Differences in EPG contact dynamics between voiced and voiceless lingual fricatives

Marko Liker *

Fiona E. Gibbon **

* Faculty of Humanities and Social Sciences, University of Zagreb, Croatia

** University College Cork, Ireland

Marko Liker
University of Zagreb
Department of Phonetics, Faculty of Humanities and Social Sciences, Ivana Lucica 3, 10000 Zagreb
Croatia
telephone: + 385 1 6120098; fax: + 385 1 6120096
mliker@ffzg.hr

Differences in EPG contact dynamics between voiced and voiceless lingual fricatives

ABSTRACT

Achieving voicing during fricatives is complex because voicing and frication require opposite production strategies that must be managed effectively at the supralaryngeal level. Previous research has suggested differences in tongue palate contact patterns that appear to be conditioned by voicing. However, findings have been restricted to a single time point and generally inconclusive. This study used electropalatography (EPG) to investigate differences in the dynamics of contact in voiced and voiceless lingual fricatives.

Participants were 6 typically speaking Croatian adults. Speech material were symmetrical VCV sequences, C was /s/, /z/, /ʃ/, /ʒ/. EPG measures taken throughout the fricatives included place of articulation (CoG), amount of contact, groove width and target configuration onset. Results showed a stable period during the central portion of the fricative. EPG measures showed similar results for voiced and voiceless fricatives during this period. However, there were notable differences at the periphery of the fricative period; the most significant being that the voiceless fricatives reached a stable period in terms of tongue placement and groove configuration later than the voiced fricatives. More specifically, the voiced fricatives were at target position right at the start of frication, whereas voiceless fricatives only reached their target position at approximately a fifth of the way into the fricative.

The results support aerodynamic evidence that voiced and voiceless fricatives differ in the onset and the offset of turbulence.

1. INTRODUCTION

The voicing contrast is among the most frequently investigated issues in phonetics (Fuchs 2005: 2). This is hardly surprising, because there is much more to the voicing contrast than simply adducted, vibrating vocal folds during voiced and abducted vocal folds during voiceless sounds. For example, a consistent finding in the literature is that voicing contrasts are signalled by multiple acoustic cues, of which voicing is just one. There are several interdependent physiological mechanisms that make the voicing issue rather complicated to investigate: voicing requires a transglottal pressure difference, the pressure difference is closely related to the shapes and sizes of supraglottal cavities, shapes and sizes of supraglottal cavities are constrained by the place and manner of articulated sounds, voicing effects are influenced by a range of coarticulatory, prosodic and other communication-related conditions. This means that voicing can be studied at least at two levels of speech production: glottal and supraglottal. In this investigation we are concerned with the latter.

One of the most important supraglottal characteristics in phonetics is tongue-to-palate contact, which is most successfully investigated via electropalatography (EPG). Supraglottal cues for voicing are most thoroughly investigated in stops (Fuchs 2005: 21). Fricatives and affricates are somewhat less investigated in this respect (Fuchs 2005: 21; Fuchs, Brunner & Busler 2007), although recent research is closing this gap (Dagenais, Lorendo & McCutcheon 1994; Dixit & Hoffman 2004; Fuchs, et al. 2007; McLeod, Roberts & Sita 2006; Liker & Gibbon 2011; Liker, Horga & Mildner 2012; Recasens & Espinosa 2007). Most EPG studies of the voicing difference in fricatives have been concerned with static measurements at one moment in time. Therefore, in this paper we shall investigate dynamic properties of tongue-to-palate contact in voiced and voiceless lingual fricatives for the purposes that will be described in more detail in the sections that follow.

Voicing and frication require opposite production strategies. In order to maintain voicing, there needs to be a transglottal pressure difference, with the supraglottal pressure lower than the subglottal. However, in order to produce a frication, supraglottal pressure needs to increase so that turbulence can be successfully achieved. Therefore, the air stream must be carefully managed by coordinating respiratory, laryngeal and articulatory mechanisms. In contrast, voiceless fricatives have no such contradictory demands on the articulatory mechanism, because supraglottal pressure can be freely increased in order to produce a high-pressure air stream. A high amount of air flow is facilitated by an abducted glottis in voiceless fricatives (Ohala & Sole 2010). The difference in laryngeal-supralaryngeal coordination between voiced and voiceless fricatives produces differences in oral articulatory characteristics conditioned by voicing.

Several oral articulatory characteristics are considered essential for the production of anterior lingual fricatives; a narrow midline groove is the most commonly mentioned characteristic (Gibbon & Hardcastle 1987; Hardcastle & Edwards 1992; McLeod et al. 2006). In order to maintain the characteristic fricative groove, a precise relationship between the active (tongue tip/lamina) and the passive articulator (incisors/alveolar ridge/prepalatal zone) needs to be established. Apart from the midline groove, placement characteristics and the amount of contact are most frequently analysed when investigating differences in lingual fricatives conditioned by voicing (Dagenais et al. 1994; Dixit & Hoffman 2004; McLeod et al. 2006; Fuchs et al. 2007; Recasens & Espinosa 2007; Liker & Gibbon 2011; Liker et al. 2012). All these articulatory characteristics can be closely studied by means of electropalatography (EPG), which is the only physiological instrumental tool which provides a direct and detailed insight into tongue-to-palate contact patterns during speech.

EPG research into the supralaryngeal differences between voiced and voiceless fricatives has mostly shown increased anterior contact and smaller groove width in voiced fricatives (Dagenais et al. 1994; Dixit & Hoffman 2004; McLeod et al. 2006; Liker & Gibbon 2011; Liker et al. 2012). These differences are mostly explained by aerodynamic factors in the production of voiced as opposed to voiceless fricatives, whereby the air stream pressure during voiceless fricative is so high that it pushes the lateral edges of the tongue, thus creating a wider midline groove and less tongue-to-palate contact. A somewhat more complex difference between voiced and voiceless fricatives was found in Croatian (Liker & Gibbon 2011). These authors found that voiced and voiceless fricative showed that anterior groove width and posterior groove width had opposite tendencies. These authors found that the anterior width was slightly wider in voiceless than in voiced fricative, while voiced fricative was produced with a wider posterior groove than the voiceless one. They explained that a slightly wider posterior groove in voiced fricative supported claims that fricatives might manipulate constriction size behind the place of articulation in order to facilitate voicing (see also Fletcher & Newman 1991).

Most EPG studies showing differences in supralaryngeal characteristics of voicing in fricatives provide static results measured at a single temporal point in fricative production, most commonly at the maximum contact point (e.g. McLeod et al. 2006), or averaged across the whole fricative duration (e.g. Fuchs et al. 2007). However, having in mind that voiced fricatives need a stable and carefully controlled air stream to produce both frication and voicing, while voiceless fricatives have abducted vocal folds thus facilitating a fast increase in air stream pressure, differences in peak tongue-to-palate contact pressure between voiced and voiceless fricatives can be expected. It is still largely uninvestigated whether such differences produce differences in the timing of EPG characteristics between voiced and voiceless fricatives, such as differences in groove width dynamics, amount of contact dynamics and placement dynamics.

Interesting tongue pressure results were reported for Japanese stops, where the difference between voiced and voiceless stops was not found in maximum tongue pressure, but in the timing of the peak tongue pressure (Matsumura, Kimura, Yoshino, Tachimura & Wada 1994, cited in Fuchs 2005: 75). The authors investigated the measurement of tongue-to-palate contact pressure and pattern during consonant productions using a force sensor mounted palatal plate. For that purpose they developed an artificial palate with strain gauges along the palate midline. During the production of voiceless stop /t/ the maximal tongue-to-palate pressure occurred about 100ms prior to the stop burst, while in /d/ the peak pressure and the stop burst occurred closer to each other. If a comparable process occurs in fricatives, it remains to be investigated whether it has any repercussions on the timing of maximum contact point, minimum groove width point or placement in voiced and voiceless fricative. Furthermore, relatively stable turbulent noise during fricative production does not necessarily mean stable tongue-to-palate contact patterns, because frication can begin before the maximum constriction is reached and can continue during the period of separation of the active and the passive articulator (Docherty 1992: 9). In order to investigate these factors, it is important to measure the dynamics of tongue palate contact throughout the duration of the fricative period, and not at just one single point in time.

Voiced fricatives in Croatian need to maintain full voicing throughout their duration (Bakran 1996). Therefore, supralaryngeal requirements for the production of frication and voicing need to be carefully maintained from the beginning to the end of voiced fricatives. This would entail increased stability of tongue-to-palate contact, when compared to voiceless counterparts. Voiced fricatives would also require a narrower midline groove and more tongue-to-palate contact than voiceless fricatives, in order to enable frication in a low pressure air stream environment. Evidence of a narrower midline groove and increased contact at the place of articulation was found in voiced Croatian fricatives at a maximum contact point, but increased stability was not confirmed (Liker & Gibbon 2011; Liker et al. 2012). The authors explained the lack of difference in variability between the voiced and the voiceless fricatives by a very low overall variability, reflecting high coarticulatory resistance in all fricatives. However, the lack of difference in variability could partly be attributed to a statistical measurement of variability.

In this study we shall investigate the difference in the timing of tongue-to-palate contact patterns between voiced and voiceless lingual fricatives in Croatian. We aim to do this by describing the placement dynamics, fricative groove dynamics and the amount of contact dynamics during voiced and voiceless fricatives.

2. METHOD

2.1. Speakers

There were three female (F1, F2, F3) and three male (M1, M2, M3) participants in this study with no self-reported history of speech and hearing impairments. All six speakers were adult speakers of Croatian, aged between 26 to 35 years, with the mean of 30.8 years. Each speaker had an artificial palate individually constructed to fit against the hard palate (The Articulate Palate, Wrench 2007).

2.2. Speech material

Speech material was extracted from the CROELCO database: the Croatian acoustic and electropalatographic corpus (Liker et al. 2012). Analysed material consisted of symmetrical nonsense VCV sequences in which V represented three corner vowel positions: /i/, /u/ and /a/, while C represented consonants /s/, /z/, /ʃ/, /ʒ/. Each speaker repeated the sequence of 12 words six times, resulting in the total of 432 items with short-falling accent placed on the first syllable, phonotactically comparable to real Croatian words (e.g. /măsa/ (eng. mass), /bǎ:za/ (eng. base), /tîʃi:/ (eng. quieter), /nîʒi:/ (eng. shorter)).

2.3. Procedure

Speech data were recorded by WinEPG system. EPG data were sampled at 100 Hz. Acoustic data were recorded simultaneously using M-Audio MobilePre external USB sound card/pre-amplifier with the sampling rate of 22050 Hz. Annotation, segmentation and data preparation was performed by the Articulate Assistant software (Wrench, Gibbon, McNeill & Wood 2002). MS Excel was used for statistical analysis and data visualization. All participants underwent a desensitization period in two phases. The first phase consisted of five days with two-hour palate-wearing sessions each day. The second phase of desensitization procedure was prior to the recording and lasted for the maximum of one hour. The recording procedure began only when speaker's articulation was rated as acceptable by two trained phoneticians.

2.4. Data analysis

Annotation and segmentation of fricatives was performed according to acoustic criteria. The beginning of a fricative was the start of high frequency noise and/or the absence of second formant in preceding vowel on the spectrogram. The presence of a clearly visible second formant and/or the absence of high frequency noise was the acoustic cue for the end of the fricative. Four EPG measurements, detailed below, were taken from the fricatives and analysed at a previously determined number of equally spaced sample points. The number of the sample points (*nsp*) for each speaker and each fricative pair was determined by the formula $nsp = \frac{t}{10}$, where t is the duration of the shortest fricative in each speaker in milliseconds and 10 represents the distance between each EPG sample determined by the sampling frequency (100 Hz). The shortest fricative in each speaker and each fricatives pair was chosen in order to prevent over-sampling (multiple sampling of the same EPG frame). Selecting discrete points throughout the friction period in this way made it possible to compare measurement values throughout the fricatives which were of variable durations. The following EPG measures were analysed:

1. Placement dynamics measured by means of the centre of gravity (CoG) index (Hardcastle, Gibbon & Nicolaidis 1991), which measures the location of the highest concentration of contacted electrodes. As a result, CoG is a frequently used measure of place of articulation taken from EPG data (Gibbon, Hardcastle & Nicolaidis 1993; Mair, Scully & Shadle 1996; Fuchs & Perrier 2003; Gibbon, McNeill, Wood & Watson 2003; Gibbon & Wood 2003; Simonsen & Moen 2004; McLeod 2006; Cheng, Murdoch, Goozee & Scott 2007). For visualization purposes CoG values were multiplied by eight. A higher CoG value indicates a more anterior articulation, while a lower value means a more posterior articulation. EPG contact variability is also measured. This measure is available in the Articulate Assistant software (Wrench et al. 2002). Variability of EPG contact patterns is calculated across all contacts during the production of each fricative. To calculate the index, the percent frequency of activation of each contact across frames is measured. For each contact, 100% and 0% activation frequency represents invariance and are assigned a variance index of 0. The variability index increases as contact frequency approaches 50%, which is assigned a maximum index of 50 (Wrench 2008).

2. Midline groove dynamics obtained by the mean lateral measure available in the Articulate Assistant software (Wrench et al. 2002). This index measures whether there is more contact at the midline of the palate or towards the lateral sides. A higher index number indicates greater groove width (Wrench 2008).

3. Target acquisition lag measure (TAL) was used to determine the point in the fricative at which stable target tongue configuration was reached. TAL was calculated in the following way: a) The calculation of the amount of contact in the first four rows of electrodes (the first four rows were chosen because that is the region of the palate where the characteristic shape is the most critical in anterior lingual fricatives) for each sample point recorded by the EPG. The number of sample points was determined by dividing the duration of annotation by the sampling frequency. b) The target configuration was found by calculating the mode (the sequence of amount of contact indices which occurs most frequently in each data set). The beginning of the sequence of a particular mode was considered the start of the target configuration. c) The duration between the start of the annotation and the beginning of the target configuration (determined by the mode) was defined as the target acquisition lag (TAL). d) The TAL was expressed as a percentage of the total duration of the annotation (AD): $\left(\frac{TAL}{AD}\right)\times 100$ (Figure 1).

Insert Figure 1 about here.

4. Amount of contact dynamics measured by means of the whole total measure was used to visualise the difference in TAL measure. Whole total measures the total number of contacted electrodes and divides that number with the total number of electrodes on the palate (Wrench 2008). The whole total number was multiplied by 100 to express it as a percentage. Amount of contact was measured for each row of electrodes at a predetermined number of equidistant sample points. The number of sample points was determined by the duration of the shortest fricative. In order to find out the difference between the voiced and voiceless counterparts, data for each electrode in each row and at each sample point for the voiceless fricative was subtracted from the data for each electrode in each row and at each sample point for the voiced fricative. This was calculated for each speaker. The result is a detailed visualisation of contact dynamics difference between voiced and voiceless fricatives throughout their duration. The calculation can be visualised as shown in figure 2.

Insert Figure 2 about here.

The statistical significance of differences was tested by means of heteroscedastic t-test.

3. RESULTS

3.1. Placement dynamics

The results show differences (described in the next sections) in placement dynamics between voiced as opposed to voiceless fricatives. A general finding is that similar tendencies can be observed in alveolar and postalveolar fricatives.

Alveolar fricatives /s/ and /z/

Figure 3 shows average CoG values for /s/ and /z/ over the time course of the fricatives. The comparison of the CoG trendlines at each sample point shows that for each speaker, the voiced and voiceless fricatives have near-identical place of articulation throughout the mid-portion of the fricative. This is indicated by a stable plateau of CoG values throughout most of the duration of the fricative. However, differences can be observed at the periphery of the fricative, that is, at the start and end points. Here, there are consistently lower average CoG values for the voiceless compared to the voiced fricative. An illustration of this difference can be seen in figure 4. Lower CoG values occurred in all voiceless cases, and reached statistical significance ($p<0.01$) in four out of six speakers (F1, F2, M1, M3) at the start of friction and in two out of six speakers (M1, M3) at the end.

Insert Figure 3 about here.

Insert Figure 4 about here.

Postalveolar fricatives /ʃ/ and /ʒ/

As expected, CoG values for all speakers are lower for postalveolar fricatives compared to their own values for alveolar fricative shown in the previous figure. Average placement at maximum contact point in the postalveolar fricatives is more posterior (average CoG in /ʃ/ is 3.36, SD 0.34; average CoG in /ʒ/ is 3.47, SD 0.29) than in alveolar fricatives (average CoG in /s/ is 4.17, SD 0.16; average CoG in /z/ is 4.31, SD 0.14). These differences are statistically significant ($p<0.01$). This is because alveolar fricatives have a more fronted place of articulation compared to postalveolar fricatives.

The results of the placement dynamics in postalveolar fricatives show tendencies very similar to those described for the alveolar fricatives. During the middle of the fricative there are almost identical CoG values for the voiced and voiceless. Voiceless fricatives have lower average CoG values at the edges of its duration in all cases, when compared to voiced fricatives (Figure 5). The difference at the beginning of the fricatives reaches statistical significance in speakers F1, F3, M1 and M3 ($p<0.01$), while at the end of the fricatives the difference is significant in M1 and M3. On average, the difference between the voiced and the voiceless fricatives at the place of articulation is not statistically significant ($p>0.01$) in all cases.

Insert Figure 5 about here.

The difference in the timing of placement target is also reflected in the EPG variability data, which shows that voiceless fricatives are more variable (/s/ = 4.03, SD 0.27; /ʃ/ = 3.42, SD 0.25) than voiced fricatives (/z/ = 1.97, SD 0.39; /ʒ/ = 2.08, SD 0.22) in each speaker and in each vowel context. The differences in EPG variability are statistically significant ($p<0.01$).

3.2. Midline groove dynamics

The results of the midline groove dynamics show that alveolar voiced and voiceless fricatives have similar characteristics during the mid-portion of frication. However, differences between the voiced and the voiceless are similar to those seen in placement data and can be observed at the edges of fricative durations. Figure 6 shows that voiced fricative /z/ forms the target groove width right from the beginning of its duration, while in the voiceless fricative /s/ there is a slight lag in reaching the goal position. This trend is apparent in four speakers (F1, M1, M2, M3). In speaker M3 differences between the voiced and the voiceless are statistically significant at all data points, while in speaker F1 the difference is significant at the first data point only ($p<0.01$).

Insert Figure 6 about here.

The midline groove dynamics trendlines in the postalveolar voiced fricative are identical to the trendlines in the postalveolar voiceless fricative. Since virtually no difference between the voiced and the voiceless postalveolar fricatives can be observed at any sample point, we do not present the data for postalveolars here.

3.3. Target acquisition lag

The TAL measure showed that the delay in the tongue reaching its target position is longer in voiceless (/s/: 21%, SD 0.06; /ʃ/: 31%, SD 0.08) than in voiced fricatives (/z/: 12%, SD 0.04; /ʒ/: 13%, SD 0.02). This difference is observable in each speaker (Figures 7 and 8) and overall it is statistically significant ($p<0.01$) in alveolar as well as in postalveolar fricatives. Postalveolar fricatives exhibit greater TAL difference (18% difference) than alveolar fricatives (9% difference).

Insert Figure 7 about here.

Insert Figure 8 about here.

The difference in TAL between the voiced and the voiceless fricatives can be attributed to a slower increase of contacts in voiceless fricatives at the beginning of their duration in the front of the palate when compared to voiced fricatives. This slower increase is observable at the front of the palate, while in the back of the palate the increase in contacts is similar to the increase in voiced fricatives. An illustration of this difference can be seen in figure 9. The data also show that in some speakers voiceless fricatives exhibit a slightly earlier decrease of contacts at the end of its duration also in the front of the palate.

Insert Figure 9 about here.

4. DISCUSSION AND CONCLUSIONS

The results of this study reveal previously unreported differences in articulatory dynamics of voiced and voiceless fricatives produced by these speakers. The differences were located in the dynamics at the periphery of the fricative, primarily at the start of the frication. More specifically, voiceless fricatives reached their target position in term of articulatory placement and groove configuration later in the friction than voiced fricatives, with voiced fricative at target position at the start of frication, whereas voiceless fricative reaches its target approximately 20% into the fricative. This tendency is more pronounced in alveolar than in postalveolar fricatives. The results of the CoG and the midline groove dynamics are supported by the TAL measure, which shows that it takes the voiceless alveolar fricative nearly 10% more time to reach the target contact configuration, when compared to the voiced fricative. The TAL also shows that voiceless postalveolar fricative takes nearly 20% longer than its voiced counterpart to reach its characteristic EPG contact configuration. Detailed contact dynamics data revealed that voiceless fricatives increased anterior contact more slowly than voiced fricatives, while posterior contact was increased at the same time in voiced and voiceless fricatives. This means that voiceless fricatives first increased contact and formed the groove behind the place of articulation and only then increased contact in the front of the palate (at the place of articulation). Voiced fricatives, on the other hand, increased contact more evenly across the palate, when compared to voiceless fricatives.

The findings from the current study are in agreement with some well-established facts about frication and voicing. In order to maintain voicing, there needs to be transglottal pressure difference, with the supraglottal pressure lower than the subglottal. At the same time, in order to produce frication, supraglottal pressure needs to increase so that turbulence can be successfully maintained. Previous EPG studies showed that these aerodynamic processes caused increased EPG contact and a narrower midline groove in voiced fricatives (Dixit & Hoffman 2004; McLeod et al. 2006; Fuchs et al. 2007; Recasens & Espinosa 2007). However, most measurements were from one time point during the fricative, so EPG characteristics of tongue-to-palate contact over the whole time course of voiced as opposed voiceless fricatives have not yet been investigated. The novelty of the present research is that it has shown consistent differences in the timing of tongue-to-palate contact patterns between voiced and voiceless fricatives at specific time points (beginning and end of friction) and in specific regions of palate (anterior region).

Results from this paper generally support previously reported findings about pharyngeal articulation of voiced and voiceless fricatives (Proctor, Shadle & Iskarous 2010). These authors found that voiced fricatives were produced with an enlarged pharyngeal cavity when compared with their voiceless counterparts. The enlargement strategy was expected in stops, but it was surprising in fricatives. The authors showed that enlargement was mainly due to a forward displacement of the tongue dorsum, which caused the upper oropharynx to enlarge. Furthermore, these authors argued that voiceless fricatives were produced with the back of the tongue closer to the rear pharyngeal wall, thus creating an air-pressure control mechanism. Delayed formation of target placement and groove width in voiceless fricatives shown in this paper could be explained by the existence of such pharyngeal air-pressure control mechanism, which could give more time to the tongue tip to reach its optimum position. This is another mechanism which encourages the back of the tongue to contact the palate first in voiceless fricatives (because the soft palate is low), and only after the lateral lock is firmly secured in the back (and the strong air stream is directed towards the front of the oral cavity) does the front of the tongue contact the palate and create a narrow groove in the front. However, the pharyngeal data were produced by average MRI scans of the vocal tract during the sustained fricative productions, while speakers were instructed to maintain a stable articulatory position, so the analysis did not offer insight into the timing of pharyngeal control mechanism. Present findings are also consistent with one previous investigation of Croatian fricatives (Liker & Gibbon 2011), which showed that voiceless fricative was produced with a narrower posterior groove width than the voiced one, indicating an increased constriction in the posterior oral cavity at the maximum contact point.

Results of the EPG contact dynamics analysis provide further support for the claim that voiced fricatives employ a cavity enlargement strategy. The data show that voiceless fricatives demonstrate a slow increase in the amount of contact at the place of articulation (the anterior four rows) and long TAL, while voiced fricatives increase contact more evenly across the whole palate and show a short TAL. Voiced fricatives seem to employ a type of cavity enlargement strategy in which the larynx is lowered, thus lowering the back of the tongue. This prevents the back of the tongue form raising and making contact with the palate before the front of the tongue raises during voiced fricative production, while the voiceless fricative raises the back of the tongue first in order to achieve a secure lateral lock and direct a high-pressure, high-velocity air stream towards the narrow anterior groove. Other studies also showed evidence of cavity enlargement strategies in voiced fricatives (Narayanan, Alwan & Haker 1995). These findings agree with EPG data on Japanese alveolar fricatives (Yoshioka 2008). Yoshioka (2008) investigated voicing difference in whispered speech and found that EPG contact patterns during /s/ were less stable than those during /z/. The author explained this finding by concluding that vocal fold vibrations were essential for voicing distinction, but that some of the supralaryngeal mechanisms were exaggerated in order to maintain this distinction when vocal fold vibrations are not present. However, this could also mean that voicing and tongue-to-palate contact stability are not biomechanically proportional. This is only a speculation and the issue should be further investigated.

The results of this paper support aerodynamic evidence, which show that voiced and voiceless fricatives differ in the onset and the offset of turbulence (Scully 1971). However, Scully (1971) did not find any evidence of the difference in tongue movements, therefore concluding that the only significant difference in the articulation of /s/ and /z/ is in the glottal adjustment and not in the muscular tension or in breath force. The findings from this study do not support this view and are in agreement with later studies showing articulatory control of aerodynamic conditions (e.g. Fuchs & Koenig 2009).

Although, the data in this investigation were obtained from Croatian speakers, they fit nicely into the body of research done in other languages. Therefore, it is reasonable to suppose that these results are relevant for voiced and voiceless anterior lingual fricatives in other languages, as well. Nevertheless, this remains to be investigated. Also, when making generalisations based on these results, it is important to keep in mind that the analysis was performed on nonsense sequences. If the corpus consisted of real words, it would be impossible to have all the consonants in identical contexts (identical the number of syllables and sounds, vowel and consonant contexts and accent patterns), resulting in a number of uncontrolled factors. Therefore, nonsense sequences were used in this paper and they were constructed to conform to the phonotactic rules of Croatian real words (e.g. The nonsense word /uʃu/ is modelled upon the real word /guʃu/, but there is no comparable two-syllabic real Croatian word in which /ʒ/ is surrounded by vowel /u/. The closest are the words like /puʒu/, but these have different accent pattern.). Although non-words used in this investigation meet the phonotactic and accent distribution rules of Croatian, it remains to be seen whether similar results will be obtained from real words.

This study shows that the EPG difference between the voiced and the voiceless fricatives cannot be fully captured by utilizing static measurements only. Important differences, which fit nicely into research using imaging techniques, can be observed by analysing the timing of tongue-to-palate contact patterns during the whole of frication phase. The complexity of producing voicing during frication might explain a relative infrequency of voiced fricatives in worlds' languages (Ohala 1983, cited in Proctor et al. 2010). It seems that this difficulty is not only due to a complicated oral gesture, but mainly due to a complex laryngeal-supralaryngeal coordination of voicing and frication processes. Ohala and Sole (2010) note that there is a narrow range of pressure between 5.6 and 3 cm H_2O in which both voicing and frication can be maintained. The authors explain that in voiced fricatives vibrating vocal folds reduce transglottal flow, which impairs frication, and if strong frication occurs, a high intraoral pressure will stop vocal fold vibrations. Therefore, voiced fricatives tend to devoice or defricate, which can be observed both synchronically and diachronically (Ohala & Sole 2010). Furthermore, Smith (1997, cited in Fuchs et al. 2007) found that if pressure balance between voicing and frication is not achieved, voicing is more likely to disappear than frication. Results from the present investigation are relevant for phonetic and phonology theory, because they add to the growing volume of literature showing the dependency relation between the glottal and supraglottal mechanisms. These interdependent mechanisms indicate that laryngeal and supralaryneal features cannot be represented by different branches in phonology (see Ohala & Sole 2010).

The results of this study are also relevant for clinical practice. The complexity of the voicing contrast in fricatives is reflected in their late acquisition in typically developing children (Grunwell 1987; Smit, Hand, Frelinger, Bernthal & Bird 1990; Grigos, Saxman & Gordon 2005;) and voicing errors occur frequently in children and adults with speech disorders (Ansel & Kent 1992; Bunton & Weismer 2002; Bernthal, Bankson & Flipsen 2009). The differences in the timing of tongue-to-palate contacts between voiced and voiceless fricatives reported in this study can be used to improve the diagnosis and treatment of fricatives. The results show that the dynamics of EPG patterns during fricative production should be taken into account, and not just static measurements, when diagnosing and treating abnormal voiced and voiceless fricative productions.

5. REFERENCES

Ansel, Barbara M. & Raymond D. Kent. 1992. Acoustic–phonetic contrasts and intelligibility in the dysarthria associated with mixed cerebral palsy. *Journal of Speech and Hearing Research* 35, 296–308.

Bakran, Juraj. 1996. *Zvučna slika hrvatskoga govora*. Zagreb: Ibis grafika.

Bernthal, John E., Nicholas W. Bankson & Peter Flipsen. 2009. *Articulation and Phonological Disorders: Speech Sound Disorders in Children, 6th Ed*. Boston, MA: Pearson.

Bunton, Kate & Gary Weismer. 2002. Segmental level analysis of laryngeal function in persons with motor speech disorders. *Folia Phoniatrica et Logopaedica* 54, 223-239.

Cheng, Hei-Yan, Bruce E. Murdoch, Justine V. Goozee & Dion Scott. 2007. Electropalatographic Assessment of Tongue-to-Palate Contact Patterns and Variability in Children, Adolescents, and Adults. *Journal of Speech, Language, and Hearing Research* 50, 375-392.

Dagenais, Paul A., Leah C. Lorendo, & Martin J. McCutcheon. 1994. A Study of Voicing and Context Effects upon Consonant Linguapalatal Contact Patterns. *Journal of Phonetics* 22, 225-238.

Dixit, Rahul P. & Paul R. Hoffman. 2004. Articulatory Characteristics of Fricatives and Affricates in Hindi: an Electropalatographic Study. *Journal of the International Phonetic Association* 34 (2), 141-160.

Docherty, Gerard J. 1992. *The timing of voicing in British English obstruents*. Berlin - New York: Foris publications.

Fletcher, Samuel G. & Dennis G. Newman. 1991. [s] and [ʃ] as a Function of Linguapalatal Contact Place and Sibilant Groove Width. *Journal of the Acoustical Society of America* 89 (2), 850-858.

Fuchs, Susanne & Laura L. Koenig. 2009. Simultaneous measures of electropalatography and intraoral pressure in selected voiceless lingual consonants and consonant sequences of German. *Journal of the Acoustical Society of America* 126 (4), 1988–2001.

Fuchs, Susanne. 2005. Articulatory correlates of the voicing contrast in alveolar obstruent production in German. Unpublished PhD dissertation, Queen Margaret University College.

Fuchs, Susanne, Jana Brunner & Anke Busler. 2007. Temporal and spatial aspects concerning the realizations of the voicing contrast in German alveolar and postalveolar fricatives. *Advances in Speech-Language Pathology* 9(1), 90-100.

Gibbon, Fiona, William Hardcastle & Katerina Nicolaidis. 1993. Temporal and Spatial Aspects of Lingual Coarticulation in /kl/ Sequences: A Cross-Linguistic Investigation. *Language and Speech* 36 (2, 3), 261-277.

Gibbon, Fiona E., Alison M. McNeill, Sara E. Wood & Jocelynne M.M. Watson. 2003. Changes in Linguapalatal Contacts Patterns During Therapy for Velar Fronting in a 10-year-old with Down's Syndrome. *International Journal of Language and Communication Disorders* 38 (1), 47-64.

Gibbon, Fiona E. & Sara E. Wood. 2003. Using electropalatography (EPG) to diagnose and treat articulation disorders associated with mild cerebral palsy: a case study. *Clinical Linguistics & Phonetics* 17 (4-5), 365-374.

Grigos, Maria I., John H. Saxman & Andrew M. Gordon. 2005. Speech motor development during acquisition of the voicing contrast. *Journal of Speech, Language, and Hearing Research* 48, 739–752.

Grunwell, Pamela. 1987. *Clinical phonology, 2nd ed.* London: Croom Helm.

Hardcastle, William J. & Fiona Gibbon. 1997. Electropalatography and its clinical applications. In Martin J. Ball, & Christopher Code (eds.), *Instrumental clinical phonetics*,149–193. London: Croom Helm.

Hardcastle, William J., Fiona Gibbon & Katerina Nicolaidis. 1991. EPG Data Reduction Methods and Their Implications for Studies of Lingual Coarticulation. *Journal of Phonetics* 19, 251-266.

Hardcastle, William & Susan Edwards. 1992. EPG-based description of apraxic speech errors. In Raymond D. Kent (ed.), *Intelligibility in speech disorders: Studies in speech pathology and clinical linguistics*, 287–329. Amsterdam/Philadelphia: John Benjamins.

Liker, Marko & Fiona E. Gibbon. 2011. Groove width in Croatian voiced and voiceless postalveolar fricatives. In Wai-Sum Lee & Eric Zee (eds.) *Proceedings of the 17th International Congres of Phonetic Sciences in Hong Kong, China,* 1238-1241, Hong Kong: University of Hong Kong.

Liker, Marko, Damir Horga & Vesna Mildner. 2012. Electropalatographic specification of Croatian fricatives /s/ and /z/. *Clinical Linguistics & Phonetics* 26 (3), 199-215.

Mair, Sheila J., Celia Scully & Christine H. Shadle. 1996. Distinctions Between [t] and [tʃ] using Electropalatography Data. In Timothy H. Bunnel & William Idsardi (eds.), *Proceedings of the 4th ICSLP in Philadelphia, vol. 3,* 1597-1600.

McLeod, Sharynne. 2006. Australian adults' production of /n/: An EPG investigation. *Clinical Linguistics & Phonetics* 20 (2/3), 99-107.

McLeod, Sharynne, Amber Roberts & Jodi Sita. 2006. Tongue/palate contact for the production of /s/ and /z/. *Clinical Linguistics and Phonetics* 20(1), 51-66.

Narayanan, Shrikanth S., Abeer A. Alwan & Katherine Haker. 1995. An articulatory study of fricative consonants using magnetic resonance imaging. *Journal of the Acoustical Society of America* 98 (3), 1325-1347.

Ohala, John J. & Maria-Joseph Sole. 2010. Turbulence and phonology. In Susanne Fuchs, Martine Toda & Marzena Zygis (eds.), *Turbulent Sounds: An Interdisciplinary Guide*, 37-102. Berlin/New York: De Gruyter Mouton.

Proctor, Michael I., Christine H. Shadle & Khalil Iskarous. 2010. Pharyngeal articulation in the production of voiced and voiceless fricatives. *Journal of the Acoustical Society of America* 127 (3), 1507-1518.

Recasens, Daniel & Aina Espinosa. 2007. An electropalatographic and acoustic study of affricates and fricatives in two Catalan dialects. *Journal of the International Phonetic Association* 37 (2), 143-172.

Scully, Celia. 1971. A comparison of /s/ and /z/ for an English speaker. *Language and Speech* 14 (2), 187-200.

Simonsen, Hanne Gram & Inger Moen. 2004. On the distinction between Norwegian /ʃ/ and /ç/ from a phonetic perspective. *Clinical Linguistics & Phonetics* 18 (6-8), 605-620.

Smit, Ann Bosma, Linda Hand, Joseph J. Frelinger, John E. Bernthal & Ann Bird. 1990. The Iowa articulation norms project and its Nebraska replication. *Journal of Speech and Hearing Disorders* 55, 779-798.

Wrench, Alan. 2008. *Articulate Assistant User Guide, version 1.17*. Articulate Instruments Limited, QMU: Musselburgh.

Wrench, Alan A. 2007. Advances in EPG palate design. *Advances in Speech-Language Pathology* 9 (1), 3-12.

Wrench Alan A., Fiona E. Gibbon, Alison M. McNeill & Sara E. Wood. 2002. An EPG therapy protocol for remediation and assessment of articulation disorders. In John H.L. Hansen & Brian L. Pellom (eds.), *Proceedings of ICSLP-2002*, 965-968.

Yoshioka, Hirohide. 2008. The role of tongue articulation for /s/ and /z/ production in whispered speech. *Acoustics 2008 Paris*, 2335-2338.

Figure captions:

Figure 1. An illustration of the TAL measure calculation.

Figure 2. A visualisation of the difference in the amount of contact between the voiced and the voiceless postalveolar fricatives.

Figure 3. Average CoG values measured at equally spaced sample points during alveolar fricative productions in each speaker (F1, F2, F3, M1, M2, M3). Full line represents voiceless fricative /s/ and dashed line represents voiced fricative /z/. Encircled are data points at which statistically significant differences were found between the voiced and the voiceless ($p<0.01$).

Figure 4. EPG printouts of alveolar fricative /s/ (above) and /z/ (below) in the context of vowel /a/ in speaker F1. Slower increase of EPG contacts at the place of articulation during the voiceless /s/ is clearly observable.

Figure 5. Average CoG values measured at equally spaced sample points during postalveolar fricative productions in each speaker (F1, F2, F3, M1, M2, M3). Full line represents voiceless fricative /ʃ/ and dashed line represents voiced fricative /ʒ/. Encircled are data points at which statistically significant differences were found between the voiced and the voiceless ($p<0.01$).

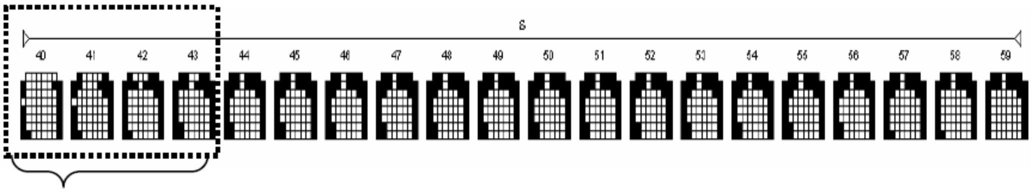
Figure 6. Average lateral values measured at equally spaced sample points during postalveolar fricative productions in each speaker (F1, F2, F3, M1, M2, M3). Full line represents voiceless fricative /s/ and dashed line represents voiced fricative /z/. Encircled are data points at which statistically significant differences were found between the voiced and the voiceless ($p<0.01$).

Figure 7. TAL measure in alveolar fricatives for each speaker. Encircled are speakers who show statistically significant differences between the voiced and the voiceless ($p<0.01$).

Figure 8. TAL measure in postalveolar fricatives for each speaker. Encircled are speakers who show statistically significant differences between the voiced and the voiceless ($p<0.01$).

Figure 9. Amount of contact difference (vertical axis) between /s/ and /z/ (left chart) and /ʃ/ and /ʒ/ (right chart) in speaker F1 in each row of electrodes (horizontal axis) throughout fricative duration (z-axis). Positive values indicate greater contact in the voiced, while negative values indicate greater amount of contact in the voiceless.

Figure 1



$$TAL = \left(\frac{40}{200}\right) \times 100 = 20\%$$

Figure 2

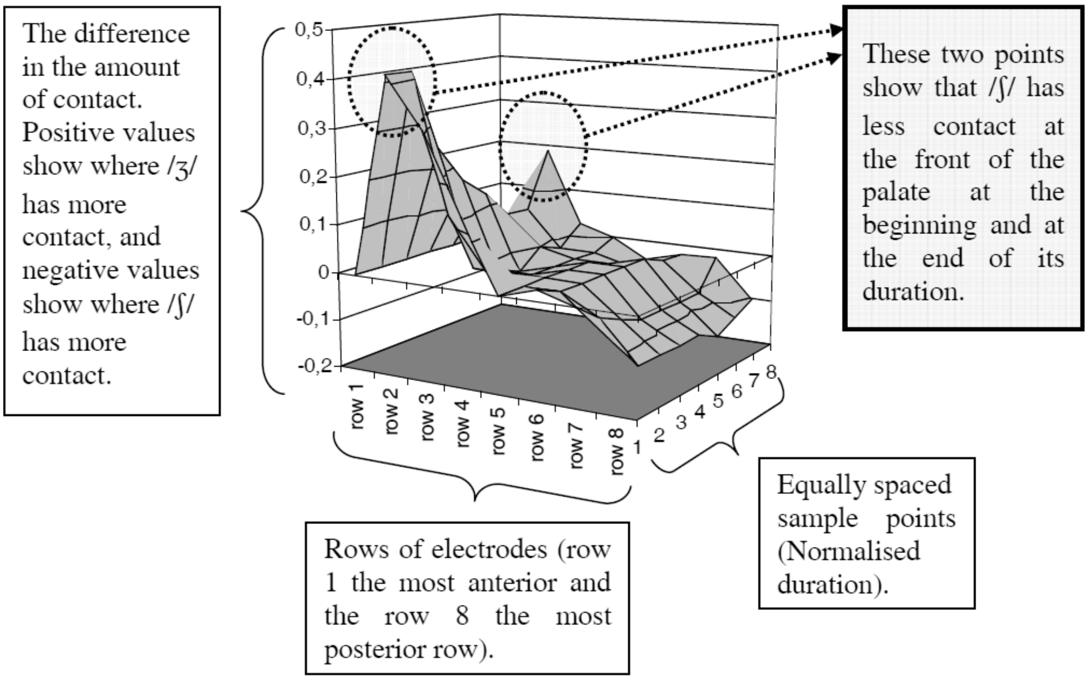

The difference in the amount of contact. Positive values show where /ʒ/ has more contact, and negative values show where /ʃ/ has more contact.
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
row 1
row 2
row 3
row 4
row 5
row 6
row 7
row 8
1
2
3
4
5
6
7
8
These two points show that /ʃ/ has less contact at the front of the palate at the beginning and at the end of its duration.
Rows of electrodes (row 1 the most anterior and the row 8 the most posterior row).
Equally spaced sample points (Normalised duration).

Figure 3

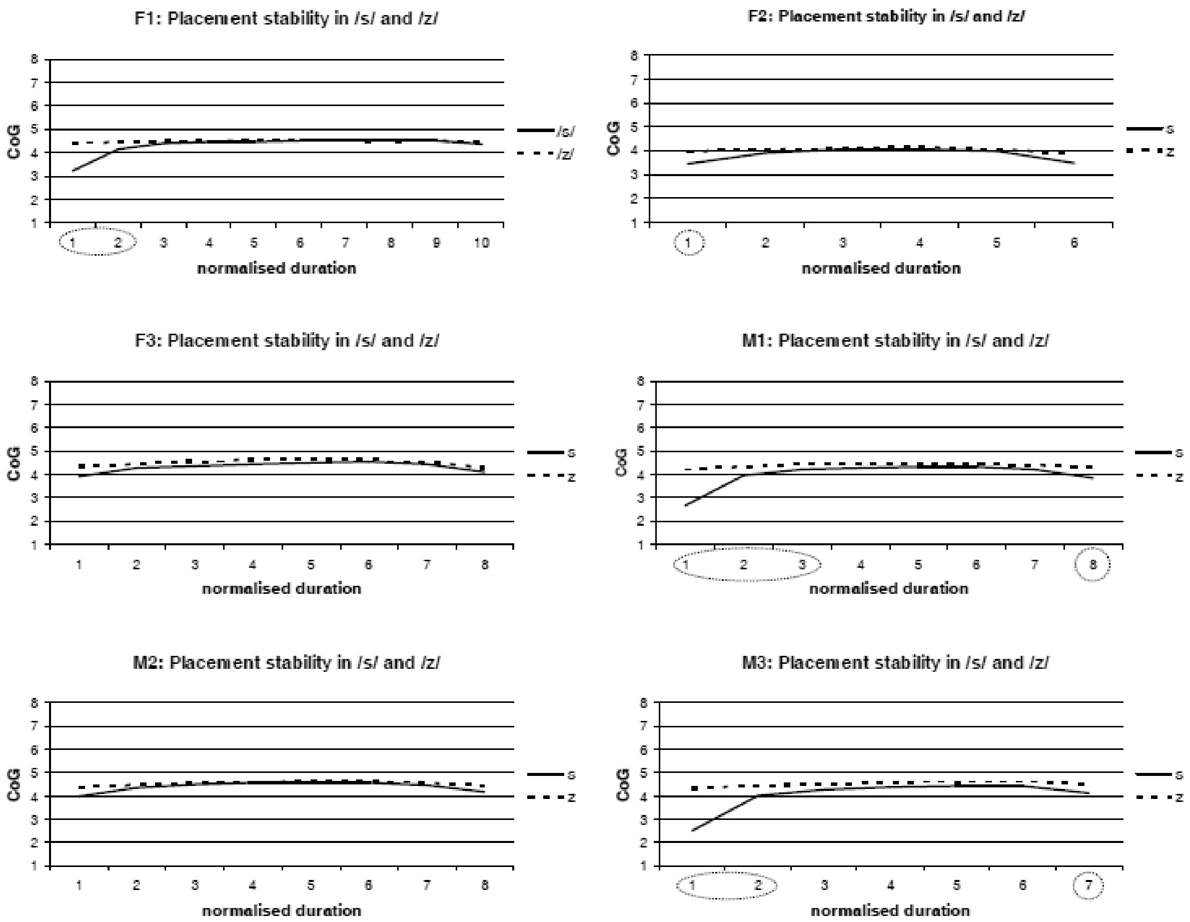

F1: Placement stability in /s/ and /z/
F2: Placement stability in /s/ and /z/
F3: Placement stability in /s/ and /z/
M1: Placement stability in /s/ and /z/
M2: Placement stability in /s/ and /z/
M3: Placement stability in /s/ and /z/
CoG
normalised duration
/s/
/z/
s
z

Figure 4

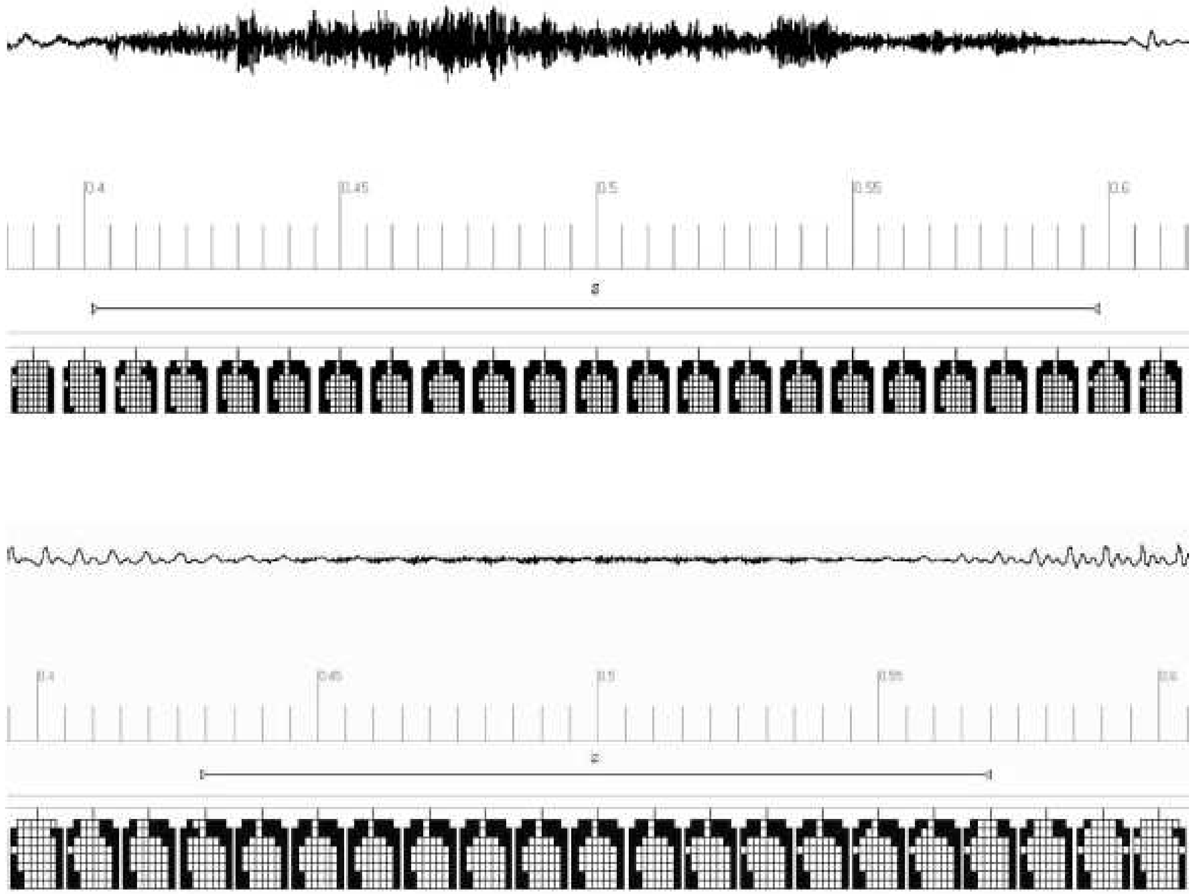


Figure 5

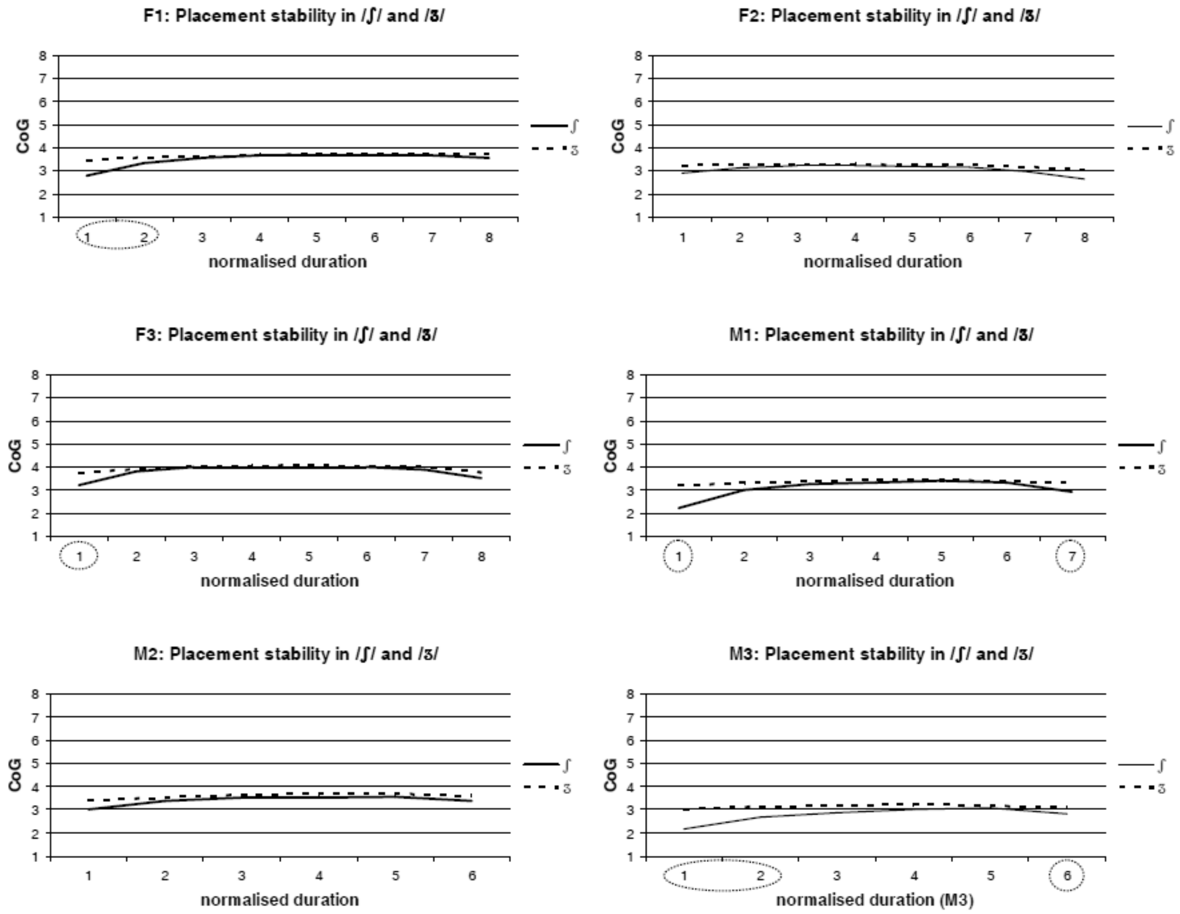

F1: Placement stability in /ʃ/ and /ʒ/
F2: Placement stability in /ʃ/ and /ʒ/
F3: Placement stability in /ʃ/ and /ʒ/
M1: Placement stability in /ʃ/ and /ʒ/
M2: Placement stability in /ʃ/ and /ʒ/
M3: Placement stability in /ʃ/ and /ʒ/
CoG
normalised duration
normalised duration (M3)
ʃ
ʒ

Figure 6

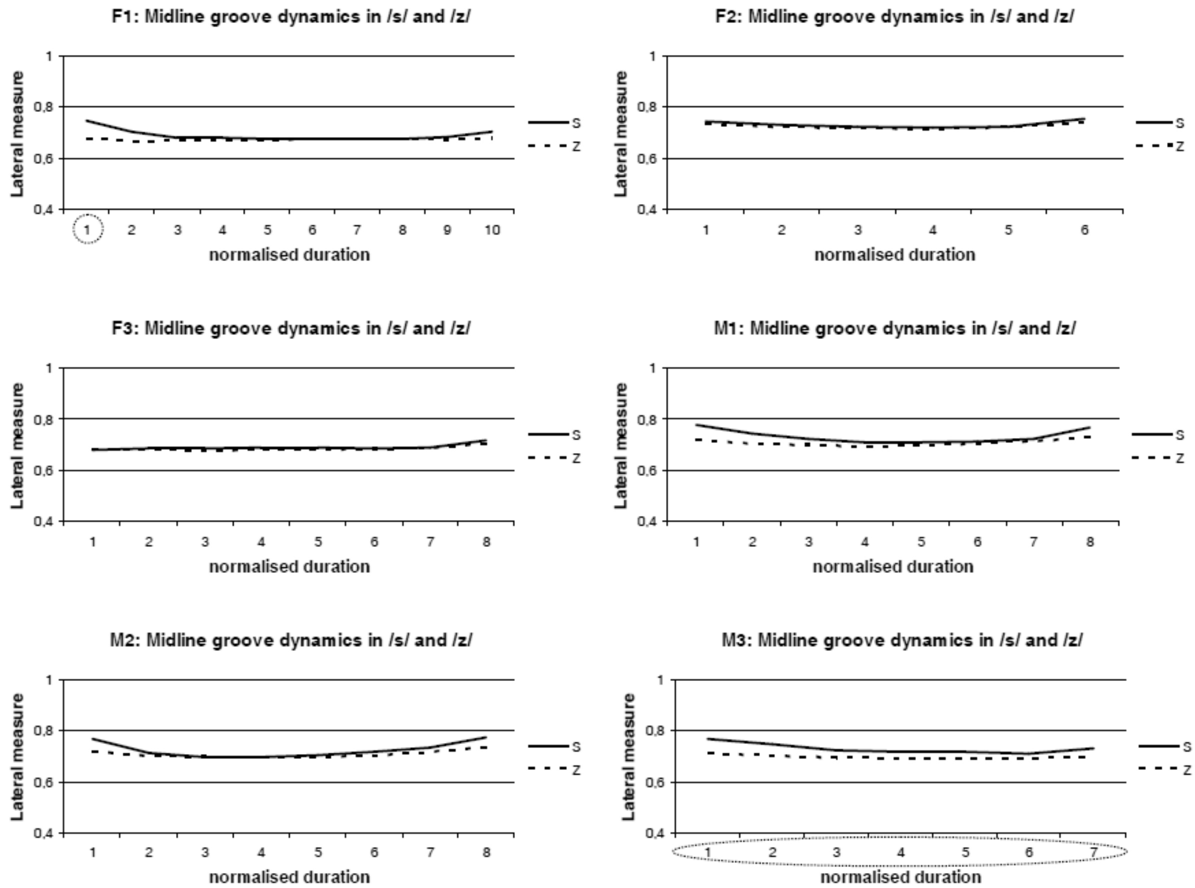

F1: Midline groove dynamics in /s/ and /z/
Lateral measure
1
0,8
0,6
0,4
1 2 3 4 5 6 7 8 9 10
normalised duration
s
z
F2: Midline groove dynamics in /s/ and /z/
1 2 3 4 5 6
F3: Midline groove dynamics in /s/ and /z/
1 2 3 4 5 6 7 8
M1: Midline groove dynamics in /s/ and /z/
M2: Midline groove dynamics in /s/ and /z/
M3: Midline groove dynamics in /s/ and /z/
1 2 3 4 5 6 7

Figure 7

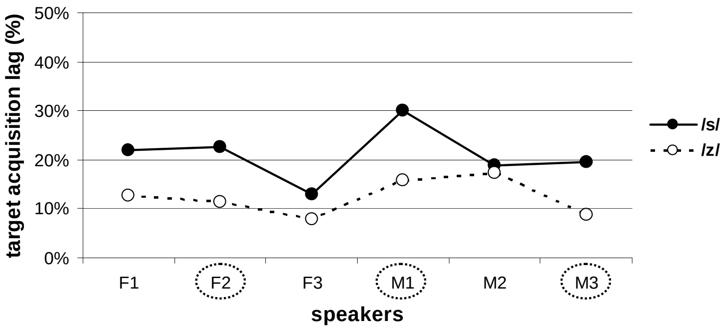

50%
40%
30%
20%
10%
0%
target acquisition lag (%)
F1
F2
F3
M1
M2
M3
speakers
/s/
/z/

Figure 8

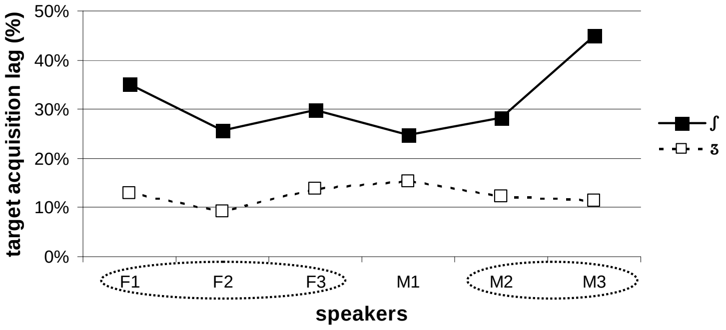
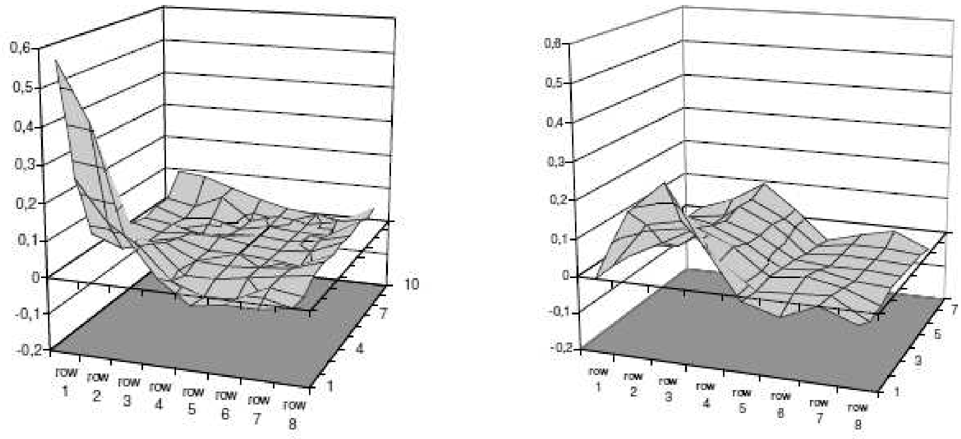

50%
40%
30%
20%
10%
0%
target acquisition lag (%)
F1
F2
F3
M1
M2
M3
speakers
ʃ
ʒ

Figure 9


0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
row 1
row 2
row 3
row 4
row 5
row 6
row 7
row 8
1
4
7
10
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
row 1
row 2
row 3
row 4
row 5
row 6
row 7
row 8
1
3
5
7