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Sonority effects in the production of *fricative* + *sonorant* clusters in polish

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This paper presents the results of a phonetic study on the occurrence of transition elements in Polish *fricative* + *nasal* clusters. An acoustic study was carried out using the CSL system, with simultaneous observation of the waveform, spectrograph, glottal waveform and glottal pulses. The results reveal differences in glottal activity depending on place of articulation of the fricative and in its duration with respect to the extent of glottal vibration. Differences in the glottal activity pattern and the transition elements between the fricative and the nasal were also observed. In the fricative-nasal limit three phenomena were found: a voiceless interval, a voiced interval and the absence of any transition element. It was also observed that the occurrence and the characteristics of the transition interval depend on the place of articulation of the fricative.

Keywords: Polish phonetics, consonant clusters, fricatives, nasals

1. Introduction

This paper is part of a broader project whose aim is to provide an acoustic analysis of voicing in Polish consonant clusters. The objective of the general project is twofold: on the one hand, to contribute to the understanding of voicing in consonant clusters from the view of general phonetics, and on the other hand, to provide data for the phonetic description and phonological analysis of the Polish language. More specifically, it will provide empirical data on glottal activity and other relevant parameters in sonority, which may be important for explaining voice distribution and sonorant transparency effects in complex consonant clusters, as has been suggested in Castellví & Szmidt (2002) and Castellví (2003).

The study of fricatives has not had as much attention as that of, for example, occlusives. As regards sonority, occlusives have been thoroughly analysed since the seminal work of Lisker & Abramson (1964) and the establishment of the VOT parameter. In the case of the sonority of fricatives, there are few studies on the coordination between glottal and supraglottal activity.

This article is organized as follows: in section 2, fricatives and nasals are described in terms of their glottal and supraglottal articulation; in section 3, to the extent that they are relevant to our goals, other contributions to the study of fricatives and nasals are presented; and in section 4 the methodology and procedures of our study are provided. Finally, in section 5 our results are reported; and in section 6 a number of conclusions are drawn.

2. The study of sonority: articulatory realization and acoustic correlates

One of the most important aspects in the study of sonority is the analysis of the coordination between glottal and supraglottal articulations. Despite the existence of anatomic interactions between both areas, glottal gestures are independent from supraglottal gestures to an important extent. The main physical constraint on their coordination relies on the fact that sonority can stand only as long as the drop in transglottal pressure is enough to allow it.

Our analysis focuses on clusters with labiodental or dental fricatives before a nasal. Before discussing previous studies on the sonority of Polish fricative + nasal clusters, we will recall the most important facts related to glottal and supraglottal articulations in the production of fricatives and nasals.

2.1. Fricative consonants

Fricative consonants are produced by forcing air through a narrow constriction along the vocal supralaryngeal tract. In the case of voiceless fricatives, the only relevant constriction is the oral one, so that there is a main drop in pressure in the constriction and a minor drop in the glottis. The airflow through the supraglottal becomes a turbulence and generates noise. Vocal folds are open enough and the drop in pressure in the larynx is small enough to ensure that there is no glottal vibration during the realization of the oral constriction. In the production of voiced fricatives, both glottal and supraglottal articulators must form similar constriction areas in order to produce at the same time the vibration of the vocal folds in the larynx and friction noise in the supralaryngeal tract. A relatively small increase in the area of one of these constrictions would entail a significant fall of pressure and, as a consequence, a decrease in the amplitude of the source sound.[1]

2.2. Nasals

Nasals are consonants that are produced by blocking the airflow in the oral tract and, at the same time, by lowering the velum. The air stream expelled by the lungs passes exclusively through the nasal cavity, while the oral cavity still acts as a resonator. Nasals are similar to stops because of the occlusion in the oral tract, and also to approximants, because the air stream is not interrupted despite the fact that it does not pass through a constriction narrow enough to produce a local turbulence. In Polish, as in most languages, nasals are voiced. They present glottal vibration over their entire realization, except for cases of partial

[1] See Stevens 1997 for a more complete explanation.

or total devoicing in complex consonant clusters (Castellví & Szmidt 2002; Castellví 2003). The amplitude of nasals is slightly smaller than that of vowels as a consequence of the addition of the nasal resonance, which is due to the anti-resonances or spectral zero produced in the velo-pharyngeal area, which absorbs energy, especially at higher frequencies (Ladefoged & Maddieson 1996:116, among others). The frequency of this spectral zero is inversely related to the volume of the cavity formed by the tongue and the velo-pharyngeal port. A more forward articulation of the tongue or a lower position of the tongue body will produce larger cavity volumes, and more retracted articulations or a higher position of the tongue body will result in a smaller cavity. As a consequence of this, the frequency of the first nasal resonance and the oral zero are both higher the nearer the oral articulation is to the uvular region.

3. Previous research into *fricative* + *nasal* groups

As mentioned above, voicing in fricatives has been much less often investigated than voicing in stops. The main studies on the sonority of fricatives are Stevens et al. (1992) and Docherty (1992) for English; Löfqvist & McGarr (1987) and McGarr & Löfqvist (1988) for Swedish and Icelandic; Hutters (1984) and Slis (1986) for Danish; Burton & Robblee (1997) for Russian; Snoeren & Segui (2003) for French; and finally Kleśta (1999) for Polish.

In this section we will review the contributions of Docherty (1992), Barry & Kunzel (1978), and Kleśta (1999), in their studies concerning *fricative + nasal* consonant clusters.

In Standard British English (SBE), in /s/ + /m/, /n/ sequences, Docherty (1992) observes an interval during which there is no periodicity or high frequency noise as that observed in the preceding fricative. The mean duration of this voiceless transition[2], which occurs in every realization, varies depending on the informant. Statistical analysis shows that neither the nasal nor the context before the fricative has a significant effect on the transition length. This interval that appears from the acoustic point of view to be a delay in voice onset following /s/ in /s/+nasal sequences, in articulatory terms is interpreted by the author as a result of the lengthening of the interval during which the vocal folds are not vibrating in conjunction with some compression of the supralaryngeal gesture corresponding to the fricative, due to the complex articulatory transition from /s/ to the nasal (Docherty 1992: 150).

Barry & Künzel (1978) present six possible articulatory transitions from /s/ to a nasal:

A. voiceless fricative → voiceless nasalized fricative → voiced nasalized fricative → nasal
B. voiceless fricative → voiced fricative → voiced nasalized fricative → nasal
C. voiceless fricative → voiceless nasalized fricative → voiceless nasal → nasal
D. voiceless fricative → voiced fricative → voiced occlusive → nasal
E. voiceless fricative → voiceless occlusive → voiceless nasal → nasal
F. voiceless fricative → voiceless occlusive → voiced occlusive → nasal

Barry & Künzel consider that English speakers tend to perform type C, while other languages may present other tendencies. Canellada & Madsen (1987) observe that in Spanish, speakers tend to perform type A o B.

[2] What Docherty calls "VOT", the same term as for occlusives (Docherty 1992: 149).

Given the variability of patterns in the transition from /s/ to *nasal* depending on the language, Docherty (1992) claims that experimental data show that the phonetic realization of the sequences */s /+ nasal* in SBE responds to rules, that is, it is *rule-governed*. Docherty draws similar conclusions for the lateral /l/ in the sequences (/s/, /f/, /Θ/ + /l/). He also observes that the duration of the friction noise in these sequences is longer than before a vowel, although it is well attested in the literature (Haggard 1978; Klatt 1973, among others) that consonant durations are reduced when they occur in clusters. This may be due to the fact that the noise portion that has been measured consists of two components: noise corresponding to the fricative and noise corresponding to a delay in voice onset at the start of the sonorant. Docherty claims that this delay is due to the articulatory complexity of the transition from the voiceless fricative to the sonorant. The fricative requires velic closure, glottal abduction, high intra-oral air pressure and a finely balanced stricture between the tongue and the alveolar ridge. The nasal, however, requires changes at each of these levels: velic opening, glottal vibration and complete closure in the oral tract.

In a different approach, Kleśta (1999) shows that in Polish fricative + sonorant sequences there are a number of transition elements, such as a burst in the fricative [ɕ] before the lateral and the presence of a zero element between the fricative [ɕ] and the nasal [ɲ].

4. Methodology

4.1. Materials and procedure

The analysed corpus contains 21 words with the fricative + nasal sequence inserted in a carrier sentence. The fricatives included in our study were the labiodentals /f/, /v/ and the dental sibilants /s/, /z/. The nasals were /m/, /n/. In order to be consistent during the analysis, the corpus is limited to word-internal positions, since voiceless labiodental fricative + nasal do not occur word-initially in Polish. The studied consonant clusters are also consistent in terms of their place of articulation. In the case of the labiodentals, the sequence /vm/ was excluded since the corresponding voiceless sequence /fm/ does not exist in Polish, and consequently only /fn/ and /vn/ were compared.

The right context of the consonant cluster is a non-high vowel /e/, /a/, /o/. A vowel height restriction was introduced to avoid possible influences on sonority, since, despite the lack of conclusive studies on the influence of vowel height on the preceding fricative, there are studies that do show this influence for occlusives. In early studies dealing with this question no significant effects of vowels on the VOT of the preceding occlusive were found (Lisker & Abramson 1967), but in later studies (Klatt 1975; Ohala 1981; Summerfield 1975) differences were found between high and low vowels in English. Klatt (1975) shows that the VOT of /p/, /t/, /k/ is 15% longer before high vowels than before /a/ and /ɛ/.[3]

The left context of the consonant cluster is any of the six Polish vowels. Following (Stevens et al. 1992: 2979)[4] we assume that in word-internal position the preceding vowel

[3] Klatt (1975: 691) points out the possibility that Lisker and Abramson's data may not be appropriate to check the effect of vocal height on VOT.

[4] "the duration of a vowel up to the time of frication onset tends to be shorter when the vowel is followed by a voiceless fricative then by a voiced fricative, when the consonant is in prepausal position. The duration of a vowel is negligible when the fricative is in nonprepausal position" (Stevens et al. 1992: 2979).

has no influence on the length of the fricative, which is a cue for voicing. We examine the preaccentual (stressed syllable) and non-preaccentual (pretonic) positions. Syllabic position was not included as a parameter in our study, since the syllabification of Polish consonant clusters is an unresolved issue (Sawicka 1995).

4.2. Recordings

Recordings were carried out at the Phonetics Laboratory at the University of Barcelona by means of a Kay Elemetrics 6103 electroglottograph attached to a CSL Kay Elemetrics 4300B. The corpus was read by four female speakers: AB, KG, KC and KL. They were all Erasmus programme students from Adam Mickiewicz University, Poznań, who had recently arrived in Barcelona.

The whole corpus consists of 252 sentences, which were read at a comfortable rate, in series of six tokens, which corresponds to a 20-second CLS capture frame. Sentences were recorded by means of a microphone and electromagnetic transducers placed on the speaker's neck at the level of the thyroid cartilage. Informants were asked to pronounce the sentences with a declarative intonation.

4.3. Measurements

The electroglottograph attached to the oscillograph and spectrograph allows us to measure simultaneously both glottal and oral activities. Waveform, spectrogram glottal pulses, intensity of glottal vibrations and time are provided synchronically. This allows us to work with a very complete set of synchronic information. In previous studies on the sonority of consonant clusters this combination of measurements has not been used: Stevens et al. (1992) and Burton & Robblee (1997) used spectral analysis only, Docherty (1992) used a glottal microphone attached to the oscillograph, and Cuartero (2001) worked with an electropalatograph attached to an oscillograph and a glottograph. The present set of measurements is especially useful to detect transition elements (see 5.1 below) between the fricative and the nasal. These transition elements are not noticeable in the oscillogram and, although they can be detected in the spectrogram, it is not possible to establish correspondence with glottal activity.

Regarding segmentation, we believe that the fricative begins when the regular vibrations on the waveform of the preceding vowel end, which can coincide with the end of the formant spectrum, and usually overlaps with high-frequency friction noise. We measure the duration of the fricative to determine the glottal pattern from this point, where the formant structure ends and the stable phase of the fricative begins. As for the nasal, the left boundary is set at the beginning of the low frequencies in its spectrum. The end of the nasal is clearly identified by the next vowel's formant structure in all its frequencies.

4.4. Analytic procedure

The corpus was analysed in two stages: data collection through instrumental analysis, and statistical analysis of those data.

In the instrumental analysis we have, on the one hand, data about the consonant quantity (absolute values concerning the duration of the fricative, the nasal and the transition event, in ms); and, on the other, data on the glottal activity patterns (relative values concerning the duration and amplitude of the glottal vibration). Four glottal activity patterns were observed:

1 – Absence of glottal vibration over the entire segment;
2 – Continuous glottal vibrations over the entire segment;
3 – Glottal vibrations over the first half of the segment;
4 – Absence of vibration in the central part of the segment.

The data obtained in the instrumental analysis (segment duration and glottal activity patterns) have been analysed taking into account possible variability factors, such as:

– The fricative place of articulation: labiodental, dental;
– The fricative underlying voice specification: /-voice/, /+voice/;
– The relative position with respect to the stressed syllable: tonic, non-tonic;
– The fricative and the nasal glottal activity pattern (see above);
– The nature of the transition event found in the boundary between the fricative and the nasal: a voiceless interval, a voiced interval, the lack of an interval.

The fricative, the nasal and the transition event are numerical variables. The glottal activity pattern in the fricative and the nasal, as well as variability factors, are analysed as categorical variables.

The data were analysed by means of contingency tables, which provide information about the frequency distribution, and Pearson's chi-square, which determines the degree of dependence between variables. In addition, T-tests and univariate analysis of variance (UNIANOVA) were used to compare numeric and categorical variables.

5. Results

5.1. The structure of *fricative* + *nasal* clusters: transition events

Three types of transition events were observed in the boundary between the fricative and the nasal:

– presence of a voiceless interval,
– presence of a voiced interval,
– absence of any interval in the transition between the fricative and the nasal.

Contingency tables show different tendencies for sequences with the labiodental and sequences with the dental fricative. 51.3% of sequences with the labiodental have a transition element as compared to 79.4% of sequences with the dental. With the labiodental fricative the interval is voiceless in 32% of cases, while for the dental in 50.6% of cases. The frequency of occurrence of the voiced interval is similar in both types of sequence: 18.3% for the dental and 17.1% for the labiodental. Consequently, with the labiodental the transition event is predominantly the absence of any kind of interval, while for the dental, the most common event is a voiceless interval. In Figure 1 the distribution of the transition event frequencies is shown: the absence of transition elements, the voiceless interval and the voiced interval, for the labiodental and the dental fricatives.

The relationship between fricative duration and nasal duration and the type of transition event is presented in section 5.3.

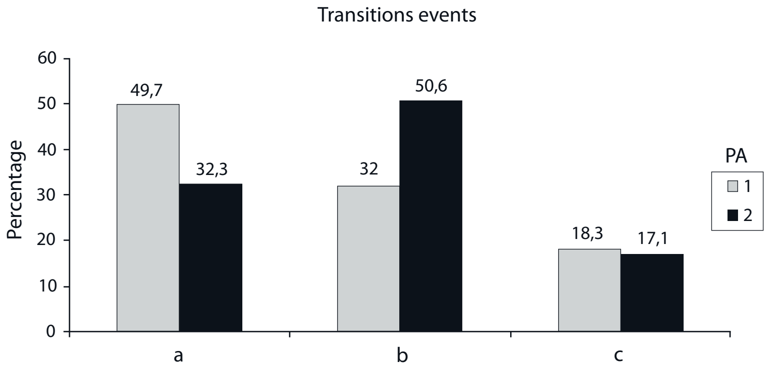

Figure 1: Fricative + nasal. Distribution of occurrence frequencies of transition events (in %):

a – absence of transition elements; b – voiceless interval; c – voiced interval. Consonant clusters: PA1 (labiodental + nasal), PA2 (dental + nasal)

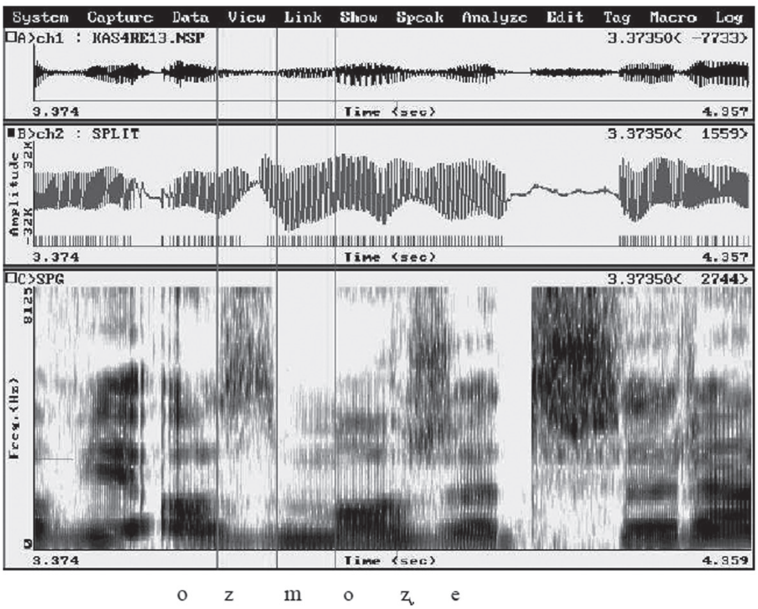

Figure 2: Oscillogram, electroglottogram and spectrogram of the sequence "o zmorze", with the absence of transition elements between the fricative (in this case pattern 4) and the nasal. Speaker KL

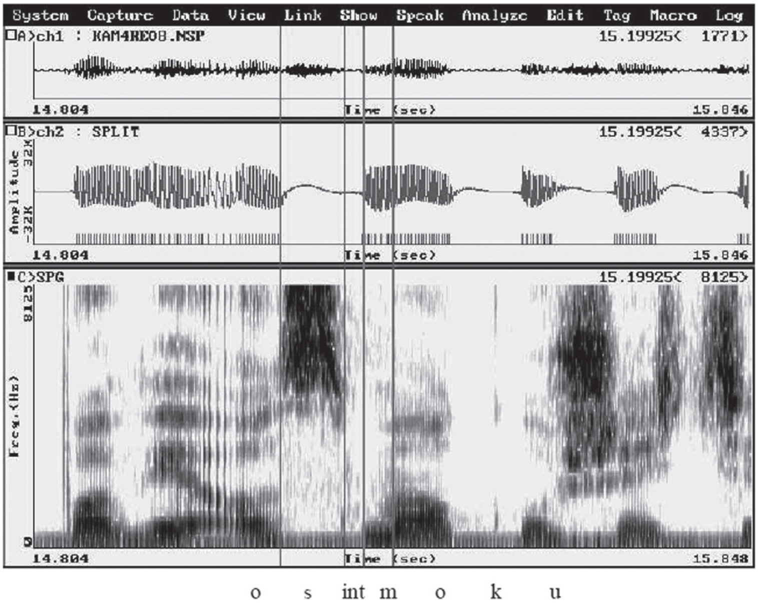

Figure 3: Oscillogram, electroglottogram and spectrogram of the sequence "o smoku", with a voiceless interval between the fricative (in this case, pattern 1) and the nasal. Speaker KG

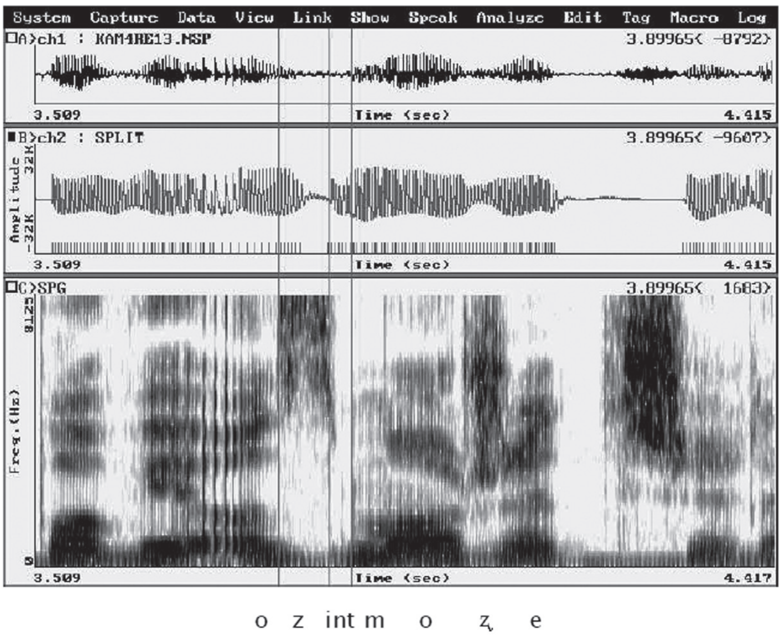

Figure 4: Oscillogram, electroglottogram and spectrogram of the sequence "o zmorze", with a voiced interval between the fricative (in this case, pattern 3) and the nasal. Speaker KG

5.2. Glottal realization of the fricative, the transition event and the nasal

Contingency tables show that /-voice/ fricatives are realised mainly with pattern 1 (100% of cases with the labiodental and 94.3% of cases with the dental). The relationship (Pearson's chi-square test) between glottal activity patterns and the underlying voice specification is not significant for /-voice/ fricatives, but it is for /+voice/ fricatives (Table 1). As regards air glottal inertia from the preceding vowel to the stable phase of the fricative, there are cases where weak vibrations in the glottal activity are observed, but in no case exceeding 10 ms, regardless of the place of articulation of the fricative.

Table 1: Fricative + nasal. Pearson's Chi-square $p < 0.05$): Glottal activity pattern of the fricative (F. pattern) – Place of articulation of the fricative (F. PA)

	F. pattern – F. PA
/-voice/	0.343
/+voice/	0.001

The glottal activity pattern of the nasal is stable in both groups: 97.2% of cases with glottal vibration over the entire segment for the labiodental and 94.2% for the dental. In all other cases (just 3.25% of the total) it corresponds to devoicing of the nasal (absence of glottal vibration over the entire segment, in this case, over the entire cluster), which only happens when the fricative is realized as voiceless.

As for the interval, when considering /-voice/ and /+voice/ fricatives separately, in the case of /-voice/ fricatives no differences are observed between the labiodental and the dental group (88.9% of cases with a voiceless interval in labiodental + nasal clusters and 88.6% for dental + nasal sequences). Rather, in clusters with a /+voice/ fricative, the labiodental /+voice/ lacks any kind of interval in 69.4% of cases as compared with 37.7% in clusters with the dental (Table 2). For this reason, further analysis in our study will be restricted to /+voice/ fricatives.

Table 2: /+voice/ fricative + nasal. Distribution of transition events among labiodental + nasal and dental fricative + nasal sequences (in %)

	labiodental	dental
Absence of transition elements	69.4	37.7
Voiceless interval	11.1	33.3
Voiced interval	19.4	29.0

5.2.1. /+voice/ Fricatives

The results of Pearson's chi-square test show that the dependence between glottal activity patterns of the fricative and its position with respect to the accent is not significant in clusters either with a labiodental fricative or with a dental fricative (Table 3).

Table 3: Fricative /+voice/ + nasal. Relation (Pearson's chi-square): Fricative glottal pattern – Position with respect to the accent

	labiodental	dental
Position with respect to the accent	0.1	0.394

In the following section, results on glottal activity patterns in labiodental and dental fricatives + nasal will be presented separately.

5.2.1.1. Glottal realization in sequences with the /+voice/ labiodental

Here, 84.5% of instances exhibit vibrations over the entire duration of the segment (pattern 2); pattern 3, glottal vibrations over the first half of the segment, is observed in 12.0% of cases; and pattern 4, absence of glottal vibrations in the central part of the segment, occurs in 1.4% of cases. In 0.7% of cases the labiodental is realized without glottal vibrations over the entire segment. In all instances the nasal is pronounced fully voiced, except for those where the fricative is completely devoiced, which also entails the devoicing of the nasal.

Figure 5 shows the distribution of the glottal activity patterns of the labiodental fricatives.

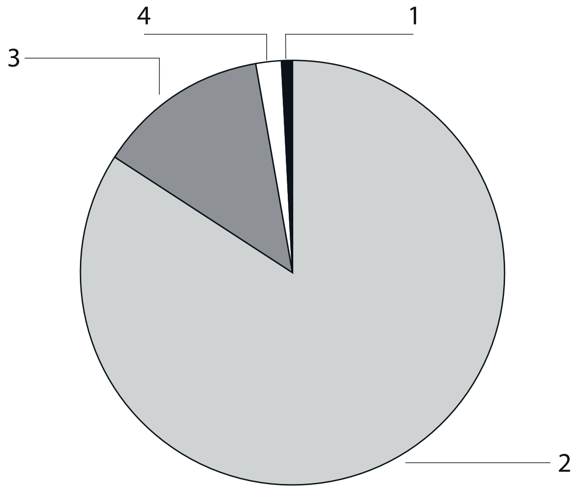

Figure 5: /+voice/ fricative labiodental + nasal. Glottal activity pattern distribution in the labiodental

1 – absence of glottal vibrations over the entire segment; 2 – continuous glottal vibrations over the entire segment; 3 – glottal vibrations over the first half of the segment; 4 – absence of vibration in the central part of the segment

5.2.1.2. Glottal realization in sequences with the /+voice/ dental

In clusters with the dental fricative, 55.9% of cases exhibit glottal vibration over the entire segment (pattern 2); 29.4%, correspond to the loss of vibrations in the second half of the segment (pattern 3); in 5.9% of instances, the absence of vibrations in the central part of the segment is observed (pattern 4); and, finally, in 8.8%, the fricative is realized fully devoiced (pattern 1). As with the labiodental, the nasal devoices together with the dental fricative (with pattern 1). Figure 6 shows the distribution of glottal activity patterns.

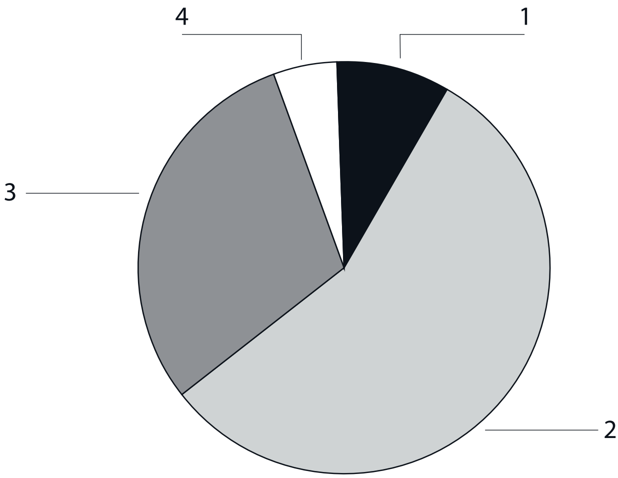

Figure 6: **/+voice/ dental fricative + nasal. Glottal activity pattern distribution in the labiodental**

1 – absence of glottal vibrations over the entire segment; 2 – continuous glottal vibrations over the entire segment; 3 – glottal vibrations over the first half of the segment; 4 – absence of vibration in the central part of the segment

These data show that here, the labiodental and the dental fricatives, as far as glottal activity is concerned (the glottal activity pattern), behave differently. Glottal vibration over the entire segment is significantly more frequent in groups with the labiodental. The glottal pattern in the nasal, however, is quite stable with both fricatives, independently of the underlying voice specification, /+voice/ or /-voice/.

5.3. Duration of the fricative, the interval and the nasal

The average duration is higher in the dental than in the labiodental in all four glottal activity patterns (Figure 7).

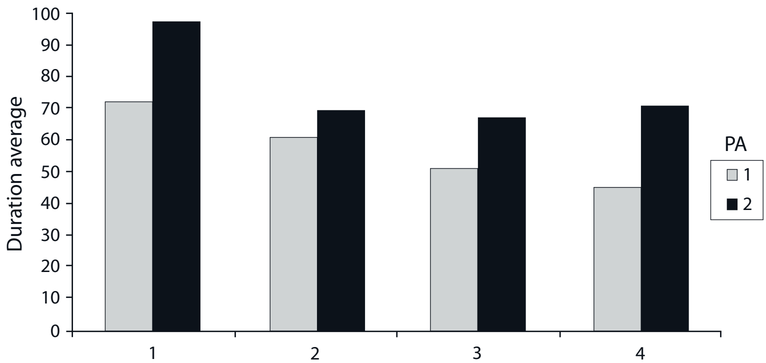

Figure 7: Nasal + fricative. Average duration distribution for glottal patterns of the fricative

1 – absence of glottal vibrations over the entire segment; 2 – continuous glottal vibrations over the entire segment; 3 – glottal vibrations over the first half of the segment; 4 – absence of vibration in the central part of the segment) and the place of articulation (PA1: labiodental, PA2: dental)

UNIANOVA tests were performed separately for the labiodental and dental fricative in order to compare the fricative duration with the other parameters being considered. In Table 4 the relation between glottal activity patterns and the duration of the labiodental fricative is presented.

Table 4: Fricative + nasal. Relation (UNIANOVA test): duration of the labiodental – Glottal activity pattern / type of interval

	labiodental	dental
Glottal pattern of the fricative	0.000	0.017
Interval	0.102	0.892

The figures in Table 4 show that the relation between fricative durations and the glottal activity pattern is significant. However the relation between the duration of the fricatives and the type of interval is not significant.

Tables 5 and 6 show T-test results for the average durations of labiodental and dental fricatives /-voice/ and /+voice/, taking as a grouping variable the glottal activity pattern of the fricative.

Table 5: Fricative + nasal. Relation (Independent T test): Labiodental fricative duration – Glottal activity patterns

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
1	37	72.57	12.119	1.992	
2	95	62.47	14.609	1.499	0.000

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
2	95	62.47	14.609	1.499	
3	38	58.34	12.777	2.073	0.130

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
3	38	58.34	12.777	2.073	
4	9	69.11	18.564	6.188	0.043

Table 6: Fricative + nasal. Relation (Independent T test): Dental fricative duration – Glottal activity patterns

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
1	158	95.94	20.824	1.657	
2	95	66.21	15.551	1.596	0.000

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
2	95	66.21	15.551	1.596	
3	68	61.54	11.989	1.454	0.050

Glottal pattern	N	Average duration	Standard deviation	Average typical error	Bilateral Sig. $p < 0.05$
3	68	61.54	11.989	1.454	
4	13	68.62	9.060	2.513	0.057

Tables 5 and 6 compare average durations of labiodental and dental fricatives between their glottal activity patterns. Despite the fact that the duration in pattern 3 is shorter than in pattern 2, the difference is not significant. A one-sample T test was performed to compare the duration of the fricative, the duration of the nasal and the interval in sequences with the labiodental and the dental fricative (Tables 7 and 8).

Table 7: Labiodental fricative + nasal. One-sample T test of the duration of the fricative, nasal and the interval. Place of articulation: PA1 = Labiodental, PA2 = Dental

	N	Average duration	Standard deviation	Average typical error
Duration of labiodental	108	63.44	14.234	1.370
Duration of nasal	106	50.47	13.300	1.292
Duration of interval	53	27.57	8.628	1.185

Table 8: Dental fricative + nasal. One-sample T test: Duration of the fricative, nasal and interval. Place of articulation: PA1 = Labiodental, PA2 = Dental

	N	Average duration	Standard deviation	Average typical error
Duration of dental	142	82.72	22.874	1.920
Duration of nasal	140	52.35	15.730	1.329
Duration of interval	111	27.03	8.879	0.843

Tables 9 and 10 refer to a T-test for two independent samples comparing the average duration of the nasal and the place of articulation on one hand, and the average duration and the place of articulation of the fricative on the other.

Table 9: Fricative + nasal. T-test for two independent samples: Duration of the nasal – Place of articulation: PA1 = Labiodental, PA2 = Dental

PA	N	Average duration	Standard deviation	Average typical error	Mean differences	Bilateral Sig. $p < 0.05$
1	106	50.47	13.300	1.292		
2	140	52.35	15.730	1.329	–1.88	0.323

Table 10: Fricative + nasal. T-test for two independent samples: Duration of the interval – Place of articulation: PA1 = Labiodental, PA2 = Dental

PA	N	Average duration	Standard deviation	Average Typical error	Mean differences	Bilateral Sig. $p < 0.05$
1	53	27.57	8.628	1.185		
2	111	27.03	8.879	0.843	0.54	0.712

The relation between the average durations of the nasal and the place of articulation of the fricative and the duration of the interval and the place of articulation of the fricative are not significant, i.e. the duration of the nasal and the interval is similar in *labiodental* and *dental + nasal clusters*.

6. Discussion and conclusions

In *fricative + nasal sequences,* /-voice/ fricatives are largely realized with glottal activity pattern 1. In sequences with /+voice/ fricatives, the dental gives rise to a significantly higher number of cases of loss of glottal vibrations than the labiodental.

As regards the glottal activity pattern of the nasal, it is stable both in sequences with the labiodental and the dental fricative, both for /+voice/ and /-voice/ fricatives.

Regardless of the underlying specification of the fricative, the nasal generally presents pattern 2 (glottal vibrations over the entire segment), in 97.2% of cases with the labiodental and 94.2% with the dental.

The relation between glottal activity patterns and the position with respect to the accent is not significant for sequences either with the labiodental or with the dental.

Dental fricatives are longer than the labiodentals in all four glottal activity patterns.

In the boundary between the fricative and the nasal, three possible types of transition events were observed: a voiceless interval, a voiced interval and the absence of any transition element. These results are consistent with Kleśta's claim (1999: 125) concerning the presence of an element between fricatives and nasals (specifically between /ɕ/ and /n/), although this transition element is voiceless, a "zero element". The present analysis allows us to confirm the presence of boundary elements for Polish fricatives and provides quantitative data about the differences in the fricative depending on the place of articulation and the type of transition.

Considering consonant clusters separately with a /-voice/ and /+voice/ fricative + nasal, there are not considerable differences in the boundary interval. In the case of the /-voice/ labiodental the interval is always voiceless, while with the dental, in 5.7% of instances the interval is voiced. In most cases, groups with /-voice/ fricatives present a voiceless interval (88.9% of cases with the labiodental and 88.6% with the dental). Absence of transition elements in clusters with underlying voiceless fricatives occurs in 11.1% of cases with the labiodental and 5.7% with the dental. Significant differences can be found in clusters with a /+voice/ fricative, where 69.4% with the labiodental do not have any kind of interval, 11.1% exhibit a voiceless interval, and 19.4% of instances are realized with a voiced interval. Figures for the dental are quite different: 37.7% are realized without any transition element, 33.3% with a voiceless interval and 29.0% with a voiced interval. In other words, with the dental the interval is realized more often and it tends to be voiced, while with the labiodental, the opposite tendency is found.

In the previous literature, only Docherty (1992) analyses *fricative + nasal clusters* (specifically /s/ + /m/, /n/ in SBE). After the fricative friction noise phase and before the beginning of the nasal sonority phase, an interval without friction noise or periodicity is observed. This voiceless transition is present in all of the analysed sequences. Neither the nasal context nor the context preceding the fricative have any statistical significance for the duration of the transition. In the present work we have seen that this transition element in Polish is present in /-voice/ *dental fricative + nasal sequences* and in /+voice/ *fricative + nasal* (both with the labiodental and the dental) sequences, where the interval can be realized with glottal vibrations.

Other works regarding sonority in /-voice/ *fricative + sonorant* sequences in English, such as Bladon & Al-Bamerni 1976, Dent 1984, do not distinguish between the fricative's friction noise and the noise related to the interval they call the "devoiced sonorant". Nevertheless, they observe some delay in the beginning of glottal activity in voiceless fricative + nasal sequences, compared with voiceless fricative + vowel.

As regards the possible transitions from the fricative to the nasal described in Barry & Kunzel 1978 (see section 3, above), in the present study no evidence has been found showing that this transition element is an occlusive or a voiceless nasal. In some cases, we have found one or more release bursts in the transition element. These release bursts are more likely to be the result of incidental obstacles which the air stream finds in the nasal cavity during the expiration that occurs between the fricative and the nasal[5], rather than transition bursts to the plosive (see section 3).

As regards average durations with respect to glottal activity patterns, the differences between patterns 2, 3 and 4 are not significant either for labiodental or for dental fricatives.

The average duration of the nasal and of the transition element are similar in clusters with the labiodental and the dental fricative.

As this work has shown, the asynchrony between glottal and supraglottal makes it difficult to define where sonority begins and ends, since the F0 plot in the spectrogram does not always correspond straightforwardly to the presence or absence of glottal pulses.

In considerations of voiced and voiceless consonants, at least in the case of fricatives, the reference is often an abstraction of the relevant consonants based on perception and phonological knowledge. In fact, it seems clear that it is not possible to define sonority in absolute terms of glottal pulses and fundamental frequency. A consonant intended and perceived as voiced is often realized partially and sometimes even completely without glottal vibrations. For this reason, an accurate definition of sonority must take into account all relevant features that take part in the articulation, what we call phonetic cues. One of the important contributions of the present work is to show the relation between segment duration, place of articulation and glottal activity patterns.

Further study on this topic should include analysis of how sonority is perceived depending on the duration, the glottal activity pattern, and the phonological information possessed by the listener. This perception study should aim to analyse the interpretation of these parameters, in order to define the relevance of the resulting configurations as phonetic cues.

As pointed out in the Introduction, the goal of this work is to contribute to defining a phonetic basis for a comprehensive phonological analysis of voice distribution, especially in complex consonant clusters.[6] Transition events observed in *fricative + nasal* clusters suggest that there is a tendency to decrease the articulatory effort in complex articulatory

[5] This is consistent with Dukiewicz (1967: 12), who indicates that results in the analysis of nasals are not always homogeneous because of unstable blocking elements, such as secretions and hair.

[6] Castellví & Szmidt (2002) and Castellví (2003) highligt the need for empirical data to analyze the sonority of Polish consonant clusters.

gestures. Phenomena such as sonorant devoicing, uneven distribution of glottal activity over the consonant cluster and transition intervals and its correspondence in speech perception must be considered in the analysis of complex consonant clusters that violate the Sonority Sequencing Principle.

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