě, ĭ/ for long /e, i/.

In the light of the facts presented above, a question arises as to how we can explain the difference in the development of Protoslavic /t͡ʃʲ/ in Czech and Polish.

The answer, as it is argued in the present study, is provided by a different development of Protoslavic /tʲ/ and its perceptual impact on the already existing affricates. In Polish the Protoslavic /tʲ/ originating from /tj/ was converted to the alveolo-palatal [t͡ɕ] around the 13th century; for instance, i[dʲ]e[tʲ]e→i[d͡ʑ]e[t͡ɕ]e (Stieber 1962:63). Subsequently, [t͡ɕ] was phonemized, and since then it has formed an integral part of Polish consonantal inventory. Hence, until the 16th century /t͡ɕ/ was found along side /t͡ʃʲ/ in a Polish phonemic inventory, and then the latter changed to /t͡ʂ/.

In contrast to Polish, /tʲ/ was not affricatized in Czech. Instead, it had gradually changed to the palatal [c] and around the end of the 14th century it entered the phonemic inventory of Czech (Lamprecht, Šlosar & Bauer 1977). Since then it has co-occurred with /t͡ʃ/.

The motivation for the differences in the development of /t͡ʃʲ/ becomes clearer if we consider the acoustic/perceptual properties of [c] and [t͡ɕ], which will be discussed in section 5 in more detail. It will be shown that in contrast to [t͡ɕ], the palatal [c] does not share the fricative-like properties with affricates. Therefore, the former, and not the latter, was directly involved in the formation of the affricate system. Since [t͡ɕ] (and not [c]) was perceptually close to [t͡ʃʲ], the latter sound changed to [t͡ʂ] in order to create more perceptual distance from [t͡ɕ]. In the Czech system, this change was not required, because the perceptual distance between the already existing affricates had not been changed by the entrance of the new phoneme /c/.

In summary, it has been observed that the Czech and Polish affricate /t͡ʃ/ did not develop in a parallel manner: whereas the palatoalveolar /t͡ʃ/ changed to the retroflex /t͡ʂ/ in Polish, it remained palatoalveolar in Czech. This discrepancy can be argued to be attributed to an asymmetrical development of the Protoslavic /tʲ/: while in Czech /tʲ/ had developed into palatal stop /c/, in Polish it converted to an alveolo-palatal affricate /t͡ɕ/. This difference played a significant role in the development of sibilant affricates in these languages.

## 5 Phonetic investigations: Experimental results

In this section, phonetic evidence underpinning the assumptions made in previous sections will be empirically demonstrated. The aim of this section is two-fold. Firstly, it will be experimentally shown that the Slavic affricates are indeed palatoalveolars as commonly assumed. Secondly, it will be shown what influence other phonemes of the same coronal natural class (the stops /t/ and /c/, as well as the affricates /t͡s/ and /tɕ/) have on the postalveolar affricate /t͡ʃ/, and thus on the shape of the sibilant inventory.

The study is limited to the two Slavic languages, Czech and Polish, whose relevant (voiceless) stop contrasts are repeated in (8) for convenience. Note that the Polish retroflex /t͡ʂ/ has already been assumed in this study. This assumption requires, however, further acoustic underpinnings.

| | | | | | |
|---|---|---|---|---|---|
| (8) | Czech | alveolar | | palatoalveolar | palatal |
| | | t | t͡s | t͡ʃ | c |
| | Polish | dento-alveolar | | retroflex | alveolo-palatal |
| | | t | t͡s | t͡ʂ | t͡ɕ |

The languages in (8) have been chosen for the following reasons: The place of articulation of Czech /t͡ʃ/, denoted mostly as <č>, is by no means clear from the descriptions available in the literature; see 3.2. In the same vein, the corresponding Polish postalveolar affricate is repeatedly reported as the palatoalveolar /t͡ʃ/, contrary to what is argued in the present study, see 3.1. Furthermore, the presence of the palatal stop /c/ in Czech on the one hand, and the alveolo-palatal affricate /t͡ɕ/ in Polish on the other is important because it gives a possibility for proving to what extent these sounds might influence the postalveolar affricates, in the sense that the latter convert to retroflexes.

Three predictions are made for the purposes of the present study. They are listed in (9).

(9) Predictions:

(i) The Czech postalveolar affricate is /t͡ʃ/, while the Polish corresponding affricate is the retroflex /t͡ʂ/.

(ii) The Czech palatal stop /c/ does not have any significant impact on the shape of the affricate sibilant inventory.

(iii) The Polish alveolopalatal affricate /t͡ɕ/ plays an essential role in creating the sibilant system.

In order to test the predictions in (9) the recordings of four native speakers of Czech (two females, MM, BM and two males, RS and MK) and four native speakers of Polish (two females, MR, MZ and two males, SL, CZ) were made. The speakers were asked to read the items listed in (10) five times embedded in the following carrier sentences: ‘*Powiedziala X do ciebie’,* ‘I said... to you’ in Polish and ‘*Predal jsem X. Petrovi*’ ‘I passed X onto Peter.’ in Czech. Note that the capital letter in (10) denotes a stressed syllable.

(10) Experimental items

| | | | | | |
|---|---|---|---|---|---|
| Czech | Ata | At͡sa | At͡ʃa | Aca | |
| Polish | Ata | At͡sa | At͡ʂa | At͡ɕa | At͡ʃʲa |

It has to be noted that the Polish item At͡ʃʲa in which an allophone [t͡ʃʲ] occurs has been considered for reasons of comparison to the Czech /t͡ʃ/.

The recordings were made at a sample rate of 22.05 kHz. The items were further analysed with PRAAT (version 4.2.21). For statistical calculations SPSS (version 11.0.) was used.

In order to test the predictions in (9) five acoustic parameters were investigated, listed in (11). Most parameters in (11) refer to a ‘frication phase’. In the case of an affricate the frication phase comprises the whole fricative component. In items such as *Ata* and *Aca* the frication phase refers to a brief period starting after the burst and ending at the starting point of fundamental frequency.

(11) Parameters:

(i) The duration of the closure and of the frication phase
(ii) The amplitude of the frication phase
(iii) The transition of the vowel formants F2 and F3 preceding and following the consonant
(iv) The centre of gravity values of the frication phase
(v) The correspondence of the frequency of the highest-amplitude spectral cue at the release of the burst, and at the steady-state part of the fricative to the formant frequencies of the following vowel

For the calculations of the parameters in (11) the following six temporal landmarks were extracted:

(12) Points of investigation:

(1) The steady state of the vowel preceding the consonant,
(2) The end of the formants of the vowel preceding the consonant,
(3) The burst,
(4) The steady state of the frication,
(5) The beginning of the formants of the following vowel,
(6) The steady state of the following vowel.

All six places in (12) are exemplified on the spectrogram of Polish [at͡ɕa] in Figure 6.

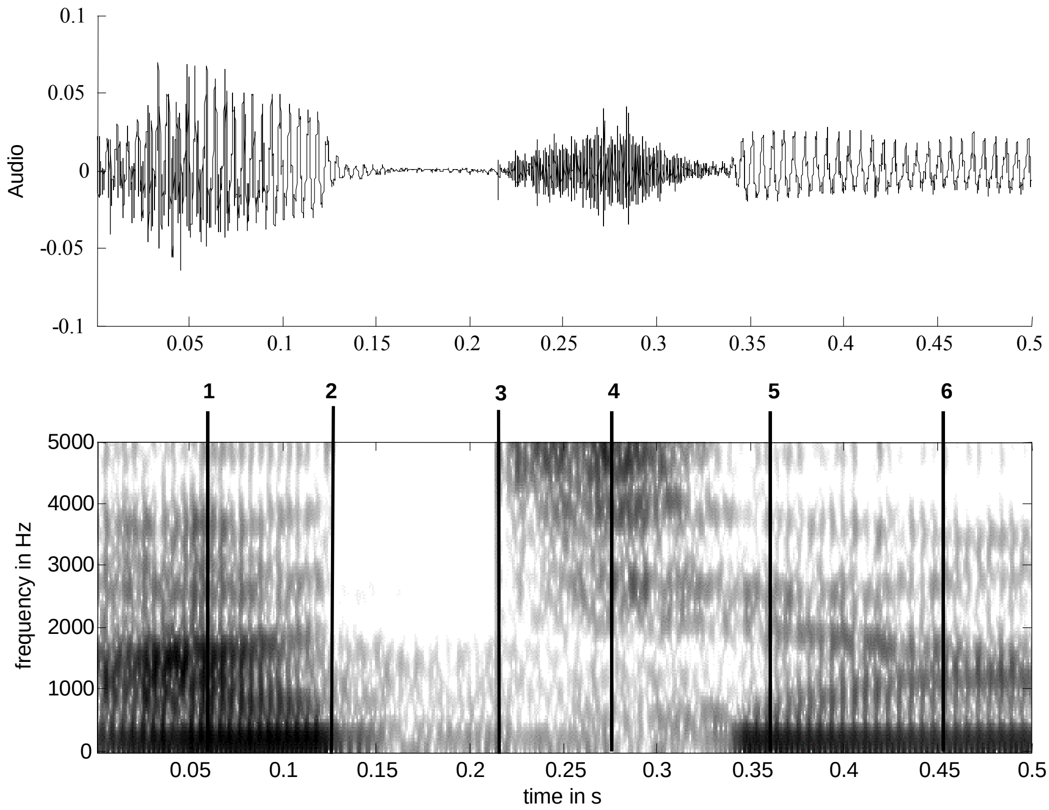



**Figure 6:** Oscillogram and spectrogram of [at͡ɕa] as pronounced by a Polish native speaker.

In the following the experimental results will be presented. The order of the presentation is in accordance with the parameters listed in (11).

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

In the investigation of the parameter (i), the duration of the closure (from 2 to 3 in Figure 6) and the duration of frication (from 3 to 5 in Figure 6) were measured.

Figure 7 shows mean duration values of the closure and frication phase as obtained from four Czech speakers. The differently coloured error bars (with +/- 1,0 standard deviation) stand for mean duration of the closure and frication as indicated by the legend on the right. They are assigned to the appropriate consonants as indicated on the horizontal axis.

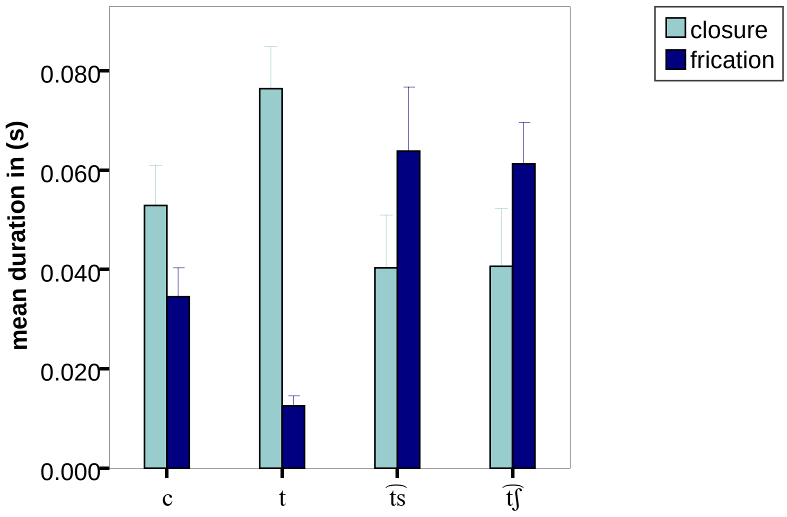



**Figure 7:** The average duration of closure and frication in Czech consonants.

The results displayed in Figure 7 show that the frication phase of the affricates /t͡ʃ/ and /t͡s/ is longer than the closure phase. As far as /t͡ʃ/ is concerned, its mean closure duration amounts to ca. 40.8 ms followed by a 61.3 ms frication. Very similar results are obtained for the affricate /t͡s/: 40.3 ms vs. 63.7 ms. Conversely, the closure phase of the stops are longer than their releases.

A one-factorial ANOVA calculated for every consonant separately with *duration* as dependent variable and *closure&frication*, i.e. the two affricate components, as an independent variable shows a significant effect for all consonants in Figure 7 with respect to the difference between the closure and frication durations: /t/ F(1,39)  1098.947 p<.001, /c/ F(1,39) = 66.072 p<.001, /t͡s/ F(1,39) = 39.465 p<.001, /t͡ʃ/ F(1,39) = 43.023 p<.001. In addition, the differences in closure duration of the two affricates, as well as the differences in their frication duration, are not significant.

Figure 8 presents the results split by speaker.

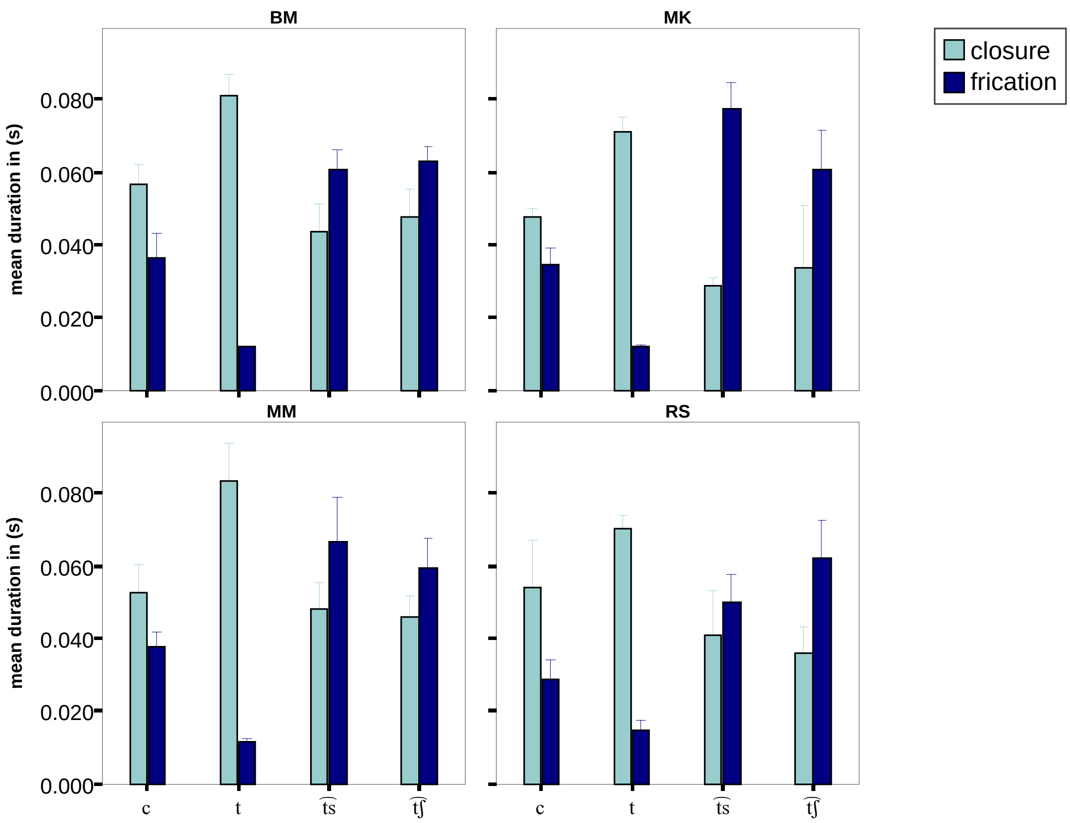



**Figure 8:** The average duration of closure and frication split according to Czech speakers.

All Czech speakers show an asymmetry: closure is shorter than frication in affricates /t͡s/ and /t͡ʃ/, whereas a reverse pattern is found in the stops /t/and /c/. From a statistical point of view, the relation between the closure and frication duration is significant for almost all items. The only exception is the item /t͡s/ as produced by speaker RS where the closure is shorter than the frication but the difference is not statistically significant. The detailed statistic calculations are given in Table 1.

**Table 1:** Statistical analysis of the relation between closure and frication duration in Czech consonants split by speakers

| | /t/ | /c/ | /t͡s/ | /t͡ʃ/ |
|---|---|---|---|---|
| speaker BM | F(1,9)=767.410 p<.001 | F(1,9)=25.157 p<.01 | F(1,9)=16.725 p<.01 | F(1,9)=16.288 p<.01 |
| speaker MM | F(1,9)=236.247 p<.001 | F(1,9)=15.756 p<.01 | F(1,9)=8.344 p<.05 | F(1,9)=9.111 p<.05 |
| speaker MK | F(1,9)=916.053 p<.001 | F(1,9)=33.665 p<.001 | F(1,9)=203.195 p<.001 | F(1,9)=8.899 p<.05 |
| speaker RS | F(1,9)=971.253 p<.001 | F(1,9)=16.971 p<.01 | F(1,9)=1.971 n.s. | F(1,9)=21.973 p<.01 |

As far as the palatoalveolar /t͡ʃ/ is concerned, its closure duration does not significantly differ from the frication of /t͡s/ for each speaker. A similar conclusion can be drawn with respect to frication duration of /t͡ʃ/and /t͡s/ with the only exception noted in the results of speaker MK where the frication in /t͡ʃ/ is significantly shorter than in /t͡s/, p<.05.

Let us compare these results to those obtained from Polish. Figure 9 presents the averages of closure and frication duration of Polish consonants for all four speakers together.

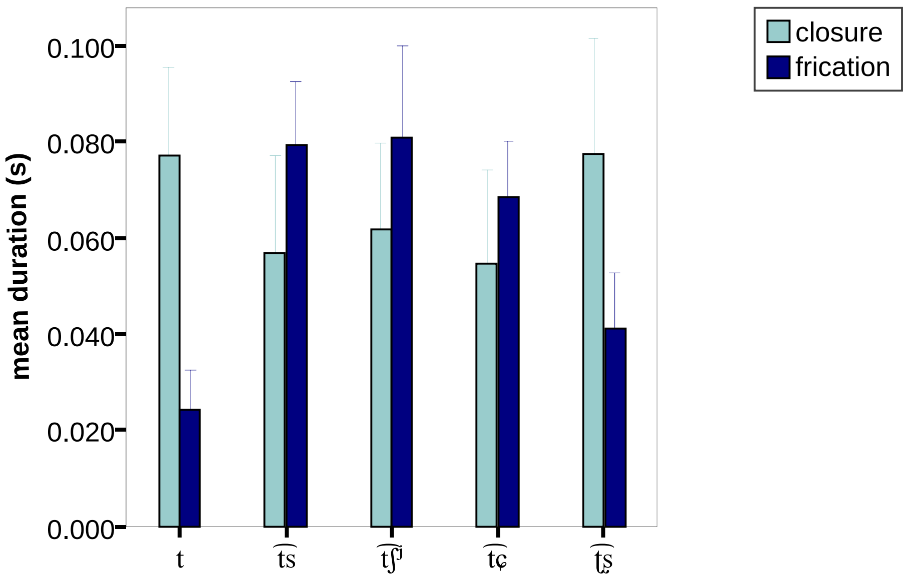



**Figure 9:** The average duration of closure and frication in Polish consonants.

The duration differences between closure and frication are significant for all items presented in Figure 9: /t/ F(1,39) = 136.774 p<.001, /t͡ɕ/ F(1,39) = 7.222 p<0.05, /t͡s/ F (1,39) = 17.072 p<.001, /t͡ʂ/ F(1,39) = 37.195 p<.001, /t͡ʃʲ/ F(1,39) = 10.374 p =.003.

The most interesting result is probably the relation between the closure and frication in the postalveolar affricate, which I denoted /t͡ʂ/. This affricate, in contrast to others presented in Figure 9, displays a longer closure duration than frication duration. Its mean closure duration amounts to 77.5 ms, while its mean frication duration is 41.2 ms. Other affricates show a reverse pattern: /t͡ɕ/ 54.9ms vs. 68.6ms; /t͡s/ 56.8 ms vs. 79.5 ms, /t͡ʃʲ/ 61.9 vs. 80.8 ms. Only in the case of /t/ is the closure longer than the frication: 77ms vs. 24.3ms. From a statistical point of view the difference in closure duration is significant between /t͡ʂ/ and /t͡ɕ/ (F (4,99)=5.914 p<.05) as well as between /t͡ʂ/ and /t͡s/ (F(4,99)=05.914 p<.05). The differences between /t͡ʂ/ and /t͡ʃʲ/ as well as /t͡ʂ/ and /t/ with respect to the closure duration are not significant. As far as frication duration is concerned the only non-significant difference is the one between /t͡ʂ/ and /t/. Other affricates show a longer duration than /t͡ʂ/ does, which is highly significant (F(4,99)=71.205 p<.001).

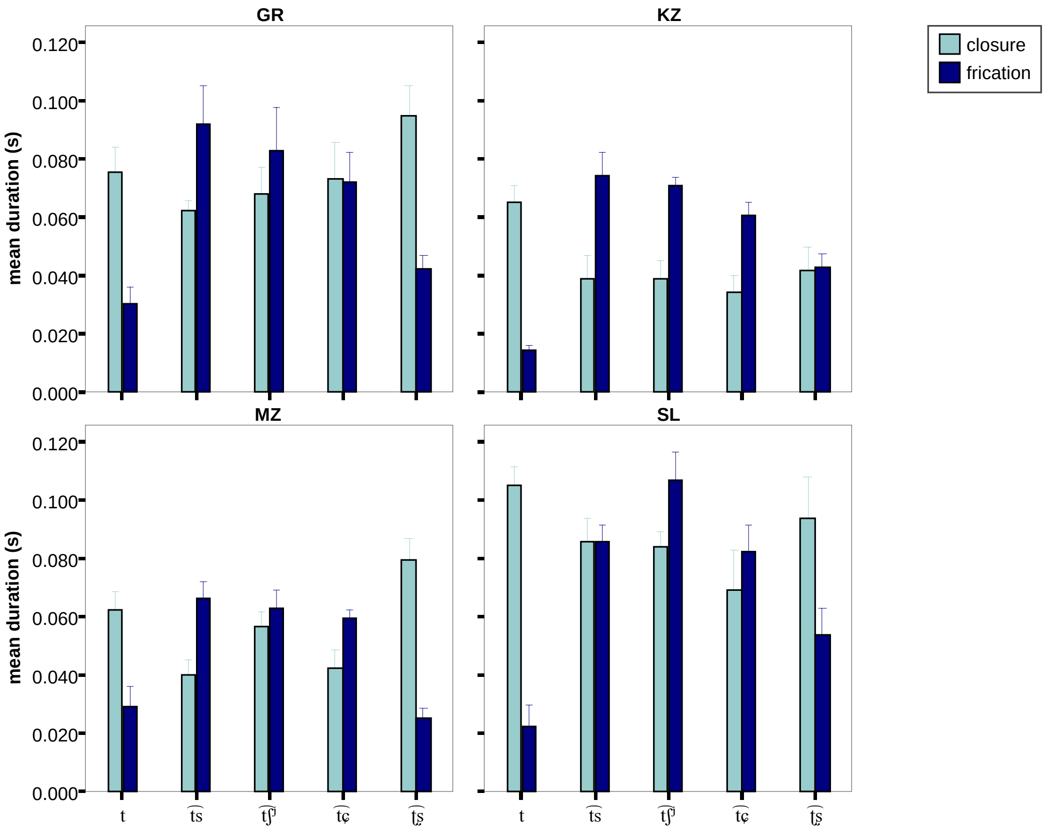



**Figure 10:** The average duration of closure and frication split according to Polish speakers.

Similar results are obtained in the pronunciation of the individual speakers, as shown in Figure 10. In the pronunciation of three speakers (GR, SL and MZ), the closure in [t͡ʂ] lasts longer than the fricative part of the affricate. These differences are significant; see Table 2. The only speaker who does not show this difference is speaker KZ in whose pronunciation of [t͡ʂ] the closure and frication are of almost the same duration and do not show any significant statistical effect. Still, the frication is short which is important for drawing conclusions with respect to articulatory characteristic of this sound, see below.

In the case of other affricates the frication is always longer than the closure phase although this effect is not always significant. Table 2 shows statistical calculation results as achieved for individual speakers.

**Table 2:** Relation between closure and frication duration in Polish consonants split by speaker from a statistical point of view.

| | /t/ | /c/ | /t͡s/ | /t͡ʂ/ | t͡ʃʲ |
|---|---|---|---|---|---|
| speaker GR | F(1,9)=101.657 p<.001 | F(1,9)=.026 n.s. | F(1,9)=22.927 p<.01 | F(1,9)=119.445 p<.001 | F(1,9)=3.457 n.s. |
| speaker SL | F(1,9)=359.850 p<.001 | F(1,9)=3.187 n.s. | F(1,9)=.000 n.s. | F(1,9)=27.645 p<.01 | F(1,9)=22.900 p<.01 |
| speaker KZ | F(1,9)=371.067 p<.001 | F(1,9)=62.861 p<.001 | F(1,9)=51.570 p<.001 | F(1,9)=.190 n.s. | F(1,9)=108.776 p<.001 |
| speaker MZ | F(1,9)=359.850 p<.001 | F(1,9)=3.187 n.s. | F(1,9)=.000 n.s. | F(1,9)=27.645 p<.01 | F(1,9)=22.900 p<.01 |

In summary, the investigation of the Polish and Czech postalveolar affricate, commonly denoted as <č> or /t͡ʃ/in IPA terms, shows that the two sounds are essentially different with respect to the closure and frication duration: whereas the closure phase in Czech /t͡ʃ/ is significantly shorter than the frication phase, a reverse pattern is observable in the corresponding Polish sound - its closure lasts significantly longer than its frication component. This property also distinguishes the sound from other Polish affricates.

The results point to an important articulatory difference between the postalveolar affricates. The Czech affricate /t͡ʃ/ is articulated with the tongue blade whereas the corresponding Polish sound is articulated with the tongue tip (also by speaker KZ). This is essential for classifying the latter sound as retroflex.

Finally, the results confirm that there is a difference between the Czech [t͡ʃ] and Polish [t͡ʃʲ]. Both the closure and frication duration are longer in the latter case which is attributed to the secondary palatalisation of the Polish sound. (closure 40.8 ms vs. 61.9 ms; frication 61.3 ms vs. 80.8 ms)

**Parameter (ii):** The amplitude of the frication phase.

Parameter (ii) includes the average of frication amplitude calculated from the end of the burst until the starting point of fundamental frequency. Figure 11 presents the results calculated for all four Czech speakers. For reasons of transparency, the results will be interpreted with focus on postalveolar affricates.

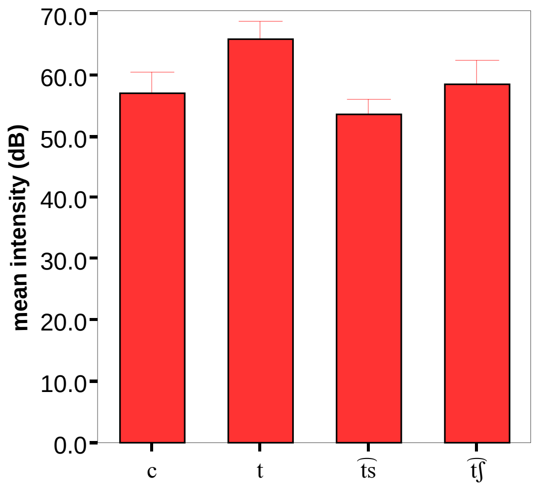



**Figure 11:** The amplitude average of frication in Czech

All consonants investigated were followed by the vowel [a] facilitating the comparison of the amplitude. The calculations of the amplitude of [a] following /t/, /c/, /t͡s/ and /t͡ʃ/ show that independently of the item, it amounts to ca. 70 dB for every speaker. The only significant amplitude difference has been found between the frication in /t͡s/and /t/ for speaker BM (69.84 dB vs. 74.45 $p<.05$; $F(3,19) = 4.392$).

The results presented in Figure 11 indicate that the average amplitude of /t͡ʃ/is significantly higher than the average amplitude of /t͡s/ ($F(3,79) = 50.255$ $p<.001$) and the average amplitude of /t/ ($p<.001$). There is no significant difference between the frication amplitudes of /t͡ʃ/ and /c/.

Figure 12 shows average amplitudes of the frication of the consonants split according to Czech speakers.

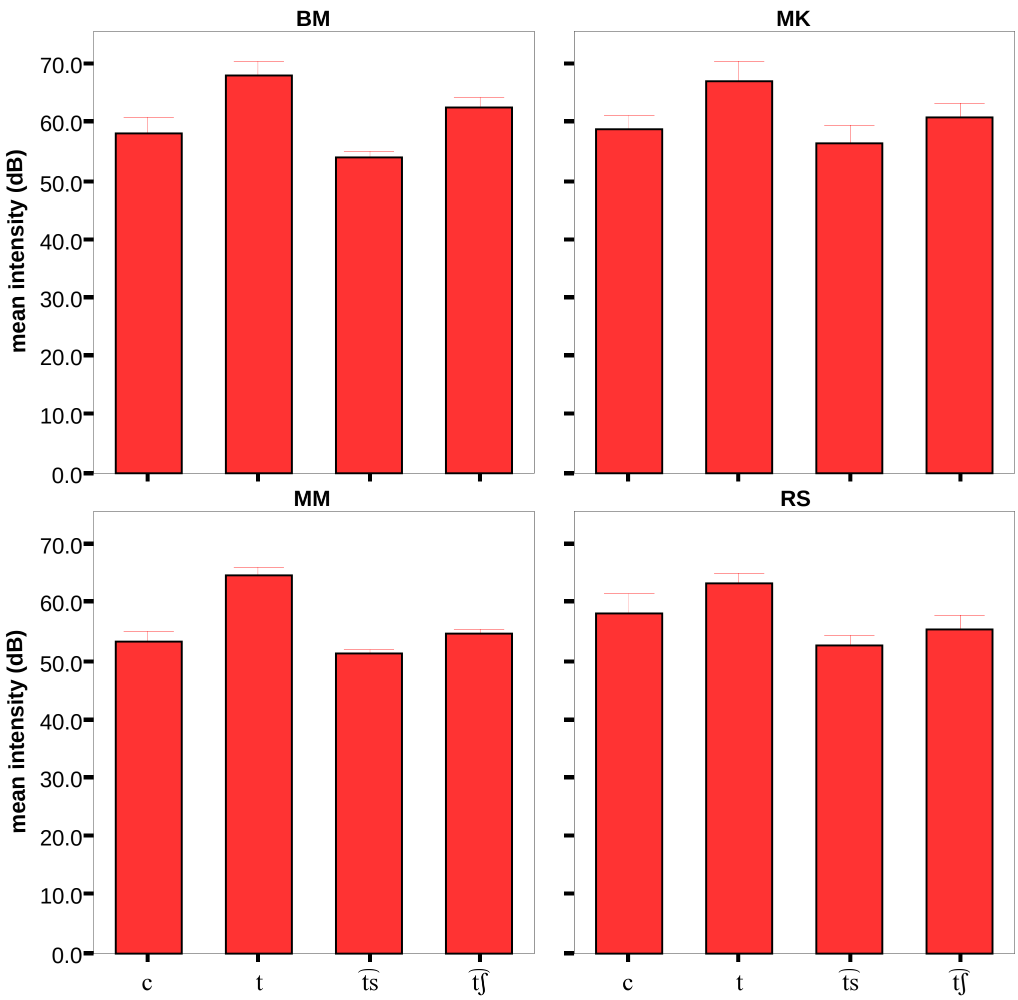



**Figure 12:** The amplitude average of the frication phase split by speaker.

The results in Figure 12 show that the amplitude of /t͡ʃ/is always higher than that of /t͡s/ but the difference is statistically significant for two speakers only (BM and MM, see
Table **3**). With respect to /t/ the difference is significant for every speaker and with respect to /c/ almost always not significant; see again
Table **3**.

**Table 3:** Mean amplitude of the consonantal frication phase split by Czech native speakers from a statistical point of view.

| | | t͡ʃ vs. t | t͡ʃ vs. c | t͡ʃ vs. t͡s |
|---|---|---|---|---|
| speaker BM | F(3,19)=41.175 | p<.01 | p<.05 | p<.001 |
| speaker MK | F(3,19)=13.264 | p<.05 | n. s. | n.s. |
| speaker MM | F(3,19)=115.230 | p<.001 | n. s. | p<.01 |
| speaker RS | F(3,19)=16.656 | p<.01 | n.s. | n.s. |

As far as Polish is concerned, the amplitude of the Polish retroflex /t͡ʂ/ does not differ from the amplitude of other consonants. The results are presented in Figure 13. It should be noted that the amplitude of the following [a] was not dependent on the consonant under investigation. No significant effect has been found between the items as produced by individual speakers. However, the mean average amplitude of [a] for all items of every speaker shows some significant effects. The mean [a] amplitude calculated for speaker GR (mean 85.75 dB) was significantly higher than the mean [a] amplitude calculated for speaker KZ (p<.001, mean 73.47 dB), speaker MZ (p<.001, mean 77.91 dB) and speaker SL (p<.001, mean 74.65 dB). Significant differences have also been found between speakers MZ and KZ (p<.001) as well as MZ and SL (p<.001, F(3,99)=197,721). The difference in amplitude between speakers KZ and SL is not significant.

Due to the significance of effects found in [a] amplitude I dispensed with presenting the amplitude averages attained for all speakers together. Figure 13 presents the results for each speaker separately.

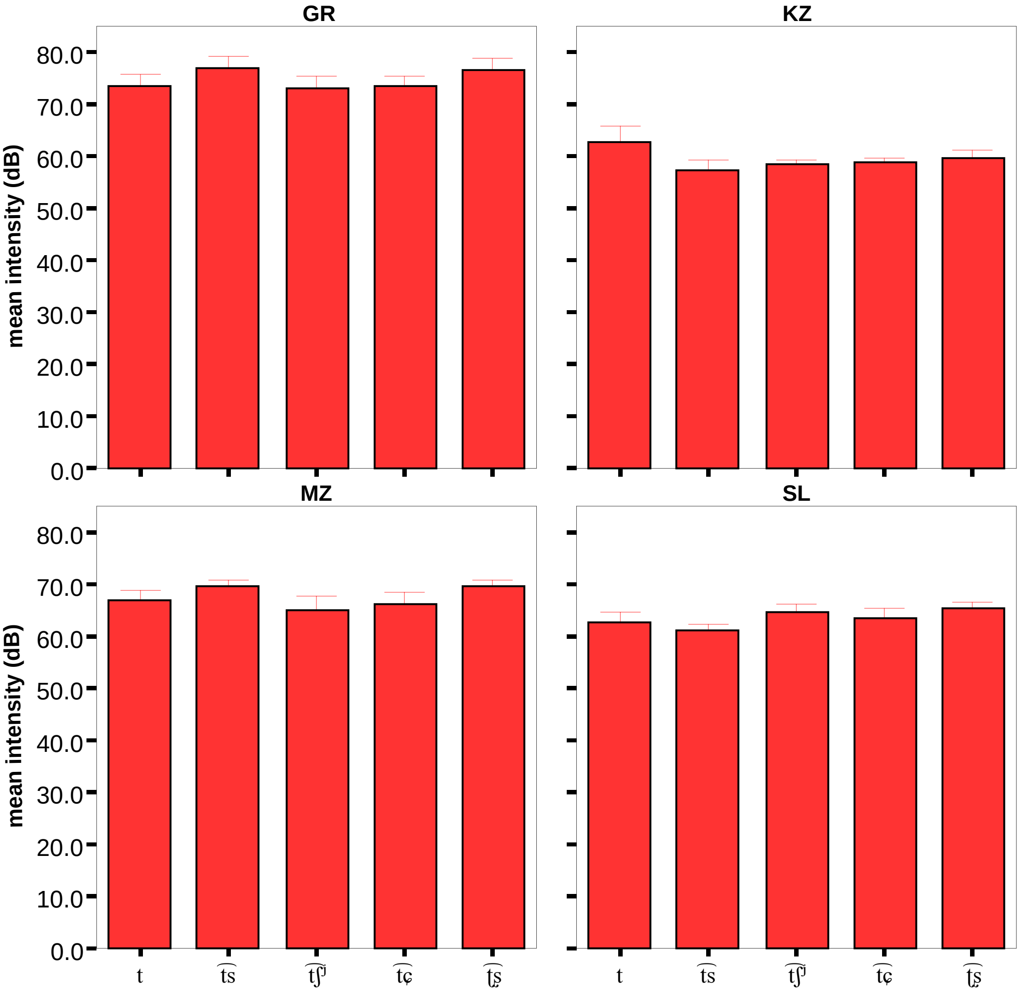



**Figure 13:** The average amplitude of the frication split by the speakers.

For speakers GR and KZ the amplitude of the consonant /t͡ʂ/ does not show significant differences with respect to other consonants presented in Figure 13. For speaker MZ the only significant difference in amplitude is that between /t͡ʂ/ and /t͡ʃʲ (F(4,25)= 6.091 p<.05) and for speaker SL it is between /t͡ʂ/ and /t͡s/ (F(4,24)=5.964 p<.01).

In summary, the investigation of frication amplitude does not show significant effects in Polish consonants. Hence, this parameter does not appear to be helpful in stating the differences among the affricates and between the Polish /t͡ʂ/ and the corresponding Czech affricate.

**Parameter (iii):** The shape of the vowel formants F2 and F3 preceding and following the consonant

As far as the formant transitions is concerned, the main point of interest is the second formant (F2) and the third formant (F3). While F2 characterizes the horizontal shape of the tongue, F3 is especially important for proving the possible retroflexivity the Polish palatoalveolar sound in question. If the F2 of the following vowel were falling, then it would indicate the transition from the palatal position. characteristic for palatalized segments or palatals which are produced with the tongue blade or tongue dorsum; see for example Ladefoged & Maddieson (1996:364).

In addition, the retroflex character of the sounds can also be postulated by looking at F3 transitions. There is a general consensus in the literature concerning a common acoustic cue of retroflexes which is a falling F3, due to the further rearwards (but still coronal) place of articulation; see for example Stevens & Blumstein (1975), Narayanan & Kaun (1999).

In order to analyze the spectral shape of the vowels preceding and following the consonant under consideration, formants of the vowel segments were measured semi-automatically by means of Linear Predictive Coding (LPC). For the formant analysis the software PRAAT (version 4.3) was used. Prior to formant analysis the sounds were downsampled to 11 KHz for female, and 10 KHz for male speakers to maintain the spectral structure of the first five formants only. The LPC was then calculated by using the following parameters: pre-emphasis frequency 50 Hz, analysis window duration 0.0256s, time step 0.001s and a prediction order of 13 for female, and 12 for male speakers. LPC spectra were calculated at four time instants (1, 2, 5, 6 in Figure 1) that were manually derived prior to calculation of the spectra. Maximally five peaks from a LPC spectrum derived by peak picking were temporarily considered as formants. As in some cases one formant value could not be detected by the peak-picking algorithm, the five temporary formant values were checked for every spectrum and manually corrected if necessary in order to determine the final formant frequencies.

Figure 14 shows the average values of the second formant in items including the palatoalveolar affricate /t͡ʃ/ as calculated for four Czech speakers. The bars represent mean F2 frequency at four different points, as described by the legend (e.g. f2_p1 stands for the mean value of the second formant at point (1)). On the horizontal axis the initials of individual speakers are shown.

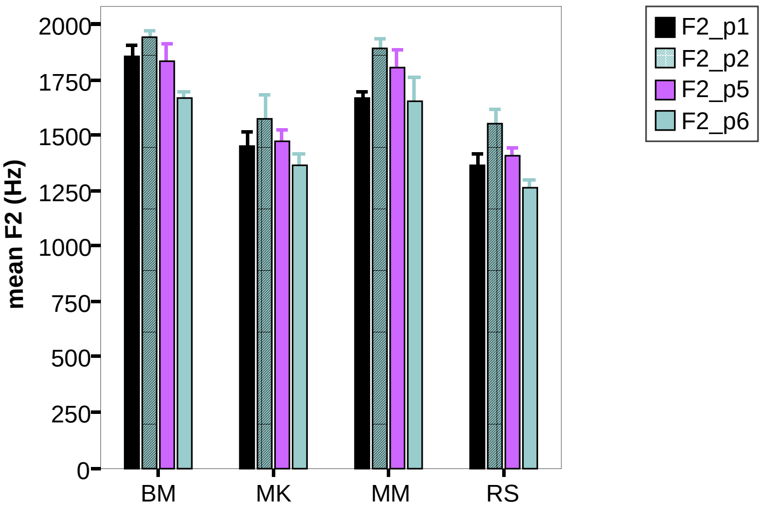



**Figure 14:** The average values of F2 as obtained for [t͡ʃ] by Czech speakers.

The results shown in Figure 14 show regularities in F2 shape in the pronunciation of all four speakers. The second formant of the vowel preceding the consonant is rising and falling when it occurs after the consonant. The rising F2 is statistically significant for two speakers MM ($F(3,19) = 13.416$ $p<.01$) and RS ($F(3,19) = 29.477$ $p<.001$). The falling F2 is significant for three speakers: MM $p<.05$, RS $p<.01$, BM $p<.01$ ($F(3,19) = 21.744$).

In addition, a clear difference between F2 of male and female pronunciation is visible in the sense that the former is considerably lower than the latter. Hence, the differences between speaker BM and MM with respect to the F2 at all measurement points (f2_p1, f2_p2, f2_p5, f2_p6) are not significant. Similarly, the differences in F2 for speakers RS and MK are not significant, with the only exception concerning f2_p1, where the difference is highly significant $p<.001$, $F(3,19) = 95.326$. All other differences are highly significant.

Figure 15 shows the mean values of F3 at the same four points as in the case of F2 calculated for each Czech speaker separately.

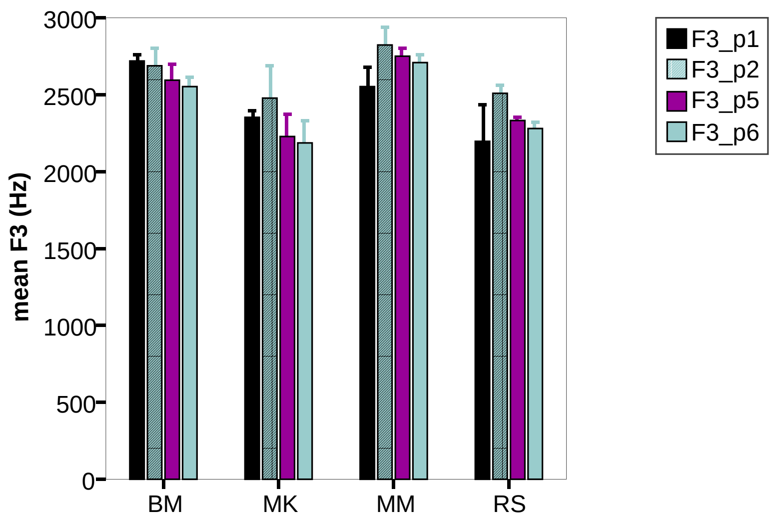



**Figure 15:** The average F3 values as obtained for [t͡ʃ] by Czech speakers.

As far as the third formant is concerned, no regularities in its shape can be stated. The only significant difference has been found in the pronunciation of speaker MM: F3 of the preceding vowel is rising (F(3,19) = 6.955 p<.01).

Figure 16 shows the shape of the second formant calculated for each Polish speaker separately.

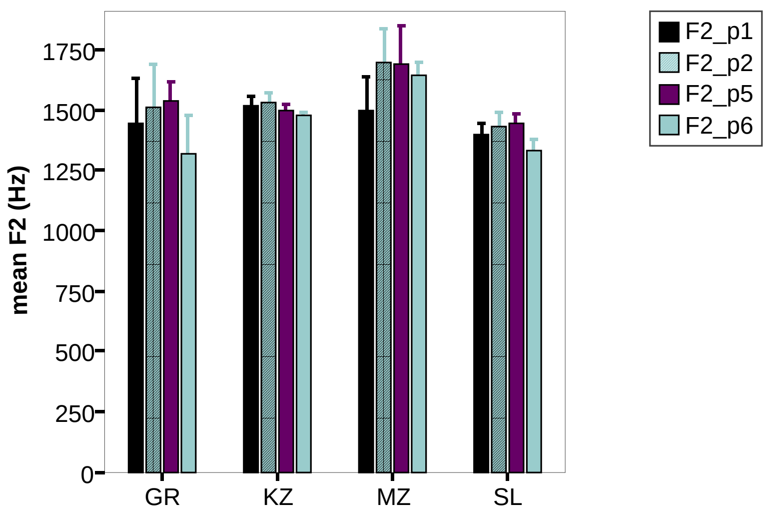



**Figure 16:** The average of F2 as obtained for [t͡ʂ] by Polish speakers.

The results presented in Figure 16 show only two significant effects on F2 shape: for speaker MZ for the preceding vowel (F(3,19) = 5.936 p<.05) and for speaker SL for the following vowel(F(3,19) = 5.345 p<.05).

With these results obtained, a conclusion may be drawn that in the pronunciation of the Polish postalveolar affricate [t͡ʂ] the formants of the preceding and following vowel remain pretty stable.

Figure 17 shows the shape of the second formant calculated for each Polish speaker separately.

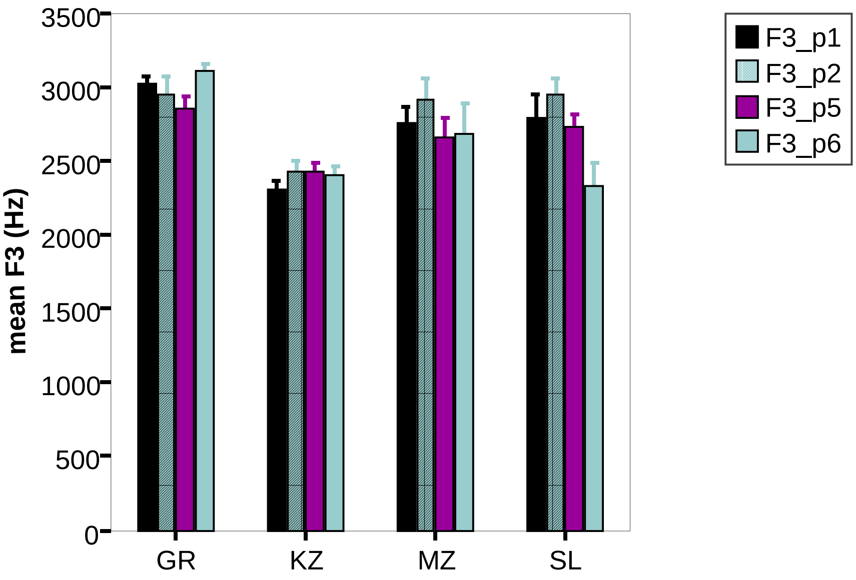



**Figure 17:** The average of F3 as obtained for [t͡ʂ] by Polish speakers.

The results presented in Figure 17 are significant in only one case. Speaker SL shows a significant difference between the beginning and steady state of the following vowel: F3 is falling $F(3,19) = 16.104$ $p<.005$.

In summary, the investigation of vowel formants reveals that in the case of the Czech [tʃ] F2 of the preceding vowel is raising whereas F2 of following vowel is falling, which is a typical pattern for sounds produced with the raised and fronted tongue blade. The corresponding Polish affricate shows pretty stable formants of the flanking vowels. Hence, the two sounds are different with respect to F2. The shape of F3 in both languages is stable, in the sense that it does not show rising or falling effects.

If we compare the Polish [t͡ʂ] and the Czech [tʃ] to the Polish palatalized palatoalveolar [tʃʲ], it turns out that the Czech [tʃ] and the Polish [tʃʲ] share some properties as far as the formants of the surrounding vowels are concerned. The results of F2 are shown in Figure 18.

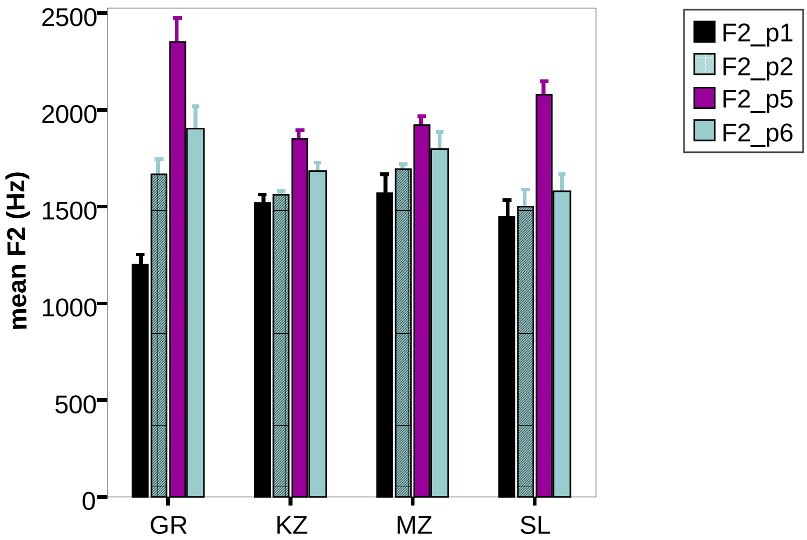



**Figure 18:** The average values of F2 as obtained for [t͡ʃʲ] by Polish speakers.

In contrast to F2 of Polish [t͡ʂ], the investigation of the F2 of [t͡ʃʲ] reveals its falling shape in the vowel following the consonant. This effect is statistically highly significant in the pronunciation of three speakers (GR $F(3,19) = 121.628$ $p<.001$, KZ $F(3,19) = 70.877$ $p<.001$, SL $F(3,19) = 55.329$ $p<.001$). As far as the shape of F2 of the vowel preceding [t͡ʃʲ] is concerned, its rising shape is significant only in the pronunciation of the speaker GR $p<.001$. The rising F2 makes the Polish [t͡ʃʲ] more similar to the Czech [t͡ʃ] which independently confirms the raised tongue blade in the production of the two sounds and the difference between the Czech [t͡ʃ] and the Polish [t͡ʂ].

Finally, the investigation of F3 does not show significant effects apart from with speaker SL, whose F2 rises into the consonant and also rises from the consonant into the following vowel. Both effects are slightly significant $F(3,19) = 7.035$, $p<.05$.

**Parameter (iv):** The center of gravity values of the frication phase

The (non)retroflexivity of the fricative part of an affricate (as well as fricatives) can be also inferred from measurements of the spectral mean, i.e., the center of gravity values (COG); see Jassem (1979), Nittrouer, Studdert-Kennedy & McGowan (1989), Gordon, Barthmaier & Sands (2002). With regard to articulation, the COG correlates to the size of the front cavity: The smaller the cavity, the higher the COG values. Consequently, if the supralaryngeal constriction is located at more posterior places, the front cavity is larger and the spectral mean is therefore lower. Lower COG values are expected for those retroflexes which display a relatively large front cavity**.**

The center of gravity values (COG) were calculated for the fricative portion of affricates and in the case of stop and vowel sequences [ta] or [ca] for the frication phase between the burst and the beginning of the following vowel. The fricative portion or frication phase respectively was extracted by a 25.6 ms long Hanning window centered on a time instant (point 4 in Figure 6) manually derived prior to the cog analysis. At first the spectrum was calculated by means of an overall spectral analysis (Fourier transform) over the frication portion. Then the center of gravity of the spectrum was calculated with the "power" setting 'p=2'.

Figure 19 presents mean COG values of frication in relation to the mean formant values of the following vowel (F2, F3, F4, F5).

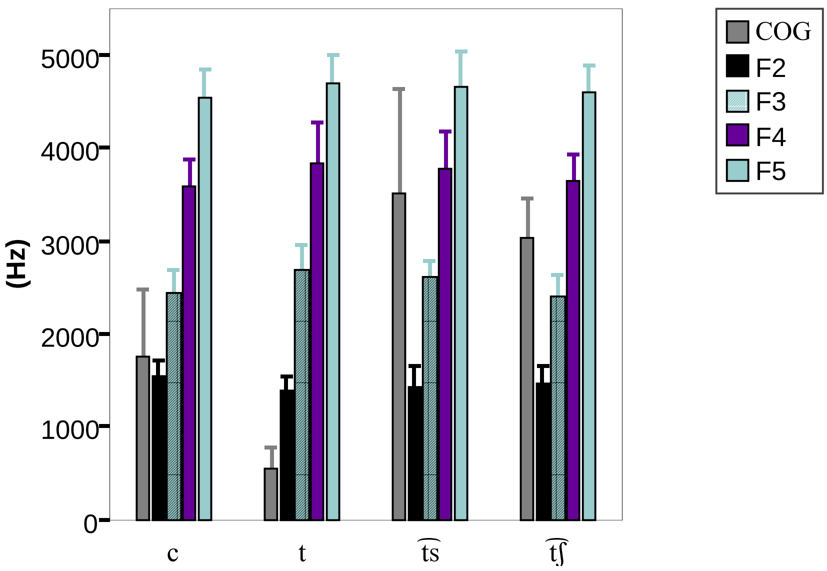



**Figure 19:** The average of COG values of frication in relation to the formant values of the following vowel as obtained for Czech.

Results presented in Figure 19 show different COG values with respect to the formant values of the following vowel. The lowest COG value is obtained for [t], followed by [c]. Much higher COGs are displayed by the fricative component of the affricates [t͡s] and [t͡ʃ], whereby the highest COGs are shown by [t͡s]. The COGs of [t͡ʃ] are situated between the third and the fourth formant. The differences here are highly significant: COG vs. F3 $p<.001$, COG vs. F4 $p<.001$ $F(4,99) = 326.140$. This is in contrast to [t͡s] COGs which are as high as the fourth formant (the difference is not significant)

In Figure 20 the results are split according to speakers. Note that all results refer to [t͡ʃ].

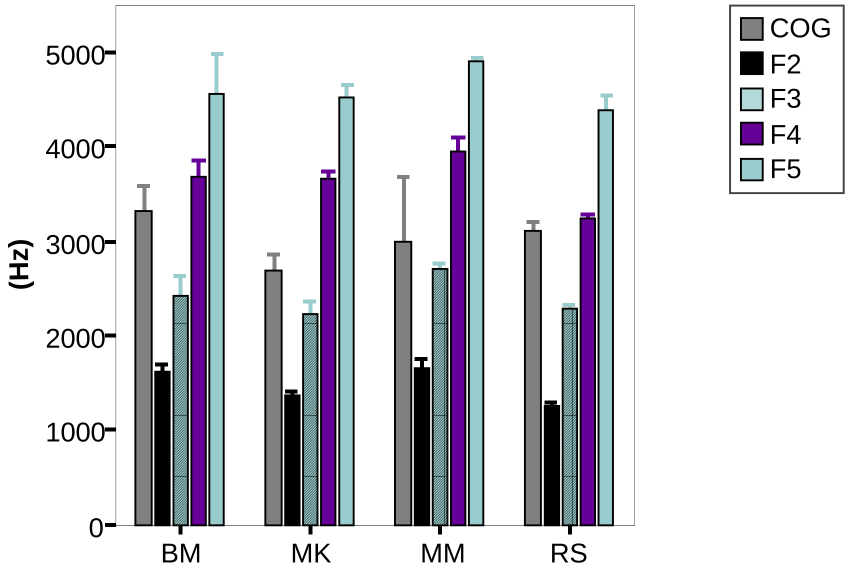



**Figure 20:** The average of COG values and formant values as obtained for [t͡ʃ] by Czech speakers.

Speaker BM shows a significant effect of the COG value in relation to F3 $p<.001$ but not in relation to F4 ($F(4,24) = 101.521$. Similar results are obtained for speaker RS: COG vs. F3 $p<.001$, COG vs. F4 not significant $F(4,24) = 847.890$. In the case of speaker MK the differences are highly significant: the COG value is higher than F3 ($p<.001$) but lower than F4 ($p<.001$, $F(4,24) = 512.544$). In the pronunciation of speaker RS the COG is not significant with respect to F3 and significantly lower with respect to F4 $p<.01$ $F(4,24) = 73.932$.

Figure 21 presents mean COG values of Polish consonants in relation to the formants of the following vowel at its steady state.[6]

The results presented in Figure 21 indicate that the COG values of [t͡ʂ] are the lowest among Polish affricates. The COGs of [t͡ʂ] are not higher than the third formant and the relation between them is not significant ($F(4,99) = 118{,}168$). The relation to other formants is highly significant $p<.001$.

6 It should be noted that COG values of the frication of [t͡s] show a very high standard deviation for both Polish and Czech affricates. In fact, this result mirrors great differences found among native speakers. It is also partly ascribed to the difficulty in extracting frication from the burst because the two components could not often be differentiated.

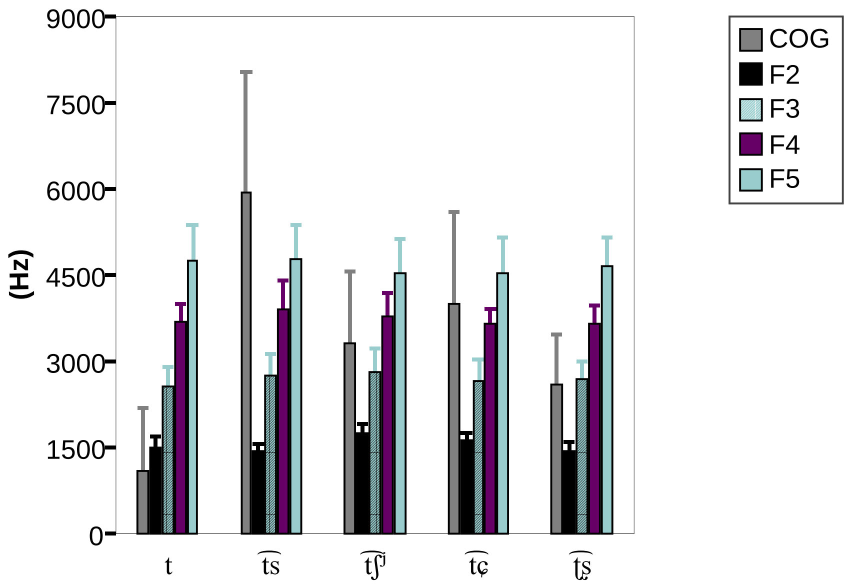



**Figure 21:** The average of COG values of frication in relation to the formant values of the following vowel as obtained for Polish.

The COG of [t] is as high as for F2 (the difference is not significant here), whereas the COGs of [t͡ʂ] relate to F3 (no significant difference). Furthermore, the COGs of [t͡ʃʲ] are higher than F3 but lower than F4. The difference is neither significant with respect to F3 nor to F4. Finally, the highest COGs are achieved by [t͡s] and are higher than F5. The difference is slightly significant ($F(4,104) = 62.705$ $p<.05$) .

Figure 22 presents the COGs of the fricative part of [t͡ʂ] split by speakers.

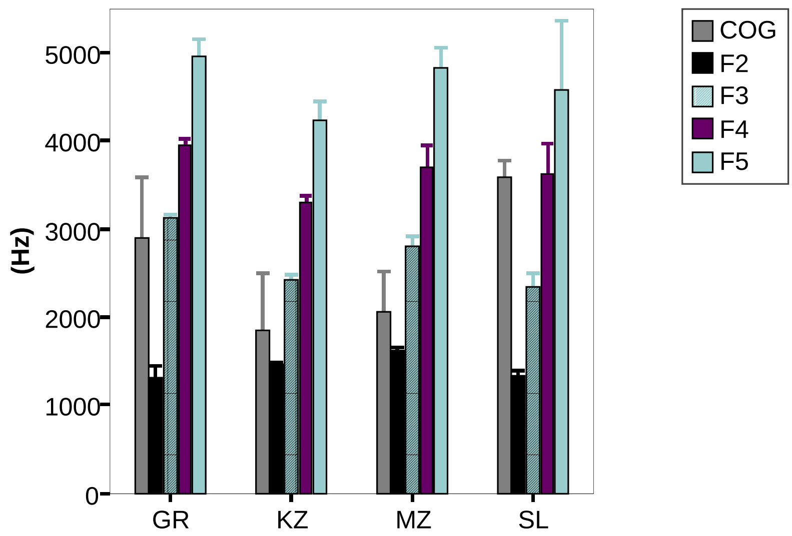



**Figure 22:** The average COG and formant values as obtained for [t͡ʂ] by Polish speakers.

Splitting the results by speaker reveals that the COG values of [t͡ʂ] are lower in comparison to Czech [t͡ʃ] in two cases. In the pronunciation of speakers KZ and MZ the COGs are not higher than the second formant of the following vowel from a statistical point of view (the relation between the COG and F2 is not significant). The COG of [t͡ʂ] in the pronunciation of speaker GR relates to the third formant (no significant effect has been found in this relation). Finally, the pronunciation of [t͡ʂ] by speaker SL shows rather high COG values - as high as the fourth formant.

In summary, the investigation of center of gravity values shows that Czech postalveolar affricates display higher COGs than the corresponding Polish sounds. The results indicate that during the articulation of the Polish sound, the front cavity is larger than in Czech. This is, however, attested for two Polish speakers. The two other speakers show higher COGs which suggests the variability in the size of the front cavity. Czech speakers show less variability and the COG values are higher which is in agreement with the expectations.

**Parameter (v):** spectral peaks of the burst and frication

The final parameter investigated in the present study included the correspondence of the frequency of the highest-amplitude spectral peak at the burst and at the steady-state part of the fricative to the formant frequencies of the following vowel. Implementing such a strategy makes possible a cross-speaker comparison; cf. Stevens (1989), Ohde & Stevens (1983), Hedric & Ohde (1993), Kim (2001).

Stevens (1989) states that in the case of [ʃ], its highest-amplitude spectral peak occurs at about the same frequency as the third formant of the following vowel [a]; see also Hedric & Ohde (1993). The alveolar [s] displays its highest spectral peak at about frequency of the fifth or higher formant of the following vowel [a].

According to Stevens (1989:26) the highest amplitude peak in its relation to the formant of the following vowel reflects the size of the front cavity. In the case of the longer front cavity the highest spectral peak is lower in relation to the following vowel formants. Since the retroflex is expected to have the largest front cavity due to its place of articulation and possible rounding, its highest spectral peak should be the lowest in comparison to the highest spectral peak of [s], [ʃ] or [ɕ].

The same strategy can be applied to affricates, as Kim (2001) suggests. Since an affricate consists of an oral closure and fricative release, and both, as claimed by Stevens (1993), can be manipulated independently, the highest spectral peak can be stated in its relation to the following vowel independently for both parts of the affricate. In experimental practice, this means that the highest spectral peak can be compared to the formants of the following vowel at (i) the release burst of the stop and (ii) the steady-state portion of the fricative. The steady-state portion of a fricative starts at least 20-30 ms after the release of the stop. This has been postulated by Stevens (1993) and adopted by Kim (2001) for the investigation of the Korean affricate [t͡s].

In the following a similar procedure will be applied for the investigation of Polish and Czech stops and affricates. In contrast to parameter (iii), the peaks will be determined for both the burst and frication.

For measurement purposes, the cursor was placed at three different points of the spectrogram of the item investigated: at the burst, i.e. point (3) in Figure 6, at the steady state portion of the frication, i.e. point (4) in Figure 6, and at the steady state portion of the following vowel, i.e. point (6) in Figure 6.

The formant frequencies of the following vowel were obtained in exactly the same way as presented for parameter (iii) above. The peak-picking algorithm objectively identified the frequency peaks of the burst and the frication. Only the frequency of the highest peak was saved.

Figure 23 present the results obtained for Czech. The bars illustrate the averages of the highest burst peaks (PEAK 1), and the highest frication peaks (PEAK 2), as well as the average formant values of the following vowel [a] in its steady state (F2 = the second formant, F3 = the third formant, F4 = the fourth formant, F5 = the fifth formant). The results show the averages for all four Czech speakers.

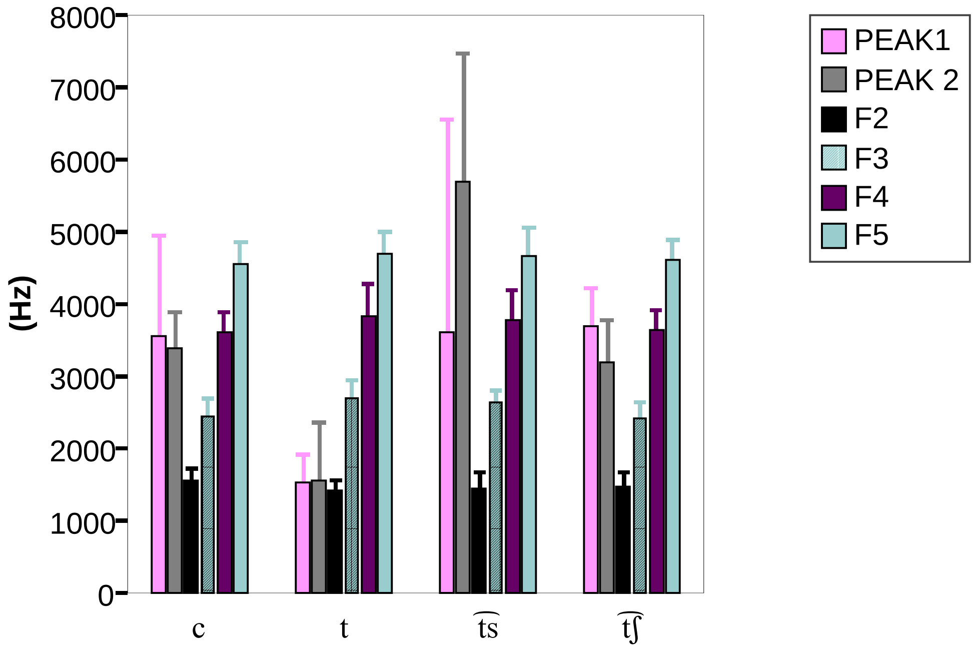



**Figure 23:** The correspondence of the highest peaks of the burst and frication in relation to the formants of the

following consonant for all Czech speakers.

The following discussion will be limited to the postalveolar affricate [t͡ʃ], the main point of interest for the present study. A Scheffé test comparing both peak values (PEAK1 and PEAK2) to four formants of the following vowel reveals that:

(i) PEAK 1 does not significantly differ from F4, whereas it is significantly higher than F2, and F3 and lower than F5 ($p<.001$), $F(5,119) = 157.665$,

(ii) PEAK 2 is placed between the third and the fourth formant. It is significantly higher than F2, F3 ($p<.001$) and lower than F4 ($p<.05$) and F5 ($p<.001$), $F(5,119)=157.665$.

Figure 24 presents the same parameters as obtained by individual Czech speakers.

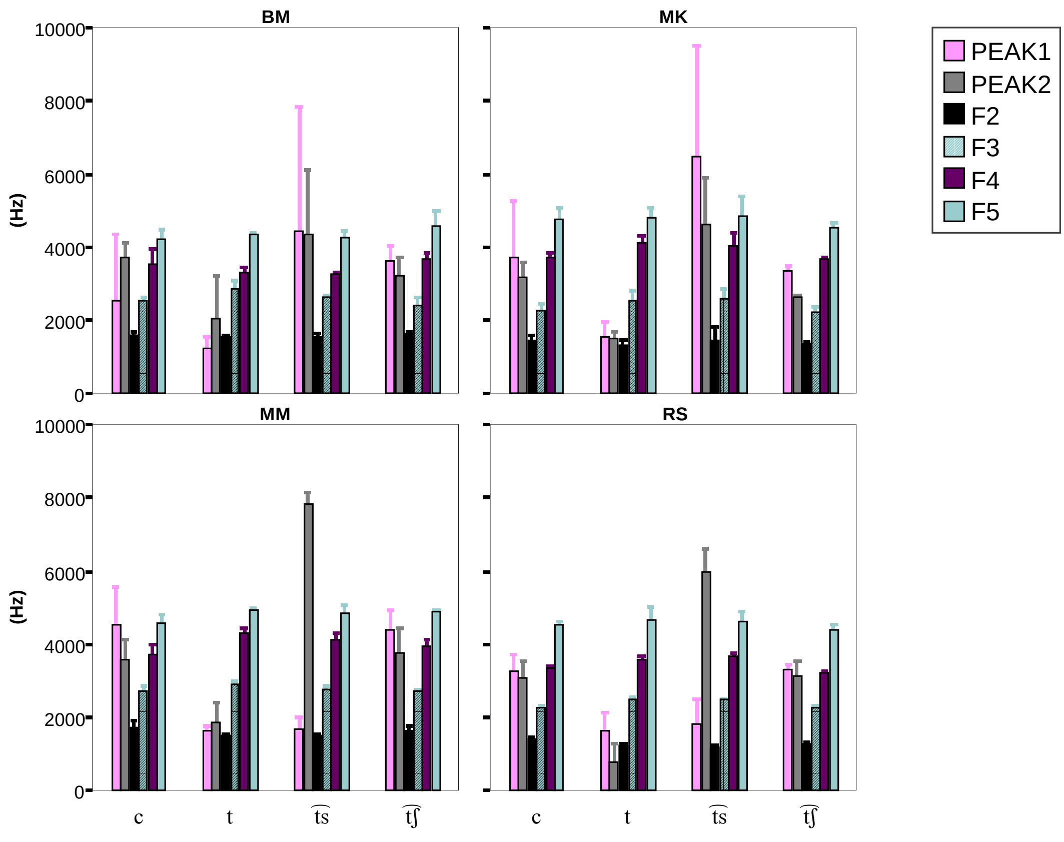



**Figure 24:** The correspondence of the highest peaks of the burst and frication in relation to the formants of the following consonant for all Polish speakers.

As far as the spectral peaks of [t͡ʃ] are concerned, in the pronunciation of three speakers PEAK 1 and PEAK 2 reach almost the same frequency as the fourth formant. In the pronunciation of speaker MM, PEAK 1 does not even significantly differ from F5. Lower peaks are observed in one case only: this is speaker MK whose PEAK 1 and PEAK 2 are higher than F3 but lower than F4. Table 4 shows the statistical details about the relation of the two spectral peaks to the formants of the following vowel.

**Table 4:** Statistical calculations obtained for [t͡ʃ] by Czech speakers.

| | | F2 | F3 | F4 | F5 | PEAK1 |
|---|---|---|---|---|---|---|
| speaker MK | PEAK1 | p<.001 | p<.001 | p<.05 | p< .001 | |
| F(5,29)= 540.759 | PEAK2 | p<.001 | p<.001 | p<.001 | p< .001 | n.s. |
| speaker BM | PEAK1 | p<.001 | p<.001 | n.s. | p.< 01 | |
| F(5,29)=49.342 | PEAK2 | p<.001 | p<.05 | n.s. | p.< 001 | p<.001 |
| speaker MM | PEAK1 | p<.001 | p<.001 | n.s. | n.s. | |
| F(5,29)= 40.072 | PEAK2 | p<.001 | p<.05 | n.s. | p< .01 | n.s. |
| speaker RS | PEAK1 | p<.001 | p<.001 | n.s. | p< .001 | |
| F(5,34)=154.131 | PEAK2 | p<.001 | p<.001 | n.s. | p< .001 | n.s. |

The results obtained for Polish are shown in Figure 25. Again, the following discussion will be limited to [t͡ʂ].

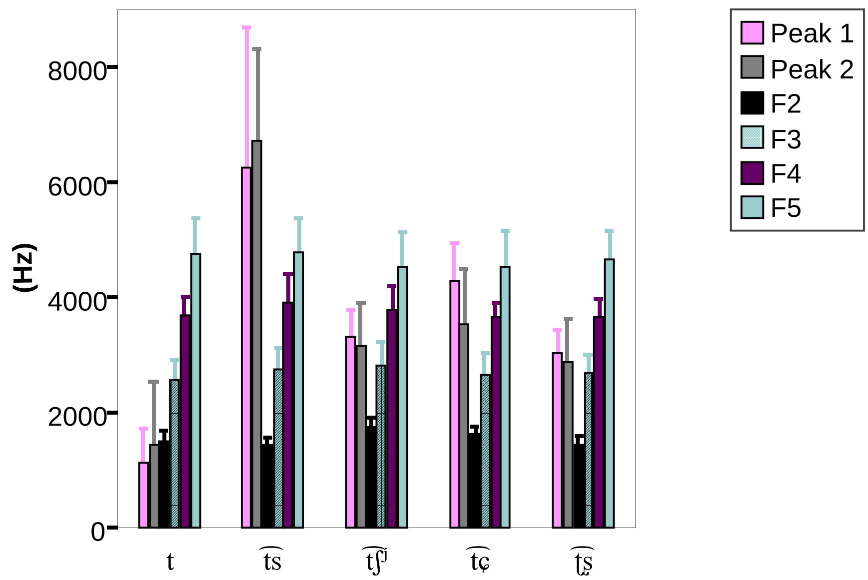



**Figure 25:** The correspondence of the highest peaks of the burst and frication in relation to the formants of the following consonant for all Polish speakers

A post-hoc Scheffé test reveals that the highest spectral peak of the burst (PEAK 1) and the fricative part of the affricate [tʂ] (PEAK 2) are both as high as the third formant, since the differences between PEAK 1 vs. F3 and PEAK 2 vs. F3 are not significant. The two peaks are higher than F2 ($p<.001$ for both PEAKS), lower than F4 (PEAK 1 $p<.01$, PEAK 2 $p<.001$) and lower than F5 ($p<.001$ for both PEAKS, $F(5,119) = 116.149$).

If we split the results by speaker we obtain the relations as presented in Figure 26.

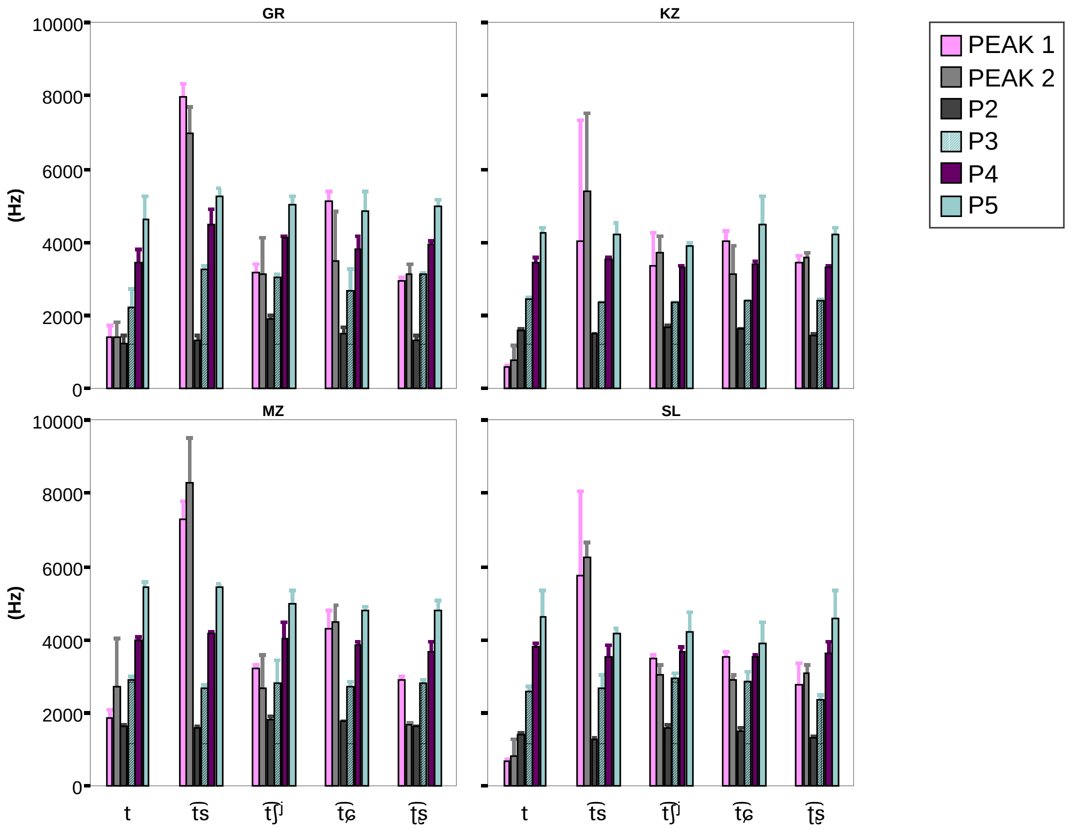



**Figure 26:** The correspondence of the highest peaks of the burst and the frication in relation to the formants of the following consonant for Polish speakers

Splitting the results according to speakers does not lead to similar effects as shown by Figure 25. Although in the pronunciation of three speakers (GR, MZ, SL) PEAK 1 is as high as F3 from a statistical point of view, other effects are attested as well. For example, for speaker SL PEAK1 is not significantly lower than F4. Speaker KZ does not show any significant effects in the relation between PEAK 1 and F4, but in his pronunciation PEAK 2 is even significantly higher than F4. For speaker MZ, on the other hand, PEAK 2 is as low as F2. Table 5 shows a more detailed picture on statistical calculations.

**Table 5:** Statistical calculations obtained for [tʂ] by Polish speakers

| | | F2 | F3 | F4 | F5 | PEAK1 |
|---|---|---|---|---|---|---|
| speaker GR<br>F(5,29)=278.248 | PEAK1<br>PEAK2 | p<.001<br>p<.001 | n.s.<br>n.s. | p<.001<br>p<.001 | p<.001<br>p<.001 | <br>n.s. |
| speaker MZ<br>F(5,29)=308.511 | PEAK1<br>PEAK2 | p<.001<br>n.s. | n.s.<br>p<.001 | p<.001<br>p<.001 | p<.001<br>p<.001 | <br>p<.001 |
| speaker KZ<br>F(5,29)=334.872 | PEAK1<br>PEAK2 | p<.001<br>p<.001 | p<.001<br>p<.001 | n.s.<br>p<.05. | p<.001<br>p<.001 | <br>n.s. |
| speaker SL<br>F(6,34)=32.806 | PEAK1<br>PEAK2 | p<.01<br>p<.001 | n.s.<br>n.s. | n.s.<br>n.s. | p<.001<br>p<.01 | <br>n.s. |

In summary, the investigation of the spectral peaks of the burst and frication phase does not show significant differences between Czech and Polish postalveolar affricates. This suggests a high variability of the front cavity size, an observation partly confirmed by COG measurements.

Finally, the investigations of different acoustic parameters have revealed significant differences between the Czech [tʃ] and the corresponding Polish sound. It has been shown that there is an essential difference between the closure duration and the frication duration. While in the Czech [tʃ], the frication is significantly longer than the closure, the Polish postalveolar affricate [t͡ʂ] shows a reverse pattern: a long closure followed by a short frication. This indicates that the affricate is an apical sound because its release, i.e. the fricative part, lasts for a short time only. In the case of the Czech [tʃ], the fricative part is of considerably longer duration because the tongue blade takes longer to separate from the prepalate. Another parameter, which also shows consistent differences between the affricates under consideration, is that of the F2 of the following vowel, which has a rising shape in the Czech [tʃ] and shows stability in Polish [t͡ʂ].

Another parameter, i.e. the amplitude of the frication phase, appears not to be helpful in determining the places of articulation of sibilants. All Polish consonants show nearly the same amplitude (without significant effects).

An average calculation of center of gravity shows a clear difference between Polish and Czech postalveolar affricates, albeit not confirmed for each speaker individually.

Finally, the correspondence of the highest spectral peaks to the formants of the following vowel show rather a large variability, and only partly confirm the differences between the two affricates. This result does not only indicate a variability of the front cavity size for Czech and Polish but it also independently confirms that the articulatory gestures are not necessarily stable. This point is discussed in Zygis (in progress).

## 6 A DT-Analysis

In the following, the development of the Czech /t͡ʃ/ and the Polish /t͡ʂ/ will be analyzed in terms of Dispersion Theory. Two types of constraints are involved in the present analysis: markedness constraints, and faithfulness constraints. The markedness constraints are grounded in the articulatory and perceptual properties of the sounds under consideration. The faithfulness constraints regulate the relation between the underlying and phonetic representation of the items investigated.

The faithfulness constraints insure a faithful parsing of features of underlying representation to the phonetic surface. For the present analysis, it is assumed that the faithfulness constraints evaluate the post-lexical mapping; see Kiparsky (1988), Padgett & Zygis (2003).

A constraint which is involved in the present analysis is $\text{IDENT}_{\text{sibilant}}$ presented in (13).

(13) $\text{IDENT}_{\text{sibilant}}$ : Sibilant features agree on the lexical and post-lexical level.

The articulatory markedness constraints follow from the scale presented in (14). This scale shows that the secondarily palatalized [t͡ʃʲ], the retroflex [t͡ʂ] and the alveolopalatal [t͡ɕ] are articulatorily more complex than the palatoalveolar [t͡ʃ]; see also Padgett & Zygis (2003) for a fricative scale. I do not attempt to rank [t͡ʃʲ],[t͡ʂ], and [t͡ɕ] with respect to each other because in my view there is not enough detailed information available about the differences in the articulatory complexity of these sounds.

(14) Articulatory complexity scale: t͡ʃʲ, t͡ʂ, t͡ɕ > t͡ʃ

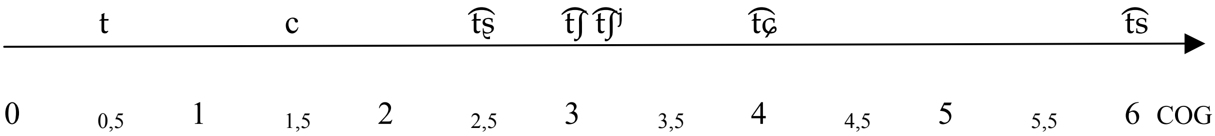
According to the scale in (14), there is a markedness ranking implying that [t͡ʃʲ, t͡ʂ ,t͡ɕ] are more marked than [t͡ʃ]. The ranking of the markedness constraints is presented in (15).

(15) *ART complexity [t͡ʃʲ, t͡ʂ ,t͡ɕ] < *ART complexity [t͡ʃ]

Besides the articulatorily based constraints, there are perceptually grounded constraints which play an important role in the analysis of sibilant systems. These constraints are based on different acoustic parameters. The present analysis will be limited to one acoustic parameter, namely the center of gravity (COG). I assume that in a complete perceptual analysis which expresses ‘hardness’ (low sibilant tonality) or ‘softness’ (high sibilant tonality) of the sounds, other parameters also have to be considered. Since the aim of the present analysis is to show a basic mechanism of phoneme change due to perceptual distinctiveness, I will focus on COG, see Zygis (2003b, 2005) for a more detailed discussion on this issue. In Padgett & Zygis (2005), the results of a perceptual experiment concerning the sibilant fricatives are presented and discussed.

The COG constraints are based on the COG scale as displayed in (16). The values assigned to each phonetic symbol approximately correspond to the averaged COGs obtained experimentally.

(16) COG scale




The constraints which regulate the distance between the sibilants are called Minimal Distance constraints, as introduced by Flemming (1995). Their aim is to maximize the auditory distinctiveness the sounds. The constraints are displayed in the format ‘Dimension:distance’ which indicates the distance between the segments along a given dimension. For example, if we took into consideration the scale in (16), then ‘MINDIST=COG:1’ would require a distance of 1 between the given stops on the COG dimension. This constraint is satisfied by, e.g., [t͡ʃ] vs. [t͡ɕ], [t͡ʂ] vs. [t͡ɕ] and others. At the same time, it is violated by, e.g., [t͡ʃʲ] vs. [t͡ʂ] or [t͡ʃ] vs. [t͡ʃʲ]. Other Minimal Distance constraints, e.g. ‘MINDIST=COG:2’ or ‘MINDIST=COG:3’ require a distance of 2 or 3, respectively.

In the following, it will be shown how the interaction of ‘markedness’ and ‘faithfulness’ constraints leads to the selection of the optimal candidates. The present analysis is limited to Polish and Czech.

The tableau in (17) presents the Proto-Slavic sibilant affricate inventory after the 1st Velar Palatalisation. It should be noted that the presentation order of the sibilants is crucial. $\text{IDENT}_{\text{sibilant}}$ evaluates the relation between input segments and the corresponding output segments displayed under the input (in the same column).

(17)

| t͡s t͡ʃʲ | IDENT$_{sibilant}$ | MINDIST=COG:1 |
|---|---|---|
| t͡s t͡ɕ | *! | |
| t͡s t͡ʃ | *! | |
| t͡s t͡ʂ | *! | |
| ☞ t͡s t͡ʃʲ | | |

Although none of the candidates listed in (17) violates MINDIST=COG:1, the pair [t͡s] vs.[t͡ʃʲ] is selected as optimal, as it satisfies the high-ranking IDENT$_{sibilant}$.

The optimal inventory /t͡s t͡ʃʲ/ existed in Polish until approximately the 13$^{th}$ century when the alveolopalatal [t͡ɕ] emerging from the palatalised stop [tʲ] entered the sibilant inventory (see 4. for details). The situation is illustrated by the tableau in (18).

(18)

| t͡s t͡ɕ t͡ʃʲ | IDENT$_{sibilant}$ | MINDIST=COG:1 |
|---|---|---|
| t͡s t͡ɕ t͡ʃ | *! | * |
| ☞ t͡s t͡ɕ t͡ʃʲ | | * |
| t͡s t͡ɕ t͡ʂ | *! | |
| t͡s t͡ɕ t͡ɕ | *! | * |
| t͡s t͡ʃʲ t͡ʃ | *!* | * |
| t͡s t͡ʃʲ t͡ʃʲ | *! | * |
| t͡s t͡ʃʲ t͡ʂ | *!* | * |

The optimal candidate /t͡s t͡ɕ t͡ʃʲ/ is the only one which does not violate the high-ranking IDENT$_{sibilant}$. It does violate MINDIST=COG:1 due to the perceptual distance between /t͡ɕ/ vs. /t͡ʃʲ/ which amounts to 0.5 on the COG scale. This inventory existed in Polish from the 13$^{th}$ until the 16$^{th}$ century. In the 16$^{th}$ century, /t͡ʃʲ/ changed to [t͡ʂ]. I conclude that this change was motivated perceptually since the perceptual distance between /t͡ʃʲ/ and /t͡ɕ/ was not optimal.

In terms of a constraint ranking, the highest postion of IDENT$_{sibilant}$ was taken by MINDIST=COG:1,5. This situation is illustrated by the tableau in (19) where all possible candidates are listed. The only sibilant which does not change in (19) is [t͡s]. I assume that [t͡s] had to be stable for at least two reasons. Firstly, its COG is the highest from all sibilants, and the only possibility of changing [t͡s] is having lower COGs and thus being closer to other sibilants. Secondly, the properties of the [t͡s] frication are perceptually prominent and [t͡s] creates optimal distance from other sibilants. For these reasons I assume that the stability of [t͡s] is assured by the high-ranking IDENT [t͡s] which I will not list in the following tables for reasons of simplification.

(19)

| t͡s t͡ɕ t͡ʃʲ | MINDIST = COG:1 | IDENT$_{sibilant}$ |
|---|---|---|
| t͡s t͡ɕ t͡ʃ | *! | * |
| t͡s t͡ɕ t͡ʃʲ | *! | |
| ☞ t͡s t͡ɕ t͡ʂ | | * |
| t͡s t͡ɕ t͡ɕ | *! | * |
| t͡s t͡ʃʲ t͡ʃ | *! | ** |
| t͡s t͡ʃʲ t͡ʃʲ | *! | * |
| t͡s t͡ʃʲ t͡ʂ | *! | ** |
| t͡s t͡ʃʲ t͡ɕ | | ** |
| t͡s t͡ʂ t͡ʃ | *! | ** |
| t͡s t͡ʂ t͡ʃʲ | *! | * |
| t͡s t͡ʂ t͡ʂ | *! | ** |
| t͡s t͡ʂ t͡ɕ | | **! |
| t͡s t͡ʃ t͡ʃ | *! | ** |
| t͡s t͡ʃ t͡ʃʲ | *! | * |
| t͡s t͡ʃ t͡ʂ | *! | ** |
| t͡s t͡ʃ t͡ɕ | | **! |

In the tableau in (19) only two candidates do not violate the high-ranking MINDIST= COG:1,5, namely, /t͡s t͡ɕ t͡ʂ/ and /t͡s t͡ʂ t͡ɕ/, which are actually the same. However, the latter inventory violates IDENT$_{sibilant}$ twice, whereas the former violates it ones, thereby being selected as the optimal candidate. This is because in the first inventory, one change took place from /t͡ʃʲ/ to [t͡ʂ]. It seems that the selected inventory is stable as it still persists in present-day Polish.

As far as Czech is concerned, the Proto-Slavic ancestor of the present Czech sibilant systems was the pair /t͡s, t͡ʃʲ/, see tableau (17). Such a situation lasted till the 14th century when the palatalised stop /tʲ/ changed to the palatal [c] and the latter was finally phonemised. This is displayed by the tableau (20).

(20)

| | t͡s t͡ʃʲ c | IDENT$_{sibilant}$ | MINDIST=COG:1 |
|---|---|---|---|
| | t͡s t͡ʃʲ t͡ʃ | *! | * |
| ☞ | t͡s t͡ʃʲ c | | |
| | t͡s t͡ʃʲ t͡ʂ | *! | * |
| | t͡s t͡ʃʲ t͡ɕ | *! | * |
| | t͡s t͡ʃ t͡ʃ | *!* | * |
| | t͡s t͡ʃ t͡ʃʲ | *!* | * |
| | t͡s t͡ʃ t͡ʂ | *!* | * |
| | t͡s t͡ʃ c | *! | |

The optimal candidate /t͡s t͡ʃʲ c/ violates neither IDENT$_{sibilant}$ nor MINDIST=COG:1. Note that the distance between /t͡s/ and /t͡ʃʲ/ amounts to 3 on the COG scale and the distance between /t͡ʃʲ/ and /c/ is 1.5. Hence, the systems seem to be relatively stable as far as the perceptual relations are concerned. Indeed, the only difference which took place was the depalatalisation of /t͡ʃʲ/ to /t͡ʃ/. I assume that this change was primarily motivated by the articulatorily complexity of the secondarily palatalised /t͡ʃʲ/, banned by the constraint in (15). This is illustrated by the tableau in (21).

(21)

| t͡s t͡ʃʲ c | *ART [t͡ʃʲ, t͡ʂ ,t͡ɕ] | MINDIST=COG1 | IDENT |
|---|---|---|---|
| t͡s t͡ʃʲ t͡ʃ | *! | * | *! |
| ☞ t͡s t͡ʃʲ c | *! | | |
| t͡s t͡ʃʲ t͡ʂ | *!* | * | *! |
| t͡s t͡ʃʲ t͡ɕ | *!* | * | *! |
| t͡s t͡ʃ t͡ʃ | | *! | *!* |
| t͡s t͡ʃ t͡ʃʲ | *! | * | *!* |
| t͡s t͡ʃ t͡ʂ | *! | * | *!* |
| t͡s t͡ʃ c | | | *! |

Two candidates /t͡s t͡ʃ t͡ʃ/ and /t͡s t͡ʃ c/ do not violate the high-ranking *ART [t͡ʃʲ, t͡ʂ ,t͡ɕ] but only the latter is selected as optimal. This is due to the next constraint MINDIST=COG1,5 which is violated by two identical segments /t͡ʃ t͡ʃ/ in the former inventory. These segments show, in fact, a merge of /t͡ʃʲ/ and /c/ into [t͡ʃ] which would be an unexpected change.

In summary, the analysis proposed above shows that the changes in Polish and Czech affricate systems are not accidental. They can be seen to be clearly motivated by perceptual relations among the affricates. In addition, the analysis shows that articulatory complexity also plays a role in creating sibilant systems.

## 7 Conclusions

Slavic sibilant inventories underlie the principle in (22).

(22) Slavic sibilant systems:

> In complex sibilant systems which include more than one postalveolar affricate or a strongly affricated /tʲ/, one of the affricate has a low sibilant tonality.

Special attention was paid to two selected Slavic languages, Polish and Czech, which display considerable differences in their coronal inventories. A diachronic study of the two inventories has contributed to the understanding of the role of perceptual relations for shaping the affricate systems in Czech and Polish. The

Protoslavic secondarily palatalized /t͡ʃʲ/ converted to /t͡ʃ/ in Czech, and to the retroflex /t͡ʂ/ in Polish. This discrepancy has been argued to have had a fundamental effect on the asymmetrical development of the Protoslavic /tʲ/; in Czech /tʲ/ had developed into the palatal stop /c/, and in Polish /tʲ/ had converted to an alveolo-palatal affricate /t͡ɕ/ as /t͡ʃʲ/ converted to /t͡ʂ/.

In the experimental part of the study it has been shown that the perceptual relations expressed in terms of acoustic parameters were of particular importance for the development of sibilant affricates in these two languages. The results have revealed a clear difference between the Czech and Polish affricate which is often assumed to be the same palatoalveolar affricate /t͡ʃ/ in both languages. Whereas the Czech affricate is indeed a palatoalveolar /t͡ʃ/, the Polish postalveolar affricate can be classified as a retroflex /t͡ʂ/. It has been also shown that stops such as /tʲ/ and /c/ do not have a direct perceptual impact on the affricate inventories, despite forming a natural class with them.

Finally, an analysis of Polish and Czech sibilant systems has been offered in the framework of Dispersion Theory.

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