Title	Tongue-palate contact timing during /s/ and /z/ in English.
Authors	Liker, Marko;Gibbon, Fiona E.
Publication date	2018-02
Original Citation	Liker, M. & Gibbon, F.E. (2018) 'Tongue-Palate Contact Timing during /s/ and /z/ in English'. Phonetica, 75 (2), pp.110-13. doi: 10.1159/000479880
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1159/000479880
Rights	© 2018 S. Karger AG, Basel. This is the peer-reviewed but unedited manuscript version of the following article: Phonetica, 75(2), pp. 110-131. (DOI: 10.1159/000479880). The final, published version is available at https://www.karger.com/DOI/10.1159/000479880
Download date	2024-08-06 13:30:46
Item downloaded from	https://hdl.handle.net/10468/5705

Tongue palate contact timing during /s/ and /z/ in English

Marko Liker *

Fiona E. Gibbon **

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

** University College Cork, Ireland

Short title:

EPG timing during /s/ and /z/ in English

Corresponding author's details:

Marko Liker
University of Zagreb
Department of Phonetics, Faculty of Humanities and Social Sciences, Ivana Lucica 3, 10000 Zagreb
Croatia
telephone: + 385 1 4092289; fax: + 385 1 4092096
mliker@ffzg.hr

Tongue palate contact timing during /s/ and /z/ in English

Abstract

Although numerous studies have investigated supraglottal strategies for signaling voicing in fricatives, there is still no agreement about the precise characteristics of tongue-to-palate contact timing during voiced as opposed to voiceless fricatives.

In this study we use electropalatography (EPG) to investigate articulatory and coarticulatory characteristics of tongue-to-palate contact timing during /s/ and /z/ in English. Five typically-speaking participants, speakers of Southern British English, produced 500 trochaic words containing intervocalic alveolar fricatives /s/ or /z/. The time between the start of the frication and the maximum contact at the place of articulation was expressed as a percentage of each fricative's total duration (TT). This measure was used to analyse articulatory and coarticulatory timing during /s/ and /z/. Data for absolute timing was also presented.

The results showed that the time between the start of the frication and the maximum contact point was longer for /s/ than for /z/. This difference was consistent across speakers, but was not significant for all of them. The results of the coarticulatory effects showed that the influence of vowel context on TT values for /s/ and /z/ did not differ significantly, but there was a tendency for /z/ to be more resistant to coarticulation effects than /s/.

Key words: fricatives, voicing, tongue-to-palate contact timing, electropalatography (EPG)

Introduction

Several studies have shown that supraglottal strategies for signalling voicing difference in fricatives are quite complex and ample evidence currently exists detailing various articulatory aspects of this difference (Dagenais, Lorendo, McCutcheon, 1994; Dixit & Hoffman, 2004; Fuchs, Brunner, Busler, 2007; Koenig, Lucero, Perlman, 2008; Liker & Gibbon, 2011; Liker, Horga, Mildner, 2012; McLeod, Roberts, Sita, 2006; Narayanan, Alwan, Haker, 1995; Proctor, Shadle, Iskarous, 2010; Recasens & Espinosa, 2007; Scully, 1971; Skarnitzl, Šturm, Machač, 2013; Tabain, 2000; Yoshioka, 2008). Available data have suggested that important clues for understanding the difference between voiced and voiceless fricatives can be found in the temporal characteristics of fricative articulation (e.g. Koenig et al. 2008; Fuchs et al. 2007), but the issue is still relatively underinvestigated and there is no agreement among authors about the precise characteristics of articulatory timing in voiced as opposed to voiceless fricatives (e.g. compare Scully, 1971; Fuchs et al. 2007). This is especially true for one of the most important aspects of supraglottal articulation - tongue-to-palate contact (Fuchs et al. 2007; McLeod et al. 2006), which is successfully investigated using electropalatography (EPG, Gibbon & Nicolaidis, 1999; Stone, 2010). The present study, therefore, explores this issue and uses EPG to investigate the characteristics of tongue-to-palate contact timing during voiced and voiceless sibilant fricatives in English. Other correlates of voicing contrast in fricatives, such as the duration of the previous vowel, or shapes and sizes of oral constrictions, and so on, were not investigated here, as these could be best addressed in a separate study.

The complexity of the phenomenon of articulatory timing in voiced and voiceless fricatives mostly stems from three well established facts: 1) lingual fricatives are precisely controlled segments (e.g. Recasens, 1999; Shadle, 1990), 2) simultaneous voicing and frication require complex and often opposite supraglottal production strategies (e. g. Fuchs et al. 2007; Ohala & Solé, 2010), and 3) languages, and speakers within languages, differ in how they typically achieve voicing and frication (e. g. Ladefoged & Maddieson, 1996). We shall briefly examine each of these three points and see how they relate to the issue of tongue-to-palate contact timing during voiced and voiceless lingual fricatives.

Fricatives are acquired relatively late in speech development and they are relatively difficult to produce, which is commonly attributed to the complexity and precise control of their articulation (Grunwell, 1987; Koenig et al. 2008; Ladefoged & Maddieson, 1996). Successful fricative production requires a controlled constriction small enough to produce a turbulent sound, but large enough to prevent the formation of a closure (Iskarous, Shadle & Proctor, 2011). In order to control the constriction, a precise relationship between the active and the passive articulator needs to be maintained throughout the fricative. Careful control of the constriction depends on the configuration of the vocal tract behind the place of articulation (demands placed on the tongue dorsum to channel the air) and in front of the place of articulation of the lingual fricative (the positioning of the obstacle towards which the air is channelled) (Catford, 1977; Hardcastle & Gibbon, 1997; Hardcastle & Edwards, 1992; McLeod et al. 2006). Research showed that in order to maintain these complex relationships between several articulatory and aerodynamic factors, fricative productions were temporally structured, i.e. their articulatory characteristics changed during their productions (Iskarous et al. 2011; Mooshammer, Hoole & Geumann, 2007). These authors found that jaw and tongue motion had specific trajectories and that variability in jaw motion was often compensated by the tongue tip in order to maintain articulatory and aerodynamic conditions for fricative production.

Voicing further complicates the precise articulatory timing in fricatives. In order to maintain voicing, subglottal air pressure needs to be higher than supraglottal pressure and the vocal folds must be adducted with appropriate tension. If the supraglottal pressure rises too much, vocal fold vibrations will stop, and if the supraglottal pressure drops too much, frication will cease. This is particularly important for voiced stops in which supraglottal air pressure rises fast due to airstream being blocked at the place of articulation (Westbury, 1983). Therefore, voiced stops employ cavity enlargement strategies, whereby the cavity behind the place of articulation expands during occlusion in order to postpone supraglottal pressure build-up (Docherty, 1992; Fuchs, 2003; Westbury, 1983).

Voiced fricatives are even more complex than voiced stops because they need to increase supraglottal pressure sufficiently to produce frication, and at the same time keep the supraglottal pressure low enough to allow voicing. This complex glottal-supraglottal coordination employed during voiced fricatives is explained by Ohala and Solé (2010), who noted that there was a narrow range of pressure between 3 and 5.6 cm H_2O in which both voicing and frication could be maintained. The authors elaborated on this, saying that in voiced fricatives vibrating vocal folds reduced transglottal flow, which impaired frication, and if strong frication occured, a high intraoral pressure would stop vocal fold vibration. Furthermore, it seems that the supraglottal pressure build-up in fricatives is so strong that articulatory strategies similar to those observed in stops need to be employed to regulate voicing during frication. Possible cavity enlargement processes in voiced fricatives have been reported in previous studies (e.g. Liker & Gibbon 2011; Narayanan et al. 1995). Voiceless fricative production, on the other hand, does not require vocal fold vibration, so their articulatory timing has a different set of requirements, when compared with their voiced counterparts. It is, therefore, reasonable to expect that voiceless lingual fricatives should show lower articulatory variability and relatively stable tongue-to-palate configuration during their production, while voiced fricatives should be more variable and have relatively less stable tongue-to-palate configuration throughout due to the requirement of regulating two complex processes - voicing and frication. Despite apparently having simpler constraints affecting voicing and frication, recent EPG data published on Croatian anterior lingual fricatives /s/ and /z/ suggested that voiceless fricative /s/ needed significantly more time to reach its articulatory target than /z/, relative to the start of frication (Liker & Gibbon, 2013). The results from this study were partially explained by biomechanics and aerodynamic processes, which might be expected to be language universal and not specific to one language: Croatian. The authors concluded that voicing difference in fricatives could not be fully captured by static measurements alone and that the timing of articulatory characteristics must be taken into account. It should be kept in mind, as the authors noted, that speech material used in their study consisted of nonsense sequences spoken by Croatian speakers. Therefore, more research is needed to investigate whether similar tongue-to-palate processes during fricatives can be observed in real words and in languages other than Croatian, i.e. whether the finding that voiceless fricative /s/ needs significantly more time than /z/ to reach its articulatory target may be a universal phenomenon in languages with /s/-/z/ contrast.

Acoustic and articulatory characteristics of voicing differ from one language to another (Browman & Goldstein, 1986; Dagenais et al. 1994; Liker et al. 2012; McLeod et al. 2006; Docherty, 1992; Fuchs, 2005; Fuchs et al. 2007; Gordeeva & Scobbie, 2007; Pinho, Jesus, Barney, 2012). For example, in languages like English or German it is common for phonologically voiced obstruents to be partially or completely voiceless phonetically, while in languages like Czech or Croatian this process is much less common (Skarnitzl et al. 2013; Bakran, 1996). These language differences suggest that the articulatory phenomena associated with voicing observed in Croatian fricatives reported by Liker and Gibbon (2013) may not be observed in English fricatives investigated here. Nevertheless, Liker and Gibbon explained their results from the Croatian study at least in part by language universal phenomena, raising the possibility that similar phenomena would also be found in English fricatives.

From the review above it is clear that voiced and voiceless lingual fricatives are temporally structured sounds and that they differ in glottal-supraglottal coordination, which may result in different timing of supraglottal articulatory gestures. The linguopalatal correlates of this difference are still to a large extent unknown and available data allow for different hypotheses. It is therefore our aim to use EPG to investigate tongue-to-palate contact timing during lingual fricatives /s/ and /z/ in English and see whether voiced or voiceless fricatives achieve faster target acquisition relative to the start of frication. We shall also investigate whether the characteristics of tongue-to-palate contact timing differ in various vowel contexts. We shall compare the results to the Degree of Articulatory Constraint model (DAC, Recasens, 1999; Recasens & Pallarès, 2001; Recasens, Pallarès & Fontdevila, 1997), which predicts that fricatives in general will show relatively high coarticulatory resistance and that voicing will decrease this resistance to the influence of neighbouring vowels. Based on the findings from these studies, we could hypothesize that the voiceless fricative in the present study will show more coarticulatory resistance than its voiced counterpart. However, it is often reported in the literature that the voiced fricative shows increased EPG contact and smaller groove width (Dagenais et al. 1994; Dixit & Hoffman, 2004; McLeod et al. 2006; Liker & Gibbon, 2011) which might perhaps warrant the opposite hypothesis: that the voiced fricative will be more resistant to coarticulation than the voiceless fricative, due to increased constraints exerted on tongue dorsum (Farnetani, 1990).

Method

Speech material

Speech material was extracted from the EUR-ACCOR database (Marchal & Hardcastle, 1993). The fricative targets included in the study were phonologically/phonetically classified as alveolar articulations. Simultaneous EPG and acoustic data were recorded as the participants read out loud a list of real words spoken in isolation, in which alveolar fricatives /s/ and /z/ were in ‘phonologically symmetrical and asymmetrical’ vowel contexts and at the beginning of an unstressed syllable (Table 1). Vowels in the unstressed position undergo vowel reduction so true symmetrical vowel context was not possible. Also, the mid central vowel schwa (/ə/) is a phoneme in Southern British English, so it is debatable whether it can be treated as some sort of an underlying /ɑ/ or /a/ in words like “Lisa”. However, we do this because it is the closest possible alternative to the phonologically symmetrical /ɑFɑ/ in real trochaic words. Therefore, in this paper terms ‘phonologically symmetrical’ and ‘phonologically asymmetrical’ are used for convenience, to easily distinguish between the two types of contexts, and they are always presented in scare quotes. Phonetic transcription is provided to avoid misunderstanding. Also, the aim was to use words with equivalent vowel context for the two fricatives wherever possible, or to use nearest equivalents provided by the corpus (e.g. “Lisa” and “freezer”). Note that there are no two syllable English words in which /z/ is in the ‘phonologically symmetrical’ vowel /u/ context in this corpus. Also, there are no two syllable words with fricatives /s/ or /z/ in the context /ɑ_u/ in the corpus. Therefore, these two contexts were not included in the analysis. Each speaker repeated the wordlist 10 times, providing 500 words for analysis.

Insert Table 1 about here.

Participants

Five English speakers were included in the study (S1 – S5). Speakers were male (S1, S4, S5) and female (S2, S3), aged between 24 and 47 years. At the time of the recording they were all faculty members of the University of Reading in the UK and they all spoke a variety of Southern British English accent.

Speakers involved in this investigation reported no history of speech or hearing impairments.

Instrumentation and recording

The data in the EUR-ACCOR database were recorded using the Reading Multi-channel System. In this investigation only the audio and the EPG signal were used. The Reading palate was used to obtain EPG data (Hardcastle, Gibbon & Jones, 1991; Wrench, 2007). The palate is made of thin acrylic resin and covers the palatal surface. It is constructed individually for each speaker according to his or her anatomical landmarks and has 62 electrodes, each of which is aligned with the anatomical features of the speaker. The acoustic signal was captured via a high quality microphone (Sennheiser MKH 40 P48). Data were digitised and imported into the Articulate Assistant software (Wrench, Gibbon, McNeill, & Wood, 2002), which was used for segmentation, annotation and analysis. The sampling rate for the EPG data was 100 Hz and for the acoustic data 22050 Hz. IBM SPSS Statistics 20 was used for statistical analyses and MS Excel was used for data visualisation.

Praat software (Boersma & Weenink, 2012) was used for measuring voicing duration in voiced fricatives. This is described in sections on annotation and segmentation reliability.

Prior to recording all speakers underwent a desensitization period, whereby their articulation was adjusted to the presence of the EPG palate in the mouth. Speakers were instructed to wear the palate for at least 2 hours before the EPG recording as they went about their day to day business. This period has been shown to be sufficient according to McLeod and Searl (2006).

Segmentation and annotation

Annotation and segmentation of fricatives were performed according to established acoustic criteria (Jesus & Shadle, 2002, Mitani, Kitama & Sato, 2006). The acoustic criterion for the beginning of a fricative was the start of high-frequency noise and/or the absence of the second formant in the preceding vowel on the spectrogram. The end of the fricative was the absence of high-frequency noise and/or the presence of a clearly visible second formant (figures 1 and 2). If the high frequency noise and the clearly visible second formant did not coincide in time, the criterion was the high-frequency noise. The acoustic criterion for fricative segmentation was chosen because to our knowledge there was no reliable, widely accepted EPG criterion for fricative segmentation and annotation.

Insert figure 1 about here.

Insert figure 2 about here.

Data analysis

Articulatory and coarticulatory timing during /s/ and /z/ were analysed in order to compare the time taken to reach target and to measure coarticulatory effects.

Articulatory timing

1. Time-to-target (TT) at the place of articulation shows how long it takes for each fricative to reach its target - the point of maximum EPG contact. TT was calculated by measuring the time needed for each fricative in each speaker to reach the point of maximum EPG contact at the place of articulation and by expressing it as a percentage of the total duration of the fricative. It can be shown as a formula:

$$TT = \left(\frac{MCP}{TD}\right) \times 100,$$

where MCP is the amount of time between the beginning of a fricative and the earliest time at which maximum contact point is achieved and TD is the total duration of a fricative.
Since places of articulation in this investigation ranged between rows 1 and 4, the point of maximum EPG contact was located in the front half of the palate (front four rows) during each fricative production.

Absolute durations for /s/ and /z/ for each speaker were also presented and data were aligned at the time at which maximum EPG contact was achieved for each fricative (marked as MCP in figure 6).

Statistical analysis was performed on TT values and on fricative duration values using repeated measures ANOVA with speakers as experimental units, while fricative type and vowel context were factors varying within each speaker (repeated measures). Differences between /s/ and /z/ within each speaker were tested by means of a paired t-test. Alpha was set at 0.05.

2. TT visualization was performed by measuring the amount of contact in each row of electrodes during each fricative. The amount of contact equals the number of contacted electrodes in each row, divided by the total number of electrodes in that particular row of

electrodes. A higher contact value means more linguopalatal contact in a particular articulatory region.

In order to average productions of different durations and visualise them, measured durations were normalised. The normalisation was performed by measuring the amount of contact in each row of electrodes at a predetermined number of sample points (N_{sp}) during /s/ and /z/. The N_{sp} was determined by the formula:

$$N_{sp} = \frac{t}{10},$$

where t was the duration of the shortest fricative in the whole speech material in milliseconds and 10 represented the number of milliseconds between successive EPG frames, determined by the EPG sampling frequency (100 Hz) (Liker & Gibbon, 2013). It was important to choose the shortest fricative in the whole speech sample in order to prevent over-sampling, because multiple sampling of the same EPG frame would have resulted in the impression of stability where it did not necessarily exist. The shortest voiced fricative in the whole speech sample was 52 ms, so data were sampled at five sample points for all voiced fricatives. The shortest duration of a voiceless fricative was 84 ms, so the sampling was set at 8 sample points for all voiceless fricatives (figure 3). The figure shows that /z/ is relatively shorter (5 sample points) than /s/ (8 sample points) and the darkest shading indicates that the average amount of contact in both fricatives is greatest around row 3. The darker shading in row 3, that increases from column 2 onwards for /s/ and from column 1 onwards for /z/, indicates that the maximum contact is reached relatively earlier in /z/ than in /s/.

Insert figure 3 about here.

Coarticulatory timing

1. In order to determine how different vowel contexts influence the lag in target acquisition in the two fricatives, TT was calculated for each vowel context for each speaker. The significance of differences was tested using repeated measures 2 (fricatives) x 5 (vowel contexts) ANOVA. Alpha was set at 0.05.

2. The relative amount of coarticulation was visualised by plotting the difference in the amount of contact between the ‘phonologically symmetrical’ vowel context a-*F*-a and every other vowel context at each sample point during fricatives /s/ and /z/. The difference in the amount of contact was calculated by subtracting the average amount of contact on the whole palate in each sample point of a fricative in the ‘phonologically symmetrical’ vowel context a-*F*-a from the same fricative in every other vowel context.

For example, the difference in the amount of contact for fricative /s/ when it is produced in the vowel context /ɑ-s-ə/ and the amount of contact in /s/ when it is produced in the vowel context /i-s-ə/ shows the relative amount of carryover coarticulation allowed by /s/ from the preceding vowel /i/. When the same difference is calculated for /z/, carryover coarticulation in /s/ and /z/ can be compared visually (figure 4). It can be observed that /s/ coarticulates more at the beginning of its production (indicated by the large difference in the amount of contact in the first two sample points) than in the middle and the end of its production. A similar coarticulation pattern can be observed in /z/, but /z/ coarticulates relatively less at the beginning of its duration when compared with /s/ (there is a small difference in the amount of contact in the initial sample points).

Insert figure 4 about here.

Data showing relative amounts of coarticulation during each production of /s/ and /z/ were compared via regression lines. The relative amount of coarticulation for /s/ was compared with the relative amount of coarticulation for /z/ using linear regression analysis. This analysis is inspired by the locus equation calculation extensively used in acoustic analyses to quantify coarticulation (e.g. Lindblom, 1963; Tabain, 2000). In this investigation the relative amount of coarticulation at the beginning of the fricative was plotted as a function of the relative amount of coarticulation at the fricative mid-point. Increased slope values indicate that the degree of coarticulation at the edges of the fricative is strongly correlated with the degree of coarticulation at the middle of the fricative (see figures 11 and 12 in the Results).

Segmentation reliability

Annotation reliability was confirmed via an annotation verification procedure. A trained phonetician re-annotated 20% of data using the annotation and segmentation criteria described above. The average difference in annotation duration was less than 3% (about 3 ms) in the voiced fricative and 1.7% (a little over 2 ms) in the voiceless fricative (table 2), which was well below the time difference between the two consecutive EPG frames at 100 Hz framerate (10 ms).

Insert table 2 about here.

Annotation reliability

Before proceeding to the analysis of articulatory timing, we wanted to confirm the voiced/voiceless status of the fricatives under investigation. The annotation verification procedure also confirmed that voiceless fricatives were significantly longer than voiced fricatives (Appendix 1). Repeated measures ANOVA showed that the difference between the voiced and the voiceless fricative was statistically significant (F(1,4) = 78.35, p=0.001). The range was between 73 and 101 ms for voiced (mean 89, SD 10) and between 120 and 187 ms for voiceless fricatives (mean 159, SD 25). Inter-speaker variability was relatively low (12% for voiced and 18% for voiceless fricatives).

In order to further verify the annotations used in the experiment, we measured the duration of voicing in voiced fricatives (Appendix 2). The purpose of this was to check whether phonologically voiced targets were phonetically fully voiced or not. This was performed by visual inspection of the waveforms and the spectrograms using Praat software (Boersma & Weenink, 2012), whereby the duration of the periodicity and the voice bar were measured. The duration of voicing was expressed as a percentage of the total duration of a fricative. Averaged across speakers 58% (SD 21.68) of the duration of the voiced fricatives was voiced, ranging between 92% (SD 17.24) for S1 and 35% (SD 22.54) for S4. The initial portion of the fricatives was always voiced and there was no example of voicing existing only in the final part of the fricative and very few examples of voicing stopping and restarting mid-fricative. This is consistent with patterns of voicing reported for English fricatives (Docherty, 1992; Stephenson, 2015). Inter-speaker variability was 37.26%.

Voiceless fricatives were fully voiceless, which was the consequence of segmentation and annotation criteria for voiceless fricatives and it was consistent with data from English (Docherty, 1992). No medial voicing in voiceless fricatives was found.

Results

Articulatory timing

The data showed that productions of voiceless fricative /s/ by all speakers had larger TT when compared with their respective productions of /z/, i.e. it took longer for /s/ to reach its maximum constriction (mean TT 50%, SD 4.97) than it did for /z/ (mean TT 40%, SD 4.61) (figure 5). TT values for /s/ ranged between 42% (SD 7.86, speaker S1) and 54% (SD 11.54, speaker S2), while TT values for /z/ ranged between 35% (SD 14.65, speaker S4) and 46% (SD 18.91, speaker S5). The difference in TT was smallest for speakers S1 and S5 (TT/s/ - TT/z/ = 4%) and the largest difference in TT was for speaker S3 (TT/s/ - TT/z/ = 15%). The observed difference in TT values between /s/ and /z/ was not an artefact of durational differences between the two fricatives, because TT was calculated as the percentage of the total duration of the fricative.

Repeated measures ANOVA showed that the difference in TT between /s/ and /z/ was statistically significant (F(1, 4)=16.59, p=0.015). The statistical analysis for each speaker showed that the difference in TT between /s/ and /z/ was significant for three speakers (S2: t(49)=3.76, p<0.0001, S3: t(49)=6.21, p<0.0001, S4: t(49)=5.24, p<0.0001) and non-significant for two speakers (S1: t(49)=1.91, p=0.062; S5: t(49)=1.17, p=0.25).

Insert figure 5 about here.

In order to present differences in absolute time, not just relative time shown by TT, absolute durations of each fricative aligned at the point of maximum constriction (MCP) are presented in figure 6. Negative values show the duration of target acquisition, i.e. the time between the start of the fricative annotation and MCP. Positive values show the time between MCP and the end of fricative annotation. All MCPs are aligned at zero value. The data showed that differences in target acquisition between /s/ and /z/ were reflected in absolute timing as well (average value for /s/ was 85 ms (SD 20.16), while for /z/ was 40 ms (SD 6.2)). Repeated measures ANOVA showed that the difference was statistically significant (F(1, 4)=78.35, p=0.001).

Insert figure 6 about here.

Places of articulation and tongue-to-palate contact during these two fricatives for each speaker are visualised in figure 7. The figure illustrates the difference in target acquisition between /s/ and /z/, but it also shows individual differences in the amount of contact, place of articulation and contact timing. For example, although speakers S4 and S5 produced their fricatives with a relatively low amount of contact at the place of articulation when compared with other speakers, the difference in target acquisition time between /s/ and /z/ was just as observable as in productions from other speakers. Two points should be noted here: 1. that these figures do not show the difference between the lateral and the medial tongue-to-palate contact, because the amount of contact is averaged across the whole row of electrodes, and 2. that a low amount of contact in fricatives can generally be understood as showing a wide central groove.

Speakers with the smallest difference in TT values between /s/ and /z/ produced their fricatives at the most posterior place of articulation (S1 and S5: row 4), while other speakers had a more fronted place of articulation (S2: row 2, S3: row 3, S4: rows 2 in /s/ and 1 in /z/).

Insert figure 7 about here.

Coarticulatory timing

The data in figure 8 show that TT values are higher for /s/ than for /z/ in all vowel contexts, but statistical analysis reveals that the difference between /s/ and /z/ is not significant (F(4, 16)=0.37, p=0.826). Figure 8 also shows that TT values for /s/ and /z/ vary as a function of vowel context. However, statistical analysis of the interaction between fricative type and vowel context showed that differences did not reach statistical significance (F(4, 16)=0.435, p=0.781).

Insert figure 8 about here.

Coarticulatory effects during the production of the two fricatives are visualised in figures 9 and 10. The amount of contact measured at each sample point for the 'phonologically symmetrical' vowel context a-*F*-a (/ɑ_ə/) was subtracted from the amount of contact measured at each sample point in each of the remaining vowel contexts (/i_i/,/ɑ_i/,/i_ə/,/u_ə/). Therefore, values of data points in figures 9 and 10 are the values for the vowel context represented in the particular panel, minus the equivalent value for the a-*F*-a context in each EPG sample point.

The extent of coarticulatory effects at the beginning of the fricative was overall larger for voiceless /s/ than for voiced /z/, which can be seen in increased differences in the amount of contact in /s/ relative to /z/. Increased coarticulation at the beginning of /s/ can be explained by its significantly longer target acquisition time, as shown by the analysis of TT values presented in figure 5. It could be argued that during their target acquisition fricatives were not as resistant to coarticulation as they were during their mid portions, so coarticulatory effects were more pronounced during their target acquisition time. During /s/, carryover coarticulation was stronger than anticipatory coarticulation (figure 9), in that the differences in the amount of contact were greater in the third and the fourth column and lower in the second column. Voiced /z/ (figure 10) showed similar coarticulatory patterns to /s/, but coarticulatory effects were more evenly distributed across its duration in all four conditions, when compared with /s/ (i.e. differences between sample points were higher for /s/ than for

/z/, especially when edges of fricatives were compared to fricative mid-points). The difference between the carryover (the third and the fourth column of charts) and the anticipatory coarticulation (the second column of charts) in /z/ was also observable, although to a lesser extent than in the case of /s/. Data presented in figures 9 and 10 also illustrate individual differences between speakers. Although all speakers followed similar trends described above, some speakers' productions evidenced very little coarticulatory effects from neighbouring vowels (e.g. S5) when compared with other speakers (e.g. S1).

Insert figure 9 about here.

Insert figure 10 about here.

Regression analysis relating the amount of coarticulation at the edges of fricative duration (at the beginning for the 'phonologically symmetrical' vowel context and carryover effects; at the end for anticipatory effects) and the amount of coarticulation at the middle of the fricative showed that the slope value was lower for /s/ (0.0684) than /z/ (0.4799) (figures 11 and 12). This meant that the edges of /s/ were more strongly coarticulated with the adjacent vowel than was the mid-point of /s/. The steeper slope and the increased slope value for the /z/ data meant that the degree of coarticulation at the edges of the fricative was fairly predictive of the degree of coarticulation at the middle of the fricative (and vice versa), whereas the two were much less strongly correlated in the case of /s/.

The difference in coarticulation between /s/ and /z/ was probably connected with the finding that frication in voiceless fricatives often started before the maximum constriction was reached (Docherty, 1992, Hoole, Gobl & Ní Chasaide, 1999), which resulted in increased coarticulation with the preceding vowel at the acoustically determined beginning of /s/. The results of the coarticulatory timing analysis also agreed with the prediction from the Degree of Articulatory Constraint model of coarticulation (DAC, Recasens, 1999; Recasens & Pallarès, 2001; Recasens et al. 1997). The early occurrence of frication in voiceless fricatives and the prediction of the DAC model will be discussed in the Discussion. The negative y-intercept value in /z/ (-0.0039) indicated that in some cases the amount of coarticulation at the beginning of the fricative was lower than at the mid-point (e.g. carryover coarticulation effect of vowel /u/ for S5 as observed in figure 10).

Coefficients of determination (R^2) were very low for both /s/ and /z/ data, thus indicating that data were not closely clustered along the line-of-best-fit. This means that regression lines in both fricatives poorly approximate to data points (that the proportion of the variance in the data presented in the horizontal axis was not successfully predicted by the proportion of the variance in the data presented in the vertical axis). Therefore, the results of the regression analysis should be used with caution.

Insert figure 11 about here.

Insert figure 12 about here.

Discussion

The results of this study showed that voiced and voiceless anterior lingual fricatives differ in articulatory timing of tongue-to-palate contact patterns. The differences in coarticulatory effects of neighbouring vowels on the timing of tongue-to-palate contacts were not significant, but certain tendencies could be observed in the presented data.

The articulatory timing data showed that the portion of the voiceless fricative /s/ between the start of the frication and its target tongue-to-palate configuration (the point of maximum EPG contact at the place of articulation) was longer than the same portion of voiced fricative /z/. This was either due to the fact that voiceless fricatives took longer to reach their tongue-to-palate target or due to the fact that frication in voiceless fricatives started earlier than frication in voiced fricatives. This phenomenon did not appear to be an artefact of durational differences between /s/ and /z/, because the time fricatives took to reach their target was expressed as a percentage of the total duration of the fricative. This effect was consistent across speakers, although the statistical analysis showed that the difference was not significant for all speakers. The same effect was observed when the absolute time from the start of the frication to the point of maximum EPG contact was analysed and the differences were significant. The results from the present investigation were consistent with the data recently published on anterior lingual fricatives /s/ and /z/ produced by Croatian speakers, which showed that voiceless fricatives took significantly more time to reach their target configuration than voiced fricatives (Liker & Gibbon, 2013). The relatively fast target acquisition in voiced /z/ produced by Croatian speakers was explained by highly controlled and precise articulatory mechanisms employed to control complex aerodynamic conditions in voiced fricatives resulting in possible cavity enlargement strategy. Liker and Gibbon explained the relatively long target acquisition lag in voiceless /s/ in the Croatian study with reference to the air-pressure control hypothesis (Proctor et al. 2010), whereby the back of the tongue in voiceless fricatives was advanced in order to control the airstream and once the airstream was successfully controlled the tongue tip/lamina was precisely positioned to produce the constriction at the place of articulation.

Evidence of precise articulatory control and possible cavity enlargement strategy in voiced fricatives had been found in other studies (Liker & Gibbon 2011; Narayanan et al. 1995), so this explanation is consistent with the data presented in the present investigation. On the other hand, the air-pressure control mechanism used by Liker and Gibbon (2013) to explain the relatively long target acquisition lag in voiceless fricatives in Croatian is a hypothesis and the present investigation does not offer data on the relationship between the back of the tongue and the rear pharyngeal wall in voiceless fricatives. Therefore, the air-pressure control hypothesis cannot be utilized to explain the data on the voiceless fricative from the present study. However, the relative lag in target acquisition in the voiceless fricative presented in the present study could be accounted for by the fact that frication in sibilant fricatives often began before the maximum constriction was reached (Docherty, 1992). This was especially so with the so-called ‘obstacle’ fricatives like /s/ and /z/ in which the fricative noise is produced not at the point of maximum constriction, but at the obstacle anterior to the constriction (i.e. front teeth), if the jet of air has sufficient velocity (Docherty, 1992). Since the early increase of intraoral pressure in voiceless fricatives is needed (Hoole, Gobl & Ní Chasaide, 1999), the mismatch between the start of the frication and the maximum constriction was expected to be larger in voiceless than in voiced fricatives. The early onset of glottal abduction as well as early build-up of oral pressure in voiceless consonants is confirmed by research on the timing of vocal fold abduction (Hoole, Gobl & Ní Chasaide, 1999). This facilitated the early occurrence of frication in voiceless fricatives, even before the maximum constriction at the place of articulation was reached.

There are studies which report no difference in articulatory timing between /s/ and /z/ (e.g. Scully, 1971) and there are studies which show evidence of very small variability in /s/ productions (e.g. Iskarous et al. 2011). Scully (1971) investigated the productions of /s/ and /z/ by one English speaker measuring oral pressure and volume of airflow through the mouth. She found no evidence of the difference between /s/ and /z/ in cross-section area of the tongue constriction or tongue constriction flow resistance and concluded that the only difference between the two fricatives was in glottal adjustment. The difference in findings between

Scully’s study and the present investigation can be explained by the segmentation procedure. In Scully’s study segmentation was performed according to aerodynamic data (labelling peaks in tongue constriction flow resistance) and articulatory approximations (labelling peaks in cross-section area of the tongue constriction), while in the present study annotation and segmentation was performed according to acoustic criteria - the start and end of the frication. Since frication in the voiceless fricative can start prior to the formation of the maximum constriction, the time it took for the voiceless fricative to reach its maximum constriction was relatively long. However, if the segmentation was done without reference to the acoustic signal, this target acquisition lag could be smaller or even non-existent. Also, the present investigation showed that these differences between /s/ and /z/ were not significant for all speakers, indicating that the issue was to some extent speaker-specific. The issue might also be related to the place of articulation, because speakers with the most posterior place of articulation showed the least difference between /s/ and /z/ in TT values.

Iskarous and colleagues (2011) analysed x-ray microbeam and acoustic data from 24 subjects to investigate the production of /s/ in /sV/ and /sC/ conditions. Among other findings the authors reported that the variability due to jaw motion was sometimes compensated by the tongue tip motion and tongue bracing against the palate to maintain a stable constriction. The authors also showed that the tongue tip had very little variability when compared with the tongue dorsum. This finding does not necessarily contradict our findings, because in this investigation we analysed the relative difference between /s/ and /z/ and found that /s/ took a longer time to reach its target. The absolute amount of change in constriction during the two fricatives was not investigated in the present paper. However, differences in the amount of contact at the place of articulation between the start and the maximum contact zone, as visualised in figures 6, 8 and 9, were about 20%, which was less than 2 electrodes in a row. This showed that the difference in constriction during fricative production was generally low.

It should also be taken into account that fricatives in the Iskarous and colleagues' study were in the stressed syllable, while fricatives in this study were in the unstressed syllable. Stress and prosodic conditions influence fricative productions, especially their duration (Silbert & de Jong, 2008), so results from this investigation should be interpreted with this in mind.

Coarticulatory timing investigated in the present study showed that the difference in target acquisition lag between /s/ and /z/ was consistent across vowel contexts and that vowel context did not influence target acquisition lag significantly. Although there was no evidence of significant differences in coarticulatory timing between /s/ and /z/, certain tendencies could clearly be observed. Generally, the results showed that voiceless /s/ coarticulated more at its edges (at the beginning for the 'phonologically symmetrical' vowel context and carryover effects; at the end for anticipatory effects) than in the middle, while such coarticulatory timing patterns were less pronounced during /z/. The regression analysis confirmed this, showing a slight tendency for /z/ to be slightly more resistant to coarticulatory effects than /s/ at their edges. However, the results of the regression analyses showed low coefficients of determination (R^2), so caution is needed when drawing conclusions from the analysis. The results of the coarticulatory timing analyses can be explained by the Degree of Articulatory Constraint model (DAC, Recasens, 1999; Recasens & Pallarès, 2001; Recasens et al. 1997) and by the already mentioned mismatch between the start of frication and maximum constriction in voiceless fricatives (Docherty, 1992; Hoole, Gobl & Ní Chasaide, 1999.

The DAC states that articulatory gestures which involve tongue dorsum in constriction formation show increased coarticulatory resistance to the influence of neighbouring sounds. Sibilant fricatives require precise tongue body configurations, thus manifesting a high degree of articulatory constraint. This is reflected in consistent differences in TT values between /s/ and /z/ across vowel contexts. Voiced consonants are often described as less resistant to coarticulation than their voiceless counterparts, which is explained by lower tongue-to-palate contact in voiced tokens (Recasens, 1999). However, many EPG studies showed that voiced fricatives had increased tongue-to-palate contact and a smaller groove than voiceless fricatives (Dagenais et al. 1994; Dixit & Hoffman, 2004; Liker & Gibbon, 2011; Liker et al. 2012), although this issue can be related to the position in the syllable (McLeod et al. 2006). The finding that voiceless fricatives showed lower tongue-to-palate contact and wider groove than their voiced counterparts was mostly explained by aerodynamic factors, whereby the air pressure during voiceless fricatives was so high that it pushed out the lateral edges of the tongue, thus creating wider groove and less tongue-to-palate contact in the voiceless than in the voiced fricative. Another explanation was that there was a trade-off between airflow and aperture (McLeod et al. 2006) - decreased airflow during the voiced when compared with the voiceless required a narrower groove to achieve frication, while in the voiceless fricative frication could be achieved with a relatively wider groove due to increased airflow in the voiceless. Findings on coarticulatory timing during /s/ and /z/ in the present study are consistent with previously discussed studies showing that /z/ was produced with increased tongue-to-palate contact when compared with /s/, and therefore its tongue dorsum was more constrained and more resistant to coarticulation.

This difference in coarticulatory timing between /s/ and /z/ can also be attributed to the already discussed fact that frication in fricatives can start well before the maximum constriction was reached. This mismatch between the start of frication and the characteristic tongue-to-palate configuration was more pronounced for /s/ than for /z/. Therefore, at the acoustically determined beginning of the voiceless fricative (at the start of the frication), the characteristic tongue-to-palate configuration was not yet achieved, so coarticulatory effects at the edges of /s/ were much more pronounced than at the edges of /z/.

The results of coarticulatory timing analysis also showed slightly larger carryover than anticipatory effects in both fricatives. This can be explained by the fact that the vowel preceding the fricative was always stressed, while the vowel following the fricative was always unstressed in our speech material. Results from previous research showed that unstressed vowels were much more sensitive to coarticulatory effects and their coarticulatory pressure on surrounding sounds was inversely proportional to their coarticulatory sensitivity (Recasens, 1999). Also, if stress and other prosodic conditions influence fricative duration (Silbert & de Jong, 2008), it remains to be seen whether changes in duration have any repercussions on fricative target acquisition time and consequently on coarticulatory sensitivity at the edges of fricatives.

The results of this study have certain limitations which should be kept in mind when comparing them to findings from other studies. The first is the low number of speakers. While sample sizes between 5 and 10 are quite common in speech production research, a sample of that size does not allow for generalizations to whole populations. The second limitation which should be kept in mind is that fricatives in this speech sample were placed in the onset position of an unaccented syllable, and other research showed that syllable position and prosody can have an impact on the production of fricatives (Docherty, 1992; Silbert & de Jong, 2008; Stephenson, 2015). Lastly, readers should keep in mind that other prosodic conditions may yield different results from those presented here. For example, fricatives in stressed syllables might show greater coarticulatory resistance, but they could also be under greater coarticulatory pressure from stressed vowels (see Recasens, 1999).

This investigation brings previously unreported details of tongue-to-palate contact timing during /s/ and /z/ in English, which are comparable to results already published on Croatian anterior lingual fricatives (Liker & Gibbon, 2013). Despite limitations of the study, the results show tendencies which raise questions for further research. Future work should be directed at addressing the limitations of this study and at investigating this phenomenon in other languages.

Acknowledgements

This research was partly supported by grant 130-0000000-0785 of the Ministry for science, education and sports of the Republic of Croatia and partly by the Marie Curie Short-Term Fellowship Programme at the EdSST Research Training Programme. We wish to thank Professor Dragutin Ivanec for his advice on statistical analyses. We are also grateful to our anonymous reviewers and to the Associate Editor for their helpful comments on earlier versions of the manuscript.

References

Bakran, J. (1996): *Zvučna slika hrvatskoga govora*. Ibis grafika, Zagreb.

Boersma, P.; Weenink, D. (2012): Praat: doing phonetics by computer, http://www.praat.org/.

Browman, C. P.; Goldstein, L. (1986): Towards an articulatory phonology. *Phonology* 3: 219-252.

Catford, J. C. (1977): *Fundamental problems in phonetics*. Indiana university press, Bloomington.

Dagenais, P. A.; Lorendo L. C.; McCutcheon, M. J. (1994): A study of voicing and context effects upon consonant linguapalatal contact patterns. *Journal of Phonetics* 22: 225-238.

Dixit, R. P.; Hoffman, P. R. (2004): Articulatory Characteristics of fricatives and affricates in Hindi: an electropalatographic study. *Journal of the International Phonetic Association* 34 (2): 141-160.

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

Farnetani, E. (1990). VCV lingual coarticulation and its spatiotemporal domain. In William J. Hardcastle and Alain Marchal (Eds.) *Speech Production and Speech Modelling*. Dordrecht: Kluwer: 93-130.

Fuchs, S.; Perrier, P. (2003): An EMMA/EPG study of voicing contrast correlates in German. In Maria Josep Solé; Daniel Recasens; Joaquin Romero (Eds.), *Proceedings of the 15th International Congress of Phonetic Sciences* (ICPhS 15). Barcelona: 1057-1060.

Fuchs, S.; Brunner, J.; Busler, A. (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.

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

Gibbon, F. E.; Nicolaidis, K. (1999): Palatography. In William J. Hardcastle; Nigel Hewlett (Eds.), *Coarticulation: theory, data and techniques*. CUP, Cambridge: 229-245.

Gordeeva, O. B.; Scobbie, J. M. (2007): Preaspiration as a correlate of word-final voice in Scottish English fricatives. In Susanne Fuchs; Martine Toda; Marzena Zygis (eds.), *Turbulent Sounds: An Interdisciplinary Guide*. De Gruyter Mouton, Berlin/New York: 167-208.

Grunwell, P. (1987): *Clinical phonology*, 2nd edn. Croom Helm, London.

Hardcastle, W. J.; Gibbon, F. E. (1997): Electropalatography and its clinical applications. In Martin J. Ball; Christopher Code (Eds.), Instrumental clinical phonetics. Croom Helm, London: 149–193.

Hardcastle, W. J.; Edwards, S. (1992): EPG-based description of apraxic speech errors. In Raymond D. Kent (Ed.), Intelligibility in speech disorders: Studies in speech pathology and clinical linguistics. John Benjamins, Amsterdam & Philadelphia, PA: 287–329.

Hardcastle, W. J.; Gibbon, F. E.; Jones, W. (1991): Visual display of tongue-palate contact: Electropalatography in the assessment and remediation of speech disorders. *British Journal of Disorders of Communication* 26: 41-74.

Hoole, P.; Gobl, C.; Ní Chasaide, A. (1999): Laryngeal coarticulation. In William J.

Hardcastle; Nigel Hewlett (Eds.), *Coarticulation: theory, data and techniques*. CUP, Cambridge: 105-143.

Iskarous, K.; Shadle, C. H.; Proctor, M. I. (2011): Articulatory-acoustic kinematics: the production of American English /s/. *Journal of the Acoustical Society of America*, 129 (2): 944-954.

Jesus, L. M.T.; Shadle, C. H. (2002): A parametric study of the spectral characteristics of European Portuguese fricatives. *Journal of Phonetics* 30: 437–464.

Koenig, L. L.; Lucero, J. C.; Perlman, E. (2008): Speech production variability in fricatives of children and adults: results of functional data analysis. *Journal of the Acoustical Sociaety of America*, 124 (5): 3158-3170.

Ladefoged, P.; Maddieson, I. (1996): *The sounds of the world's languages*. Blackwell Publishers, Oxford - Malden.

Liker, M.; Gibbon, F. E. (2011): Groove width in Croatian voiced and voiceless postalveolar fricatives. In Wai-Sum Lee; Eric Zee (Eds.) *Proc. of the 17th International Congres of Phonetic Sciences* (ICPhS 17). Hong Kong: University of Hong Kong: 1238-1241.

Liker, M.; Gibbon, F. E. (2013): Differences in EPG contact dynamics between voiced and voiceless lingual fricatives. *Journal of the International Phonetic Association* 43 (1): 49-64.

Liker, M.; Horga, D.; Mildner, V. (2012): Electropalatographic specification of Croatian fricatives /s/ and /z/. *Clinical Linguistics & Phonetics* 26 (3): 199-215.

Lindblom, B. (1963): On vowel reduction. Report 29, Royal Institute of Technology, Stockholm.

Marchal, A.; Hardcastle, W. J. (1993): ACCOR: Instrumentation and database for the cross-language study of coarticulation. *Language and Speech* 36: 137-153.

McLeod, S.; Searl, J. (2006): Adaptation to an electropalatograph palate: acoustic, impressionistic, and perceptual data. *American Journal of Speech-Language Pathology* 15 (2): 192-206.

McLeod, S.; Roberts, A.; Sita, J. (2006): Tongue/palate contact for the production of /s/ and /z/. *Clinical Linguistics and Phonetics* 20 (1): 51-66.

Mitani, S.; Kitama, T.; Sato, Y. (2006): Voiceless affricate/fricative distinction by frication duration and amplitude rise slope. *Journal of the Acoustical Society of America* 120 (3): 1600-1607.

Mooshammer, C.; Hoole, P.; Geumann, A. (2006): Inter-articulator cohesion within coronal consonant production. *Journal of the Acoustical Society of America*, 120: 1028-1039.

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

Ohala, J. J.; Solé, M.-J. (2010): Turbulence and phonology. In Susanne Fuchs; Martine Toda; Marzena Zygis (eds.), *Turbulent Sounds: An Interdisciplinary Guide*. De Gruyter Mouton, Berlin - New York: 37-102.

Pinho, C. M.R.; Jesus, L., M., T.; Barney, A. (2012): Weak voicing in fricative production. *Journal of Phonetics* 40: 625-638.

Proctor, M. I.; Shadle, C. H.; Iskarous, K. (2010): Pharyngeal articulation in the production of voiced and voiceless fricatives. *Journal of the Acoustical Society of America* 127 (3): 1507-1518.

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

Recasens, D.; Pallarès, M. D. (2001): Coarticulation, Assimilation and Blending in Catalan Consonant Clusters. *Journal of Phonetics* 29: 273-301.

Recasens, D. (1999): Lingual coarticulation. In William J. Hardcastle; Nigel Hewlett (Eds.), *Coarticulation: theory, data and techniques*. CUP, Cambridge: 80-104.

Recasens, D.; Pallarès, M. D.; Fontdevila, J. (1997): A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America* 102 (1): 544-561.

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

Shadle, C. H. (1990). Articulatory-acoustic relationships in fricative consosnants. In William J. Hardcastle; Alain Marchal (Eds.), *Speech production and speech modelling*. Kluwer publishing, Dordrecht: 187-209.

Silbert, N.; de Jong, K. (2008). Focus, prosodic context, and phonological feature specification: Patterns of variation in fricative production. *Journal of the Acoustical Society of America* 123 (5): 2769–2779.

Skarnitzl, R.; Šturm, P.; Machač. P. (2013): The phonological voicing contrast in Czech: An EPG study of phonated and whispered fricatives. In Frédéric Bimbot; Christophe Cerisara; Cécile Fougeron; Guillaume Gravier; Lori Lamel; François Pellegrino; Pascal Perrier (Eds.), *Proceedings of the 14th Annual Conference of the International Speech Communication Association* (Interspeech 2013). ISCA, Lyon: 3191-3195.

Stephenson, L. (2015). Patterns of voicing in American English voiced obstruents in connected speech. In The Scottish Consortium for ICPhS 2015 (Ed.), *Proceedings of the 18th International Congress of Phonetic Sciences*. Glasgow, UK: the University of Glasgow, Paper number 0084.1-5.

Stone, M. (2010): Laboratory techniques for investigating speech articulation. In William J. Hardcastle; John Laver; Fiona E. Gibbon (Eds.), *The Handbook of Phonetic Sciences*. Wiley-Blackwell, Oxford-Malden, MA: 9-39.

Tabain, M. (2000): Coarticulation in CV syllables: a comparison of Locus Equation and EPG data. *Journal of Phonetics* 28: 137-159.

Westbury, J. R. (1983): Enlargement of the supraglottal cavity and its relation to stop consonant voicing. *Journal of the Acoustical Society of America* 73 (4): 1322-1336.

Wrench A. A.; Gibbon, F. E.; McNeill, A. M.; Wood, S. E. (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.

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

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

Tables

Table 1

Vowel context	**Words**	
	/s/	***/z/***
a-*F*-a /ɑ_ə/	sparser /ˈspɑːsə/	parser /ˈpɑːzə/
i-*F*-i /i_i/	greasy /ˈgriːsi/	easy /ˈiːzi/
a-*F*-i /ɑ_i/	grassy /ˈgrɑːsi/	Khazi /ˈkɑːzi/
i-*F*-a /i_ə/	Lisa /ˈlisə/	freezer /ˈfriːzə/
u-*F*-a /u_ə/	looser /ˈlusə/	boozer /ˈbuːzə/

Table 2

	/s/	/z/
annotated	165 ms (SD 16)	91 ms (SD 11)
re-annotated	168 ms (SD 17)	94 ms (SD 11)

Table headings

Table 1. Words containing alveolar fricatives (*F*) /s/ and /z/ used in this investigation.

Table 2. Average durations and standard deviations of annotated and re-annotated fricatives.

Figure legends

Figure 1. An illustration of the segmentation criteria used for the voiceless fricative /s/ produced in the word “sparser” by the speaker S1 (annotation duration: 109 ms).

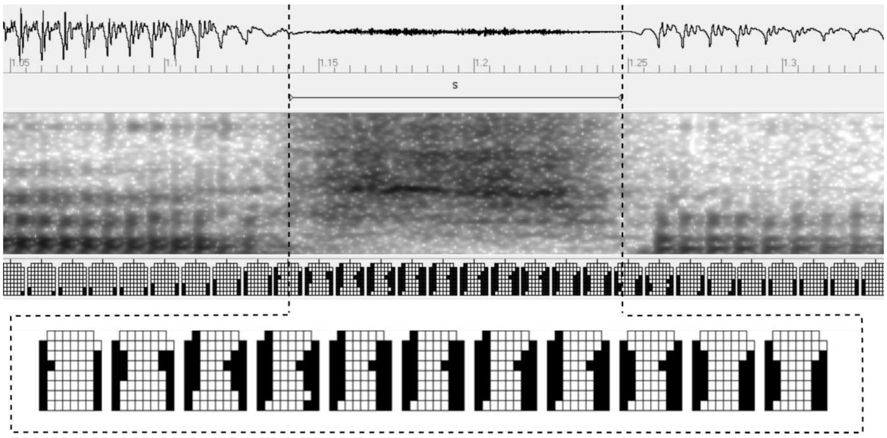


Figure 2. An illustration of the segmentation criteria used for the voiced fricative /z/ produced in the word “parser” by the speaker S1 (annotation duration: 72 ms).

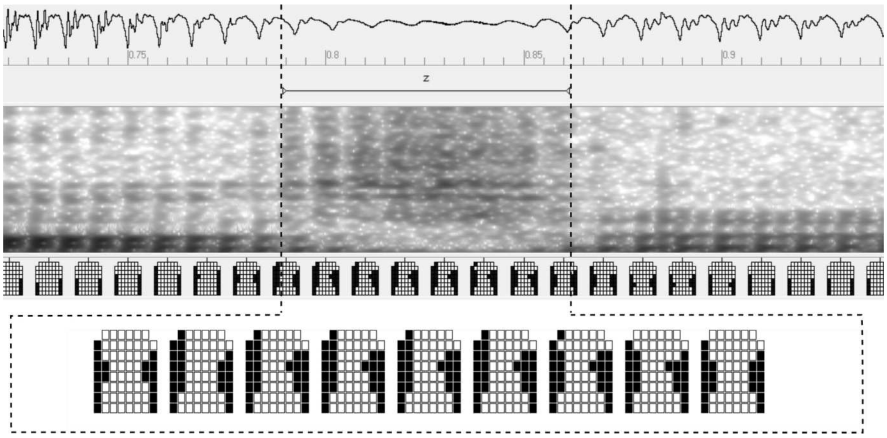


Figure 3. The amount of EPG contact during fricatives /s/ (left) and /z/ (right) averaged across all productions by speaker S3. Horizontal axis shows sample points during fricative production, vertical axis shows rows of electrodes (1st row is the most anterior row, 8th row is

the most posterior row), while the amount of contact is shown by shades of grey (darker the shade, higher the amount of contact).

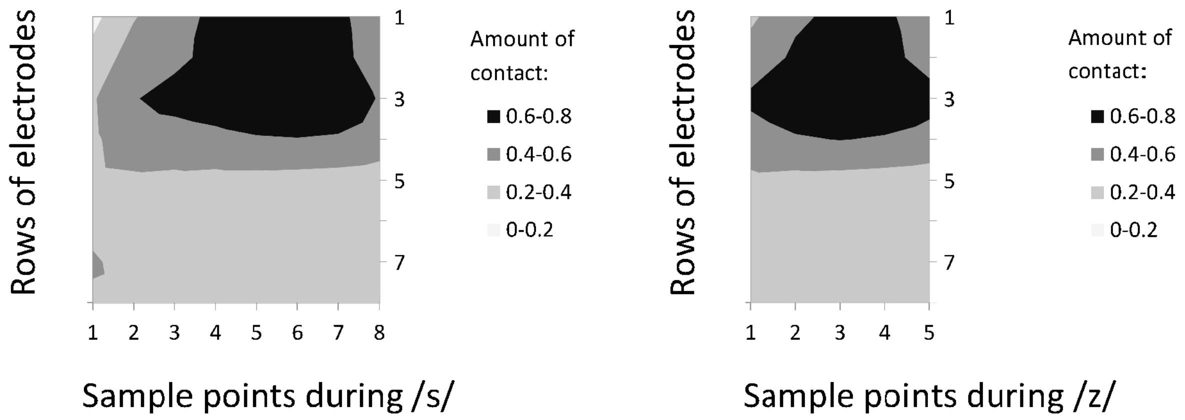


Figure 4. Difference in the amount of contact at each sample point between the fricative produced in the vowel context a-*F*-a (/ɑ_ə/) and i-*F*-i (/i_i/) by speaker S3.

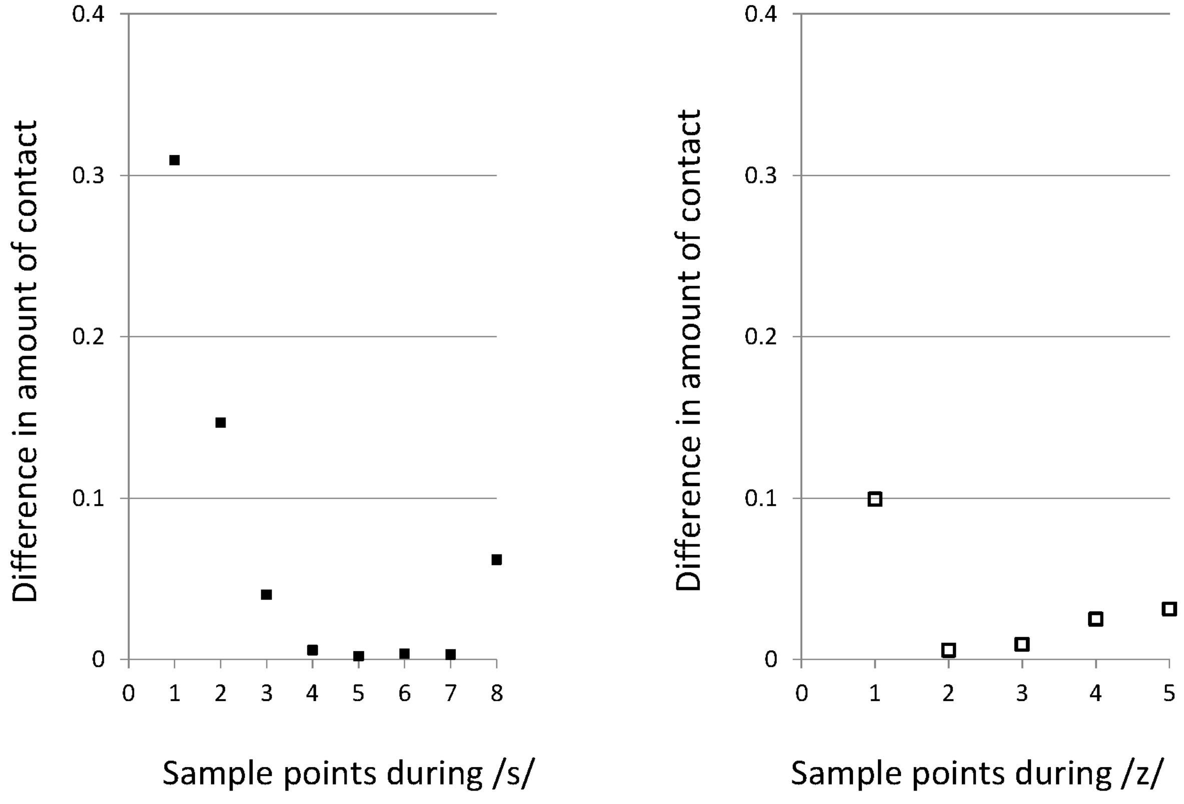


Figure 5. Time to target (TT) values for fricatives /s/ and /z/ for each speaker averaged across vowel contexts. Error bars show standard deviations.

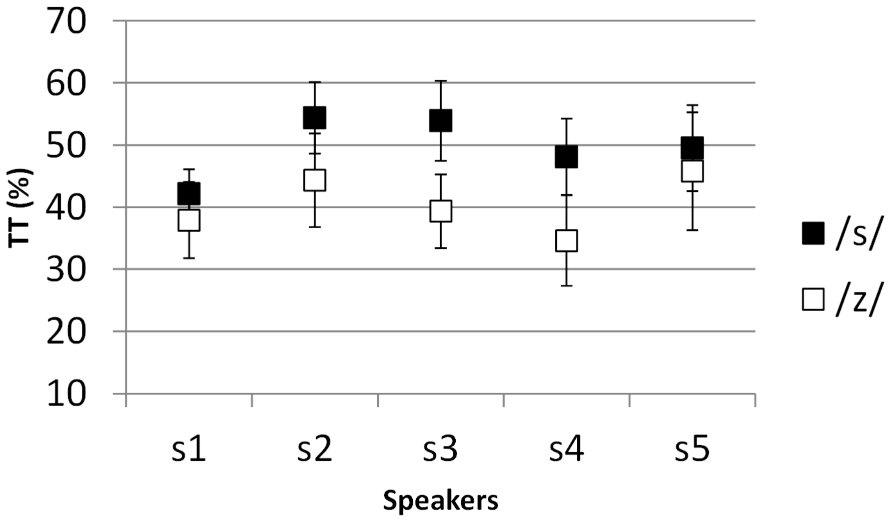


Figure 6. Absolute durations of each fricative averaged across each speaker aligned at maximum contact point (MCP). Negative values indicate the time between the start of fricative annotation and MCP, while positive values indicate the time between the MCP and the end of fricative annotation.

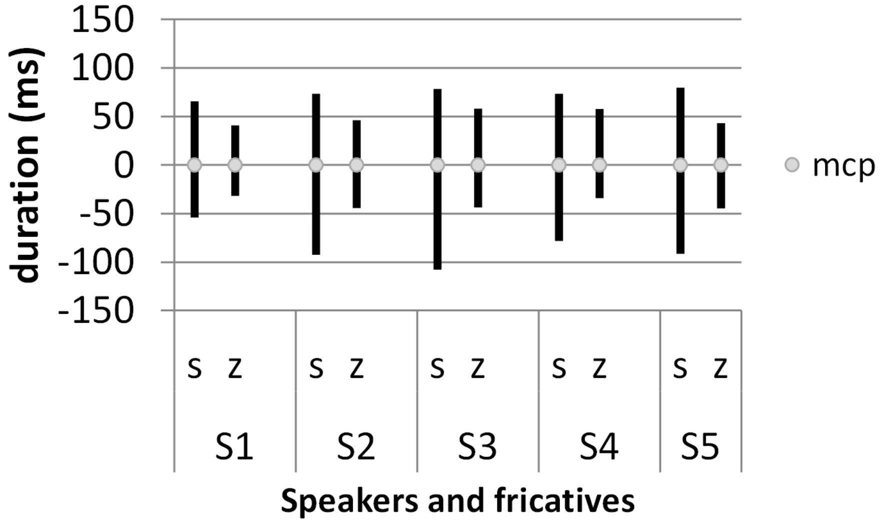


Figure 7. Amount of EPG contact during fricatives /s/ (left) and /z/ (right) averaged across all productions for each speaker. Horizontal axis shows sample points during fricative production, vertical axis shows rows of electrodes (1st row is the most anterior row and the 8th row is the most posterior), while the amount of contact is shown by shades of grey (darker the shade, higher the amount of contact).

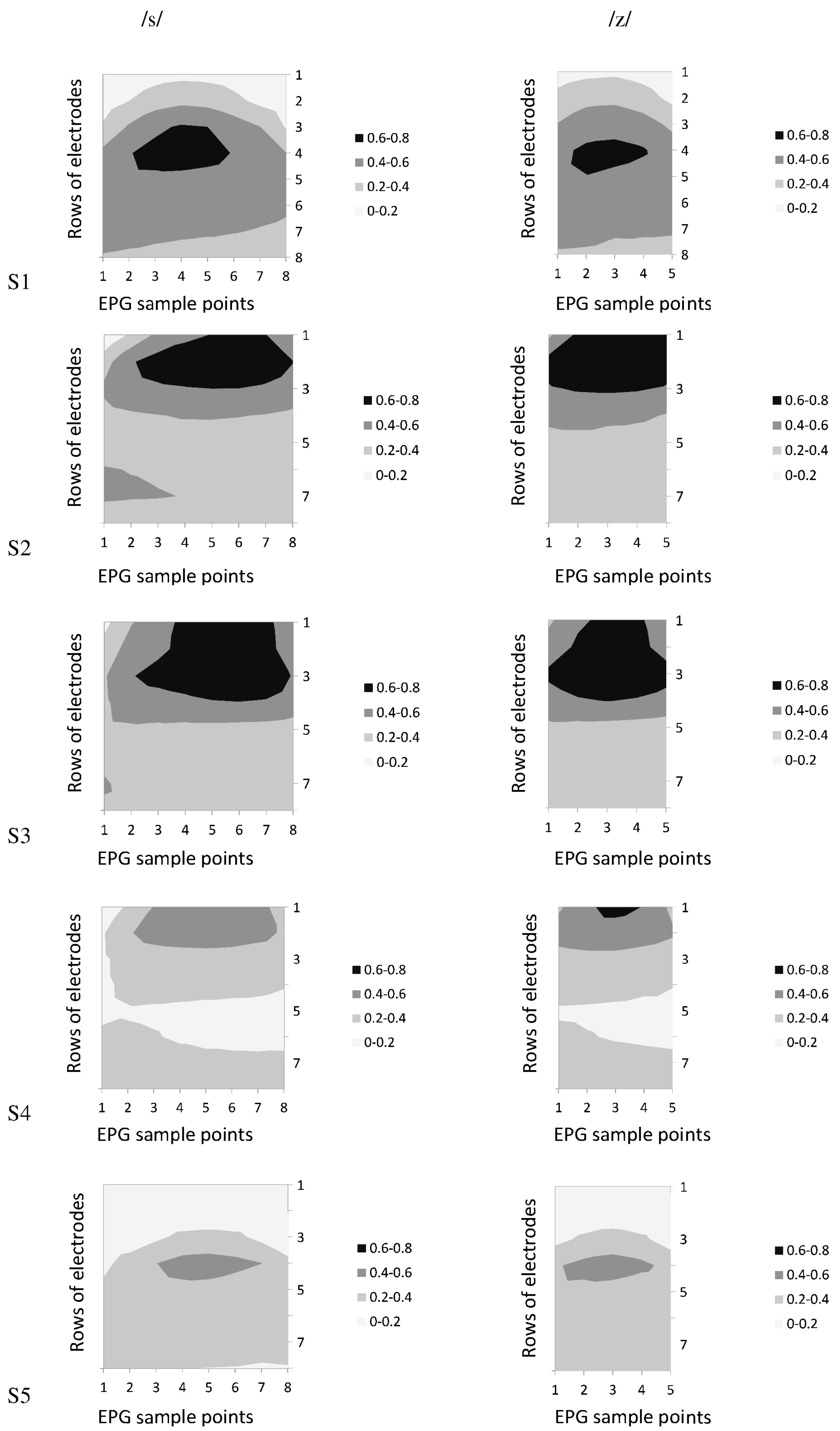

/s/
/z/
S1
S2
S3
S4
S5
Rows of electrodes
EPG sample points
1
2
3
4
5
6
7
8
0.6-0.8
0.4-0.6
0.2-0.4
0-0.2

Figure 8. TT values for fricatives /s/ and /z/ in each vowel context averaged across speakers. Error bars show standard deviations.

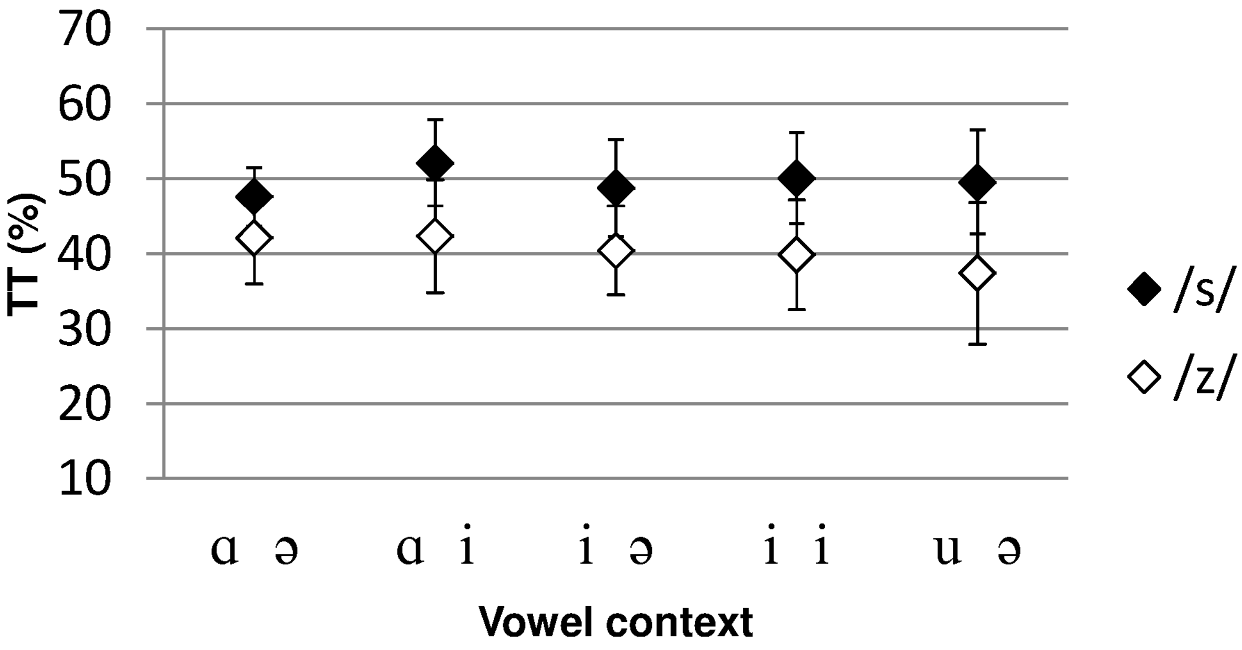


Figure 9. The amount of coarticulation during /s/ for each of the vowel contexts (/i_i/,/ɑ_i/,/i_ə/,/u_ə/), calculated as the difference in amount of contact in /s/ between the particular vowel context indicated and the vowel context /ɑ_ə/ at each EPG sample point for each speaker. Coarticulation in ‘phonologically symmetrical’ vowel contexts is shown in the first column of panels, and anticipatory in the second column, while the carryover effects are shown in the third and the fourth columns.

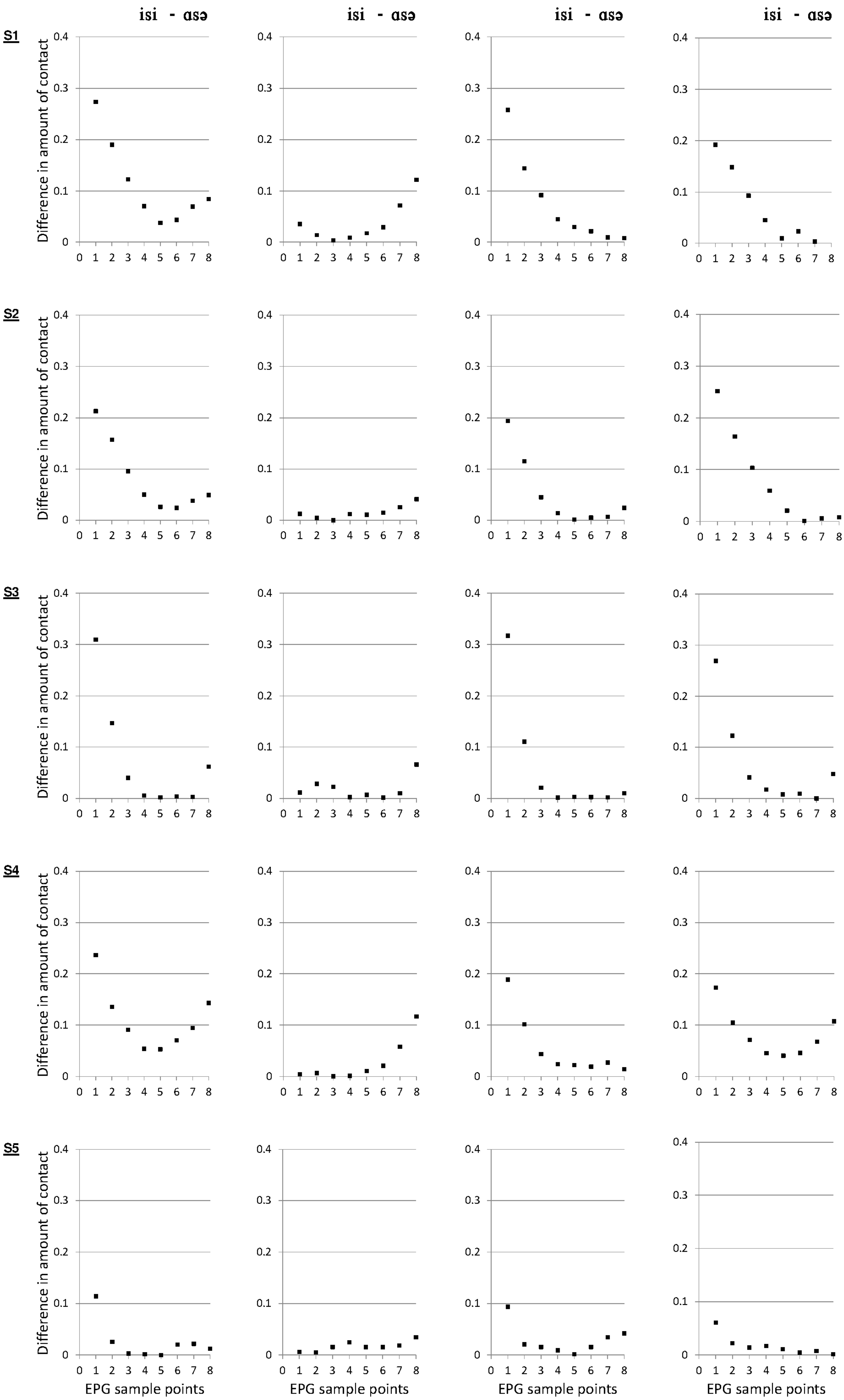
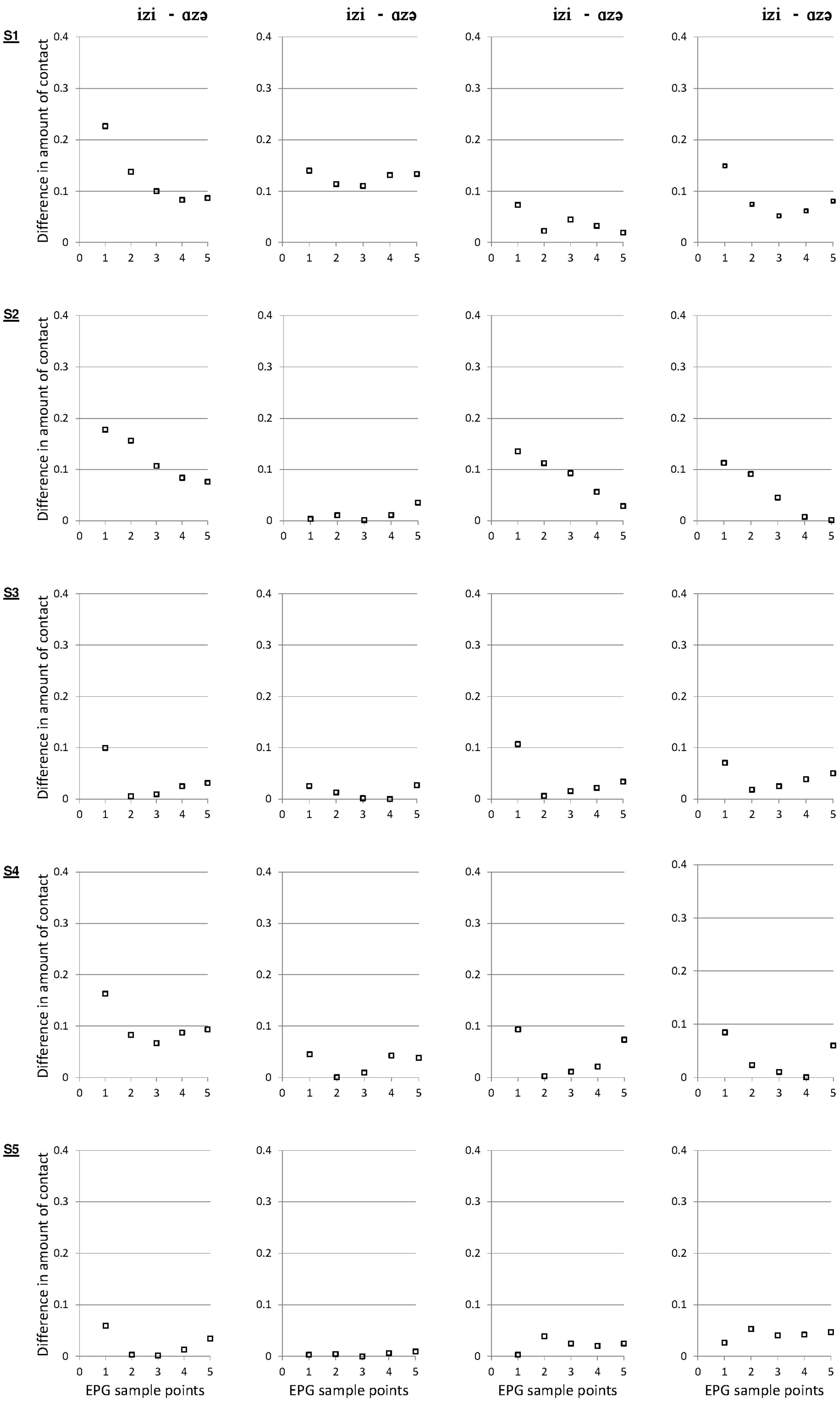

isi - ɑsə
isi - ɑsə
isi - ɑsə
isi - ɑsə
S1
S2
S3
S4
S5
Difference in amount of contact
0
0.1
0.2
0.3
0.4
0 1 2 3 4 5 6 7 8
EPG sample points
EPG sample points
EPG sample points
EPG sample points

Figure 10. The amount of coarticulation during /z/ for each of the vowel contexts (/i_i/,/ɑ_i/,/i_ə/,/u_ə/), calculated as the difference in amount of contact in /z/ between the particular vowel context indicated and the vowel context /ɑ_ə/ at each EPG sample point for each speaker. Coarticulation in 'phonologically symmetrical' vowel contexts is shown in the first column of panels, and anticipatory in the second column, while the carryover effects are shown in the third and the fourth columns.


izi - ɑzə
izi - ɑzə
izi - ɑzə
izi - ɑzə
S1
S2
S3
S4
S5
Difference in amount of contact
0
0.1
0.2
0.3
0.4
0 1 2 3 4 5
EPG sample points
EPG sample points
EPG sample points
EPG sample points

3

Figure 11. Regression analysis relating the amount of coarticulation at the edges of /s/ (at the beginning for the 'phonologically symmetrical' vowel context and carryover effects; at the end for anticipatory effects) and the amount of coarticulation at fricative /s/ mid-point. Slope value, y-intercept and the coefficient of determination (R^2) are also shown.

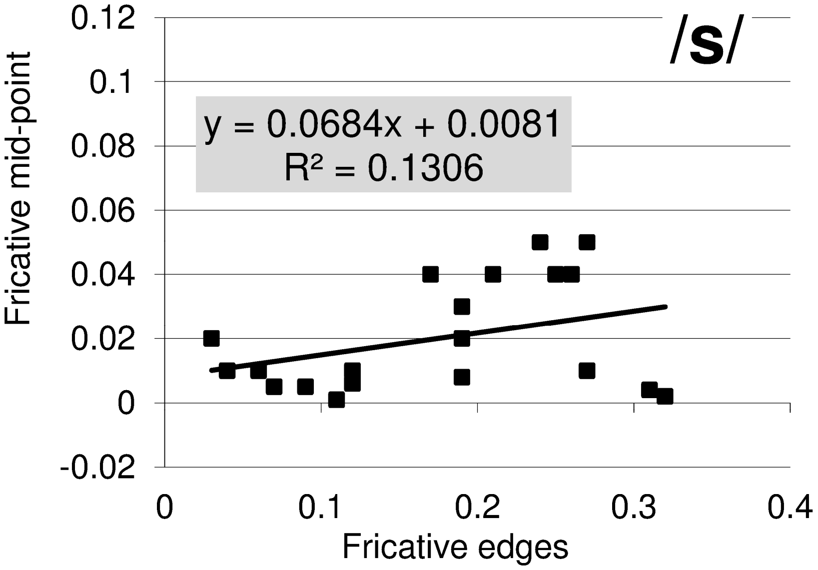
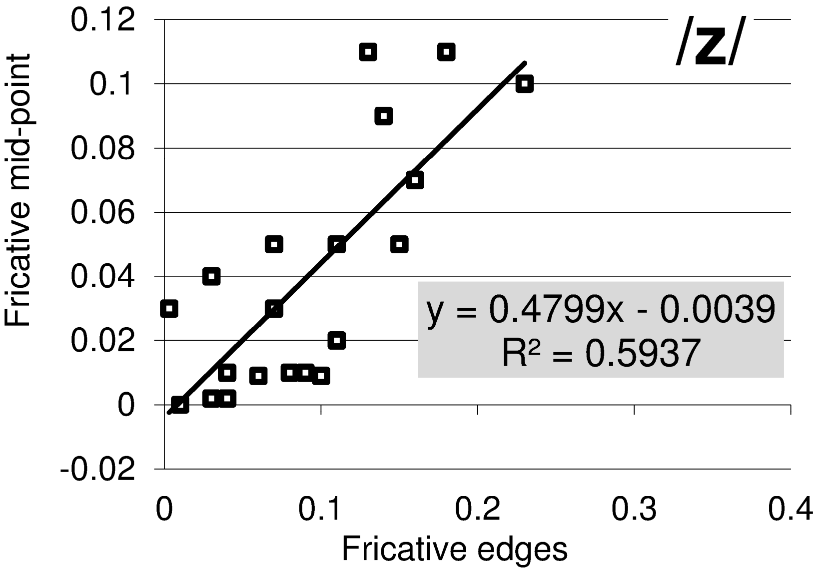
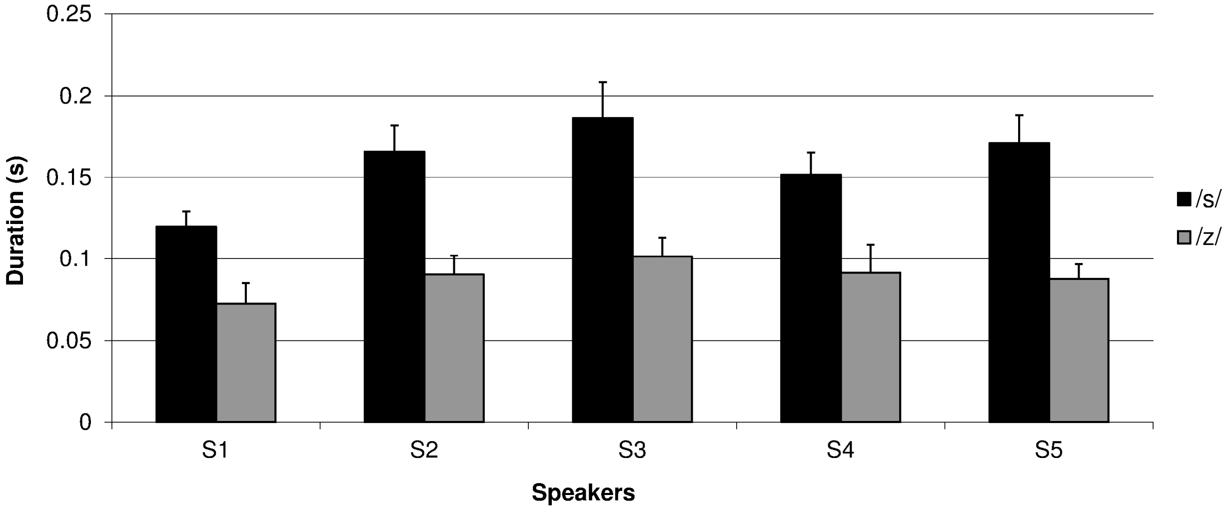


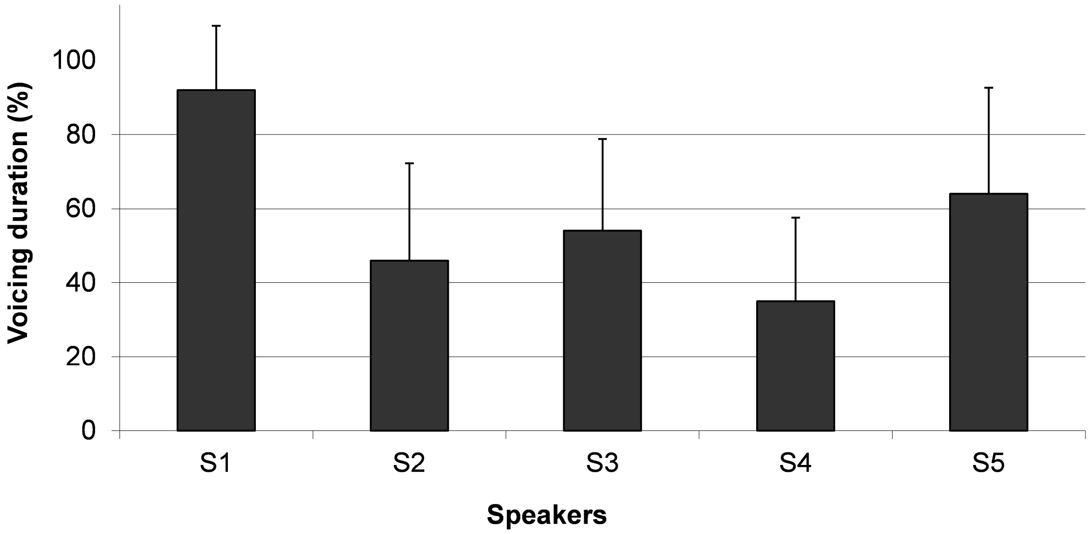
Figure 12. Regression analysis relating the amount of coarticulation at the edges of /z/ (in the beginning for the 'phonologically symmetrical' vowel context and carryover effects; in the end for anticipatory effects) and the amount of coarticulation at fricative /s/ mid-point. Slope value, y-intercept and the coefficient of determination (R^2) are also shown.



Appendix 1. Duration of voiced and voiceless fricatives for each speaker. Error bars show standard deviations.



Appendix 2. Voicing duration in voiced fricative expressed as percentage of total duration for each speaker. Error bars show standard deviations.


Voicing duration (%)
100
80
60
40
20
0
S1
S2
S3
S4
S5
Speakers