

LARYNGEAL ADJUSTMENTS IN THE PRODUCTION OF VOICELESS OBSTRUENT CLUSTERS IN BERBER

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ABSTRACT

Laryngeal adjustments in voiceless obstruent clusters in Tashlhiyt Berber were examined by means of simultaneous transillumination, fiberoptic films and acoustic recordings. This language allows a rich variety of voiceless clusters naturally. Several combinations of /s/ and /k/ clusters including singleton and geminate consonants were examined. We focused on the number of glottal opening gestures, the influence of manner of articulation and effects of word boundaries. Results of this study provide evidence that the manner of articulation of segments and their position in the clusters have a major impact both on the number and on the location of glottal abduction movements. Word boundaries did not influence laryngeal adjustment to the same extent.

INTRODUCTION

A number of studies have investigated laryngeal articulation in the production of voiceless consonant clusters in order to study coarticulation patterns at the laryngeal level. The first main objective of these works is to compare laryngeal adjustments observed in voiceless singleton obstruents with those attested in consonant clusters. A second objective is to understand the way laryngeal adjustments are coordinated with supralaryngeal events in complex sequences and the mechanisms which might determine the number, the amplitude and the location of glottal opening gestures. Most of these studies used a similar methodology - photoelectroglottography combined with fiberoptics - and a speech material consisting of different /s/-stop combinations. Germanic languages (English, German, Icelandic and Swedish) are by far the most studied languages. Pétursson (1977), Fukui & Hirose (1983) and Jessen (1999), for example, observed glottal adjustment and the number of glottal abduction gestures in fricative-stop clusters in some of these languages. One general aspect that comes out from these studies is that laryngeal adjustments can be organized in one or more continuous opening and closing gestures.

In Pétursson (1977), Icelandic [s#t^h] and [s+t^h] clusters show two glottal opening peaks whereas only one peak occurs in [#st] cluster. The author concludes that there are discrete phoneme commands for glottal abduction although the intervening boundary might have influenced the pattern too. In Fukui and Hirose (1983), the two-peakedness observed in Danish [s#p^h] clusters was rather speaker-dependent. One explanation of these differences could be that two different glottal abduction gestures are underlyingly present; in a fast speech rate condition they overlap, whereas no overlap would be found in a slow speech rate condition. Munhall and Löfqvist (1992) investigated this issue based on English [s#t^h]

clusters and simulated gestural overlap as a sum of the two underlying movements. Their simulations fit the transillumination data with respect to timing characteristics, but differences were found concerning glottal opening amplitudes. The simulations showed higher amplitudes than the experimental data. They explain these differences in terms of the non-calibration possibility of the transillumination technique as well as in terms of rate effects which can decrease movement amplitudes. Jessen (1999) raised the question of whether the monomodal versus bimodal distribution of glottal opening movements would be an effect of the word boundary or whether aspiration of the stop in the fricative-stop cluster could explain the distinction. His findings drawn from German confirm the latter idea, initially based on results from Löfqvist and Yoshioka (1980a), and Yoshioka et al. (1981) on Swedish and English respectively. These authors observed that glottal opening is characterized by one-, two or three-peaked patterns according to the nature of the voiceless obstruents and the way they are combined. Each voiceless obstruent or geminate accompanied by aspiration or frication noise tends to require a specific separate peak glottal opening. They interpret these independent glottal apertures as assuring the aerodynamic requirements for turbulent noise production during aspirated stops or fricative segments.

Laryngeal adjustments in voiceless obstruent production will be examined here in Berber voiceless clusters and compared to the organization of the laryngeal adjustment in other languages, mainly some of the Germanic languages mentioned above. We will present some general properties that appear to be commonly shared by speakers of different and unrelated languages.

Berber is an Afro-Asiatic language spoken in North Africa. Tashlhiyt Berber (Henceforth TB), which is the variety of Berber analysed in this article, is a dialect spoken in the Southern

part of Morocco. Even if some variation is pervasive across the Tashlhiyt domain, it does not hinder mutual comprehension. TB uses both voicing and gemination distinctively. Both singleton and geminate velar and dental stops may be aspirated. Following a commonly accepted view, we consider a geminate as a single melodic unit associated with two prosodic positions (Clements & Keyser, 1983). Such a representation accounts for the dual behaviour of the geminate which behaves in some respects as a consonant cluster and, in others, as a single consonant. Heteromorphemic geminates are a sequence of two identical segments separated by a morpheme boundary. They are generally homophonous with tautomorphemic geminates. In certain contexts, however, as is the case of /k#k/, the first velar stop may either be released or spirantized. Spirantization is an optional phonological process affecting simple non-coronal stops which become fricatives (i.e. /k/ is realized as [x]¹). TB is of special interest in contributing to a better understanding of the organization of laryngeal adjustment, since this language allows an unusually rich combination of voiceless sounds, large series of voiceless words and different types of geminates in initial, medial and final positions (Ridouane, 2003).

The aim of this study is to improve our understanding of laryngeal adjustment in voiceless consonant cluster production and the mechanisms underlying the temporal coordination of laryngeal and oral articulations in sequential voiceless sounds. Our data can provide additional evidence for the interpretation that a static glottal opening position of the glottis is unlikely to occur (e.g. Yoshioka, Löfqvist & Hirose 1981, Munhall & Löfqvist 1992), since we included combinations of up to 6 voiceless consonants in our data (various combinations

¹ In our transcriptions, forms enclosed between slashed lines are intended to represent the underlying structure of these forms. When a form has a phonetic output different from its underlying structure, the phonetic form is enclosed between brackets.

of /s/ and /k/). In this study we will focus on laryngeal adjustments during the production of different voiceless clusters and examine:

1. The influence of manner of articulation (stops and fricatives) or of gemination (tautomorphemic and heteromorphemic);
2. The effect of preceding, following or intervening word boundaries;
3. The presence or absence of aspiration in stops preceded by /s/.

METHOD

Two male native speakers of TB, RR, the first author, and RF were recorded by means of simultaneous transillumination (hereafter PGG), fiberoptic filming (hereafter FF), and acoustic recordings in the ZAS Laboratory in Berlin. A standard endoscope (Olympus ENF type P3) was inserted in the subjects' pharynx and a photosensor was glued externally on the subjects' neck. The endoscope was attached to a camera and connected to a video recorder with a monitor. The video images enabled the otorhinolaryngologist to control the position of the tip of the endoscope throughout the experiment. The video signals were taped to enable qualitative interpretation of the transillumination data. To provide the relevant amount of cold light for the tip of the endoscope, an external light source was attached to the endoscope².

Acoustic and transillumination data have a sampling frequency of 24 kHz, PGG data were further downsampled to 200 Hz, and the FF data have the standard video format of 25 i/s. The velocity signal of the PGG signal was calculated as the first derivative. By analyzing the velocity signal we defined the beginning and end of glottal opening and closing using a 5% threshold criterion (i.e. the point where the signal crossed 5 per cent of the corresponding

² Detailed discussion on the transillumination procedure and the factors affecting its reliability is given in Hoole (1999).

movement segment). In the acoustic data we labeled for /k/ closure onset (clon) as the second formant offset of the preceding vowel, burst (b), aspiration offset (aspoff) as the end of high frequency energy, and for /s/ frication onset (fricon) and frication offset (fricoff)³. An example of our data is presented in Figure 1. The top panel shows the acoustic waveform of the cluster /s#ks/. The second panel shows the glottographic pattern, which indicates the duration, the degree and the number of glottal opening peaks. The vertical axis shows the amount of light in arbitrary unit. In this figure, we can see that two glottal opening peaks were produced, being located during the production of the two fricatives. The third panel indicates the velocity of glottal opening and closing gestures (i.e. the derivative of the transillumination data).

- Insert FIGURE 1 HERE.

Both the transillumination technique and fiberoptic filming require a wide pharyngeal cavity, which was taken into consideration in selecting the linguistic material. The real word speech material consisted of several combinations of singleton and geminate /s/ and /k/ consonants. All the clusters were preceded and followed by the vowel /i/. Forms indicated in table 1 were produced by two subjects (RR and RF). RR participated in two experimental sessions⁴. The results of the two sessions have been merged. The second subject (RF) participated in the second session. The number of repetitions for each subject is indicated between brackets, RR produced 160 tokens and RF 77 tokens. “#” indicates word boundary.

- Insert Table 1 HERE.

³ The labeling of the acoustic data was done by visual and perceptual inspection of the signals and spectrograms.

⁴ The second experiment took place in Berlin about a year after the first one.

The number of glottal opening peaks was calculated algorithmically as the number of (negative) zero-crossings in the velocity signal. To guard against counting spuriously large numbers of local maxima (e.g. due to noise during periods of low velocity) we defined a noise band as 5% of the average peak velocity over all utterances (separately for each speaker) and only counted those zero-crossings falling in movement segments that crossed this noise band above and below zero velocity. To obtain some further basic information on the shape of the glottal movements we also counted the number of positive velocity peaks during opening movements and the number of negative velocity peaks in closing movements⁵. In the labeling of the figures below these velocity peak counts are referred to as “Vel. peaks (ab)” and “Vel. peaks (ad)”, respectively (i.e. for **ab**duction and **ad**duction phases). The simplest movements are those in which each glottal opening peak is associated with exactly one positive and one negative velocity peak. While there can never of course be less velocity maxima than amplitude maxima, if either the number of positive velocity maxima or negative velocity maxima exceeds the number of amplitude maxima, then this indicates a more complex – generally more gradual – movement pattern for abduction or adduction movements respectively.

In the figures below showing the movement pattern for each linguistic category we have included the average counts of the amplitude and positive and negative velocity maxima. For the sake of clarity we have omitted any measure of variability from the figures (e.g. standard deviation). In most cases, particularly for amplitude peaks, this information is redundant as it can be derived from the average peaks counts. For example, a peak count of 1.1 with n=10 indicates 9 tokens with one peak and one token with two peaks.

⁵ This was done analogously to the amplitude peaks by counting zero-crossings in the acceleration signal

To generate plots of the average movement pattern for each utterance type, the transillumination signal was normalized with respect to both time and amplitude. For the time normalization, the average duration of each utterance type was calculated over the interval from the start to the termination of glottal abduction (ON to OFF in Figure 1), and then each individual token was time-warped to this duration⁶. Amplitude normalization was designed to take account of gross changes in signal gain which may be caused for example by shifts in endoscope position over the course of the experiment. To this end, first the minimum amplitude preceding glottal abduction in each item was subtracted from the signal, then the average signal amplitude between ON and OFF labels was calculated for all items in a block of repetitions, and the transillumination signal was then normalized by this value. Ensemble averages for each utterance type were then calculated from this time- and amplitude-normalized data. On the basis of the amplitude-normalized data we believe that statistical comparison of glottal opening amplitude between utterance types is justified, if carried out cautiously, e.g. by using non-parametric tests.

RESULTS AND DISCUSSION

Clusters with two consonants

Results for two-consonant clusters are shown in Figures 2 and 3. Figure 2 shows clusters with /s/ in first position, while Figure 3 shows those with /k/ in first position. As can be seen from these figures two-consonant clusters for both subjects exhibit a clear single-peaked

⁶ One item was excluded from this procedure as being highly untypical (one repetition of /kk#skk/ with a duration more than 50% longer than the average duration).

pattern in the averaged traces regardless of the placement of word boundaries⁷. The peak almost always occurs during the fricative.

- Insert FIGURE 2 HERE.
- Insert FIGURE 3 HERE.

This is in agreement with results from Löfqvist and Yoshioka (1980a) based on data from Swedish. Two different strategies can explain the fact that the location of peak glottal opening follows the location of the fricative in the cluster. First, this is caused by aerodynamic conditions. The fricative requires a higher oral airflow than the stop and hence the peak glottal abduction occurs during the /s/. Second, this might be caused by two underlying glottal opening gestures which overlap – a larger one for /s/ and a smaller one for /k/. This latter view is advocated by Munhall and Löfqvist (1992) on the basis of an experimental exploration of gestural aggregation, showing that such clusters consist underlyingly of two gestures. For Browman and Goldstein (1986), the single-peaked glottal opening observed in word initial fricative-stop clusters is a phonological regularity of syllable-initial position in English, suggesting that the single peak is a property of the whole syllable onset. They capture the relevant timing of laryngeal-oral coordination in the following rule:

- If a fricative gesture is present, coordinate the peak glottal opening with the midpoint of the fricative. Otherwise, coordinate the peak glottal opening with the release of the stop gesture.

This rule, tested over various voiceless clusters in different languages, does not appear to be completely accurate (see Hoole et al. 2004). Berber material also shows that the peak glottal

⁷ The mean count of amplitude peaks indicates only two tokens that did not conform to the overall pattern: one token each of /k#s/ and /ks#/ for speaker RR.

opening is not systematically coordinated with the midpoint of the fricative. The generalization that can be drawn from our data is that peak glottal opening is almost always located within the fricative both for stop-fricative and for fricative-stop sequences. The timing of this opening peak tends to shift to a relatively earlier point in the fricative when it follows a stop (at 23.49 % of the fricative) and to later point in the fricative when it precedes a stop (at 66.06% of the fricative), regardless of the word boundary location. Figure 4 illustrates these timing patterns for each subject.

- Insert FIGURE 4 HERE.

Contrary to what has been observed in different languages (e.g. English and Swedish), in TB /k/ can be acoustically aspirated after /s/ whether separated or not by a word boundary. Previous work (e.g. as summarized by Löfqvist 1980) suggests that typically each fricative and aspirated plosive requires a separate laryngeal peak. In Swedish (Löfqvist and Yoshioka 1980a) and English (Yoshioka et al. 1981), a sequence of voiceless fricative + voiceless aspirated stop usually contain two separate peak glottal openings located during the fricative and just before stop release. In TB, this generalization has to be qualified since interestingly the language shows aspirated plosives following fricatives in initial position, but nevertheless the results, as illustrated in Figure 2, make clear that only one opening peak occurs.

This pattern may well be related to the fact that voiceless geminates also show aspiration – in fact a very similar amount of aspiration to the singleton consonants. It was shown in Ridouane (2003) that aspiration duration, based on an acoustic study for 7 subjects, is not a

significant criterion for distinguishing between singleton and geminate stops⁸. Both are produced with virtually identical aspiration durations. For dentals measurements showed that aspiration duration varies between 45 to 65 ms for singletons and between 35 to 50 ms for geminates. For velars, aspiration duration varies between 45 to 70 ms for singletons and between 45 to 65 ms for geminates.

A photoelectroglottographic study, based on one subject, showed however important differences between singletons and geminates both in terms of timing and amplitude of glottal opening (cf. Ridouane 2003). The maximum glottal opening, measured in arbitrary units, shows clearly that geminates are systematically produced with larger glottal opening than singletons. The interval between peak glottal opening and oral release is longer for geminates than for single stops. For dentals, this interval varies between 0 to 10 ms for singletons and between 55 to 120 ms for geminates. For velars, the interval varies between -10 to 20 ms for singletons and between 55 to 70 ms for geminates.

Laryngeal abduction for geminates is much larger in amplitude and longer in overall duration compared to singletons. However, the glottal opening at stop release appears to be similar for both. Figure 5 below, which is arranged so as to show the glottal opening of a minimal pair involving a geminate and a singleton stop, shows that the size of glottal opening at stop release is nearly identical for both singletons and geminates which may thus explain the fact that aspiration duration for both stops is virtually identical.

- Insert FIGURE 5 HERE.

⁸ For dentals and velars. TB lacks voiceless bilabial stops. The other voiceless stops (the uvular /q/ and the emphatic /T/ and their geminate counterparts) are not aspirated.

Löfqvist (1980) has argued rather persuasively for the importance of laryngeal-oral timing in contrasting aspirated and unaspirated plosives, but the present results for TB provides a striking example of the contrary phenomenon, namely radically different timing patterns (of peak glottal opening relative to closure release) leading to similar degrees of aspiration duration. One might speculate that the somewhat atypical aspiration in initial fricative-plosive clusters is using the same timing pattern that has emerged for the geminates, suggesting that aspiration, as was defined by Kim (1970), is essentially a function of the degree of glottal opening at stop release.

Clusters with three consonants

Tautomorphic vs. heteromorphic geminates

- Insert FIGURE 6 HERE.

Figure 6 contains the glottographic patterns of three-consonant-clusters produced by RR. These clusters are composed of two types of geminates, tautomorphic and heteromorphic ones. As was outlined above, one of the main topics of this study was to determine the possible influence of gemination on glottal adjustments. Comparisons between /kk#s/ and /k#s/ (middle column of Figure 3) on the one hand and between /ss#k/ and /s#k/ (middle column of Figure 2) on the other hand show that all these clusters are always produced with one peak glottal opening. This suggests that the presence of a geminate, instead of a singleton, is not accompanied with an additional separate laryngeal peak. There is some increase in movement complexity, however: the opening phase of /kk#s/ and the closing phase of /ss#k/ are rather gradual (indicated by velocity peak counts of 1.67 for the former and 1.33 for the latter). A major difference is nonetheless worth noting. The cluster with the velar geminate stop is systematically produced with larger glottal opening amplitude

than the singleton counterpart, in fact approximately double on the basis of the ensemble averages⁹. This seems to correspond to a systematic difference, as already mentioned above, observed between singleton and geminate stops in intervocalic position. By contrast, peak amplitude is practically identical for the singleton and geminate fricatives¹⁰.

The comparison between tautomorphemic and heteromorphemic geminates indicates that the number and the location of peak glottal opening vary according to the phonetic nature of the voiceless obstruents and the way they are combined. The glottographic patterns for the form with the velar tautomorphemic geminate /k#s/ show that the peak glottal opening is most often located during the geminate (towards the burst). The three realizations of the form /k#ks/ were not produced with the same number of amplitude peaks. One repetition was realized with two glottal openings, and two repetitions were realized with only one. A closer examination of the three repetitions shows that for the bimodal realization, the first velar was pronounced as a fricative [x]; the additional peak was thus located during this first velar fricative¹¹. This configuration, as we shall show in the following section, is identical to the one attested in the three-phone combinations where the first segment and the third are dental fricatives. Regardless of the number of observable amplitude peaks, all repetitions of /k#ks/ had 2 velocity peaks on the opening phase, which, accordingly, is much more gradual than the closing phase.

⁹ A non-parametric test of this difference proved highly significant, though note that we have only 3 tokens for the geminate.

¹⁰ The absence of systematic differences in terms of laryngeal amplitude between singleton and geminate fricatives has also been observed in Ridouane (2003), where intervocalic labiodental and dental singletons were compared to their geminate counterparts.

¹¹ The symbol indicating the burst for stops is maintained for forms realized as spirants. In this case, the symbol indicates the offset of the velar consonant.

/ss#k/ and /s#sk/ are similar to the extent that both sequences always have only one amplitude peak. Peak glottal opening for /ss#k/ is always located during the geminate /ss/. The cluster with a heteromorphemic geminate /s#sk/, produced with an uninterrupted frication noise during the two fricatives, is also produced with only one large glottal opening located during the geminate fricative. The two sequences differ in that the closing phase is longer for /s#sk/ (which has 3 velocity peaks, compared to a count of 1.33 for /ss#k/).

Overall one might say that there is some indication for greater movement complexity in the heteromorphemic compared to the tautomorphemic sequences, the former having a greater number of velocity peaks.

Clusters without geminates

Figure 7 compares two three-phone combinations /s#ks/ and /k#sk/. Looking first at /s#ks/ (right panels of Figure 7), one finds a very clear two-peaked pattern for RR. Word final /s/ in /s#ks/ is produced with a single opening peak and word initial /ks/ is produced with another one. Again, peak glottal abduction is always located during the fricatives. The same configuration was also observed for identical clusters in Swedish (Löfqvist & Yoshioka 1980a), Icelandic (Löfqvist & Yoshioka 1980b) and American English (Yoshioka et al. 1981). The glottis is only slightly adducted without complete closure between the two opening maxima. This transitory glottal closing movement is not necessarily a consequence of a pause due to a word boundary. No specific opening gesture is observed for the velar stop /k/. This segment is rather produced within the closing phase of the glottal gesture for the preceding fricative and within the opening phase for the following /s/ segment.

- Insert FIGURE 7 HERE.

The pattern for RF is at first sight more ambiguous: the amplitude peak count of 1.4 indicates that two repetitions were monomodal and three bimodal. Closer inspection indicates that the monomodal patterns had shorter durations. Taking into account that the velocity peak counts are very close to 2 for both opening and closing, this suggests that an underlyingly bimodal amplitude pattern changes into a monomodal one as the duration of the cluster decreases. This seems to correspond to what has been observed by Löfqvist and Yoshioka (1980b) in their analysis of voiceless clusters in Icelandic. For the production of the Icelandic sequence [s#sp], for example, where the duration is less than 300 ms, there is only a single glottal opening movement. For the longer productions two glottal opening movements occur during the cluster.

On average, the /k#sk/ cluster is realized with one single opening peak located during the /s/ for both subjects as is shown in Figure 7. Only two repetitions out of seven for RR were realized with two peak glottal openings, one during the fricative /s/ and the second during the following velar consonant. Closer examination of the phonetic nature of these bimodal forms shows that this velar consonant was also produced as a fricative [x] in both cases, presumably thus favouring two peaks¹².

Clusters with four to six consonants

Figure 8 contains the glottographic patterns of the three clusters /sk#sk/, /ks#ks/ and /k#sks/. All these sequences contain two dental fricatives. They are most often produced with two glottal opening peaks located during these two fricatives.

¹² This displays the same pattern observed in some repetitions of /k#ks/ discussed above. Note also that all /k#sk/ repetitions for RR are characterized by a very gradual closing phase, with a high number of velocity peaks.

- Insert FIGURE 8 HERE.

These results are, once again, in accordance with results drawn from various languages. Yoshioka et al. (1981), for instance, observed that American English fricative + stop + fricative + stop sequences were also produced with two peak glottal openings located during the fricatives. The same laryngeal adjustments were produced during the Icelandic sequence [st#sp] (Löfqvist & Yoshioka 1980b). Similar configurations observed in different unrelated languages provide a striking illustration of the tight temporal coordination of laryngeal and oral articulations in voiceless obstruent production: a sequence with two non-adjacent fricatives is most of the time produced with two glottal opening gestures. Another important observation is that /ks#ks/ and /k#sks/ are produced with virtually the same laryngeal adjustments for both subjects, showing once again that word boundaries are quite transparent as far as laryngeal gestures are concerned.

- Insert FIGURE 9 HERE.

Figure 9 firstly compares two similar four-phone combinations with different word boundary locations: /k#kss/ (left panel) and /kk#ss/ (middle panel). These clusters are produced with only one glottal opening peak achieved during the fricative. This always held true despite the placement of the word boundary and despite some slight differences in the number of velocity peaks in the opening and closing phases. Compared to the three-consonant clusters /kk#s/ and /k#ks/ (see Figure 6, top left and right, respectively), these clusters exhibit quite similar movements but the location of the peak shifts slightly more into the fricative in the sequences with geminate fricatives. The comparison here between Figure 9 and Figure 6 also in effect compares geminate with singleton fricatives. It was already mentioned that geminate

fricatives do not increase the glottal opening amplitude as much as geminate plosives do (compared to corresponding singletons). Here, too, there is not much indication that fricative gemination results in a strong increase in amplitude. /k#kss/ does not appear larger than /k#ks/ but the small number of tokens effectively precludes statistical testing¹³.

/k#kss/ and /kk#ss/, as realized here by RR, are homophonous, both forms being produced with a long closure duration followed by a release, i.e. in the first half of the heteromorphemic geminate the oral closure was maintained and the release follows in the second half of the geminate. Similar pronunciations are not produced in adjacent identical consonant sequences in which one segment is a geminate (e.g. /k#kk/ or /kk#k/). In such sequences, the geminate stop must be released and the singleton is either produced as a released stop or, if the optional spirantization rule operates, as a spirant. The sequence /k#kk/, for example, is phonetically distinct from /kk/, the first singleton velar being produced either as a stop or as a fricative (i.e. [x#kk]). This latter pronunciation was the one produced during the three realizations of /k#kks/ (right panel of Figure 9). These forms are always produced with two glottal opening peaks, the first being generally produced during the fricative [x] and the second either during the burst of the geminate /kk/ or at the onset of the fricative /s/.

Figure 10 contains clusters of five consonants. The sequence /ssk#kk/ (right panels) is produced either with two or three glottal abduction gestures. The first peak is always produced during the dental fricative /ss/. RR produced seven repetitions with 3 peak glottal openings and three repetitions with 2 peaks. The second peak in the bimodal productions is always located during the closure of the geminate stop /kk/. The third peak in the trimodal production is located during the singleton velar segment, generally realized as a spirant [x].

¹³ If /k#kss/ and /kk#ss/ are merged to a geminate group, and /k#ks/ and /kk#s/ to a singleton group (with 6 tokens in each group) no significant difference in amplitude is found.

RF always produced this cluster with a bimodal gesture. The second peak is either realized during the spirantized singleton velar stop [x] (in 1 repetition) or during the occlusion of the geminate stop /kk/.

- Insert FIGURE 10 HERE.

The glottographic pattern of the /kk#skk/ cluster (left panels) also varies according to the subjects. For RR, the overall pattern shows two amplitude peaks. The second peak is rather weak, and in two cases only one peak was detected based on our criteria. In one case, a very weak third peak was detected. The velocity peak counts are consistent with the idea that the basic pattern has two glottal opening movements, but with both opening and closing being somewhat more gradual than in the simplest two-peaked patterns. The first opening peak was located roughly at the boundary between the first geminate and the following fricative, the second peak during the second geminate¹⁴.

All the realizations of RF, by contrast, are characterised by one opening gesture. A closer examination of this monomodal pattern reveals that this configuration is presumably related to the very short closure duration for the two velar geminates. Peak glottal opening is always located during the fricative /s/. This was thus the linguistically longest sequence in our material with a clearly monomodal pattern.

- Insert FIGURE 11 HERE.

¹⁴ One of the 10 repetitions of this form by RR was not included in the average curve or the peak counts. The first repetition of the 5 recorded by RF was not considered further as it was much longer than the others (720 ms instead of 280 ms for the other realizations which are also shorter than expected probably due to degemination). The longer duration of this form is due to a long silent pause maintained during the word boundary. This silent pause was associated with clear glottal adduction (without complete closure).

The glottographic patterns for the six-consonant clusters are presented in Figure 11. For /ssk#ssk/ (left panels) the clearly predominant pattern for both subjects is for two glottal opening peaks, located during the first and second geminate fricatives respectively (note, however that both opening and closing velocity peak counts are well above two for both subjects). The movement pattern for this 6-consonant sequence is quite similar to the corresponding singleton pattern /sk#sk/ in the left panels of Figure 8. In the longer sequence, however, - with the usual caveat because of the small number of tokens - there was significantly greater opening amplitude for both subjects for the sequence containing geminate fricatives – perhaps because the double change from singleton to geminate has an amplifying effect.

The remaining sequences /ssk#skk/ and /ssk#sks/ exhibit much variability even within the same subject. Taking the simplest case first, namely /ssk#skk/ for RF, it is observed that this has a fairly clear two-peaked pattern. The most instructive sequence for comparison is once again /sk#sk/ from Figure 8 (i.e. reducing each geminate to a singleton). The overall movement pattern is very similar, supported by similar peak counts for amplitude and velocity, and there is a similar location of the opening peaks in the fricative segments. The linguistically longer sequence simply, and not surprisingly, has longer duration (464 ms for the longer sequences and 360 ms for the shorter on average) and also significantly greater opening amplitude. For RR, on the other hand, inspection of the curve as well as the high values for all the peak counts indicates substantially more movement complexity in this sequence than in either /ssk#ssk/ just discussed above, or the comparison singleton sequence /sk#sk/.

Turning finally to /ssk#sks/, this is the sequence where greatest movement complexity might be expected as it is the only sequence in the material with three separate fricative segments. By and large, this expectation is borne out. RR had a clear preference for 3 opening peaks, quite clearly associated with each of the three fricative segments (albeit rather different in amplitude). This was the only occasion in the whole material where the mean amplitude peak count went above three (caused by one exception where 4 peaks occurred). For RF the amplitude peak count was more evenly balanced: 3 repetitions with 2 peaks, and 2 repetitions with 3. In the averaged trace, peaks are found associated with the first two fricative segments. For both subjects the complexity of the movement pattern is made clear by the very high count for closing velocity peaks (4.29 for RR and 4.2 for RF), which is substantially higher than for any other sequence.

CONCLUSION

The main results of the present study are in general agreement with those obtained from some Germanic languages. We thus have further evidence from different unrelated languages that laryngeal activity during the production of voiceless obstruent clusters is organized in one, two or more glottal opening peaks. The manner of articulation of obstruents and their position in the clusters have a major impact on the number of glottal opening peaks and their locations. A major generalization that comes out from this study is that sequences produced with n fricative segments are most often produced with n peak glottal openings; these peak glottal openings are located during the production of these fricatives. In other words, segments produced with a high rate of oral air flow are produced with a separate laryngeal opening gesture. Geminate, mainly stops, are usually produced with larger glottal amplitude than their singleton counterparts. But the presence of a geminate in a cluster, instead of a singleton, is not accompanied with an additional separate laryngeal peak, although the geminate sequences exhibit an increase in movement complexity (i.e. the opening and closing phases during these sequences are rather gradual).

Another topic of interest in this article was to determine if there are laryngeal correlates of word boundaries. From the data analyzed here it appears that when a word boundary is marked by a long silent pause, it is associated with glottal adduction. According to Löfqvist & Yoshioka (1980a), such an adduction gesture is made to prevent air flow and waste of air during an ongoing utterance. Another possible interpretation would be that word boundaries are in themselves accompanied by glottal adduction. TB material however shows that glottal adduction is not necessarily associated with linguistic boundaries. Recall that adduction gestures are usually found in clusters without apparent word boundaries. Another piece of

evidence showing that word boundaries are transparent as far as laryngeal gestures are concerned is illustrated by the numerous cases where two clusters with two different word boundary locations are often produced with similar laryngeal adjustments. Glottal adduction found in these sequences seems better ascribed to segmental properties.

In addition to TB, other languages present aspirated stops after /s/. The absence of aspiration in such segments is thus not a universal phonetic feature, contrary to what was assumed by Lindqvist (1972). Pétursson (1976) cited cases observed in some Indian languages as well as in some Colombian Spanish dialects. This aspiration is rather exceptional, not only because it is not attested in the most widely studied languages, but also, at least in the case of TB, because it seems totally independent of word boundaries. The TB case is thus typologically interesting, making it possible to determine the two possible laryngeal mechanisms accounting of stop aspiration after /s/: on the one hand a large amplitude and a delay in peak glottal opening relative to fricative onset; on the other hand two peak glottal openings, each corresponding to one of the two obstruents. The second realization is the one produced in /s/-stop heteromorphemic sequences in some Germanic languages. In sum, different combinations of interarticulatory timing and glottal opening size can result in similar amounts of aspiration.

Löfqvist and Yoshioka (1980a: 800) in their analysis of long voiceless consonant clusters noted that: « *There is little, if any evidence that the glottis ever opens and maintains a static open position in speech.* » TB material, which included up to 6 voiceless consonant clusters, provides further evidence that the glottis does not simply remain open for voiceless utterances. These results can be combined with those obtained from an earlier study on TB voiceless words (Ridouane 2004). Here the whole utterances, which contain up to 10

obstruents, were voiceless, and one might have expected that the devoicing gesture might be regarded as superfluous and simply eliminated, leaving the glottis in respiratory position. However, just as in the present experiment, the results showed clearly that the glottal aperture is continuously modulated in a manner that can be related quite systematically to the individual segments in the voiceless sequence. This gives a compelling demonstration of how intimately laryngeal and supralaryngeal articulations are linked.

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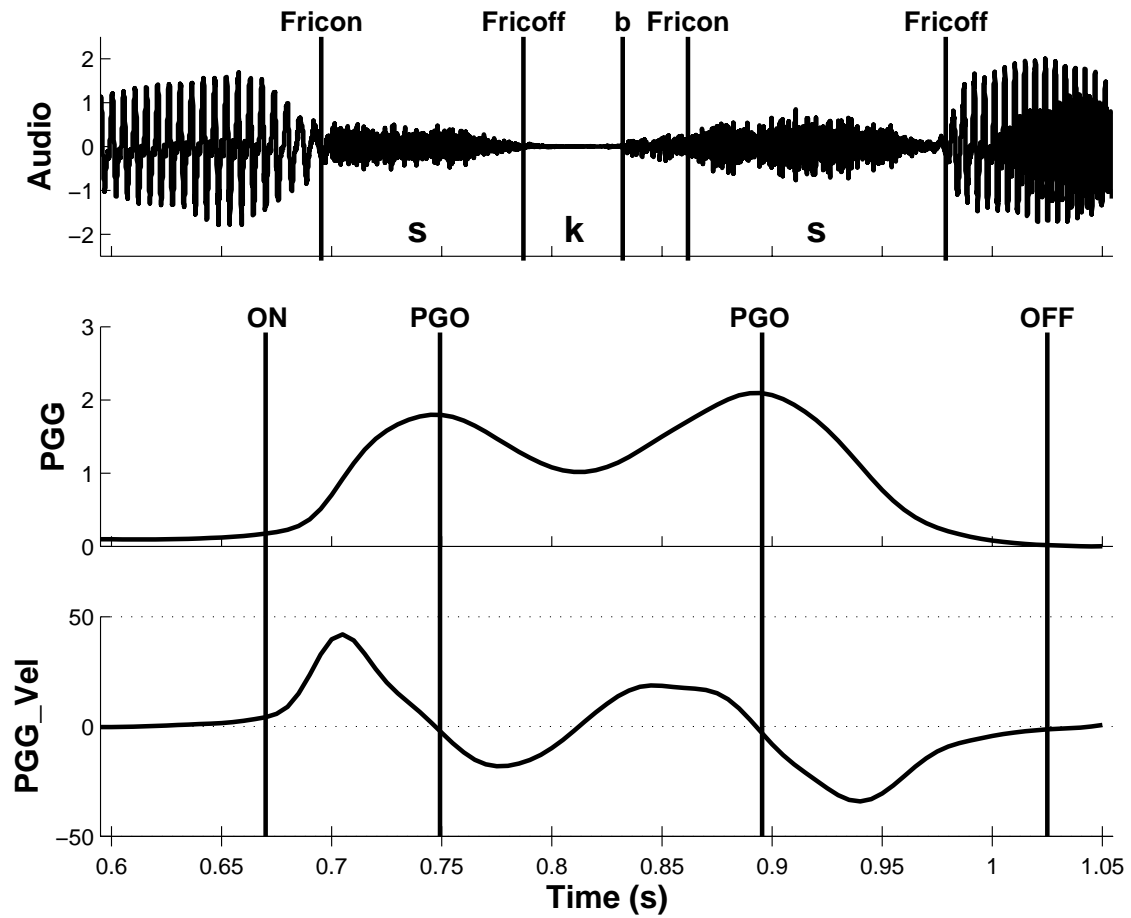


Figure XXX, 1. Example of defined time landmarks concerning acoustic and PGG data in /s#ks/. Fricon = frication onset, Fricoff = frication offset, b = burst; ON = glottal opening onset, PGO = peak glottal opening, OFF = glottal opening offset.

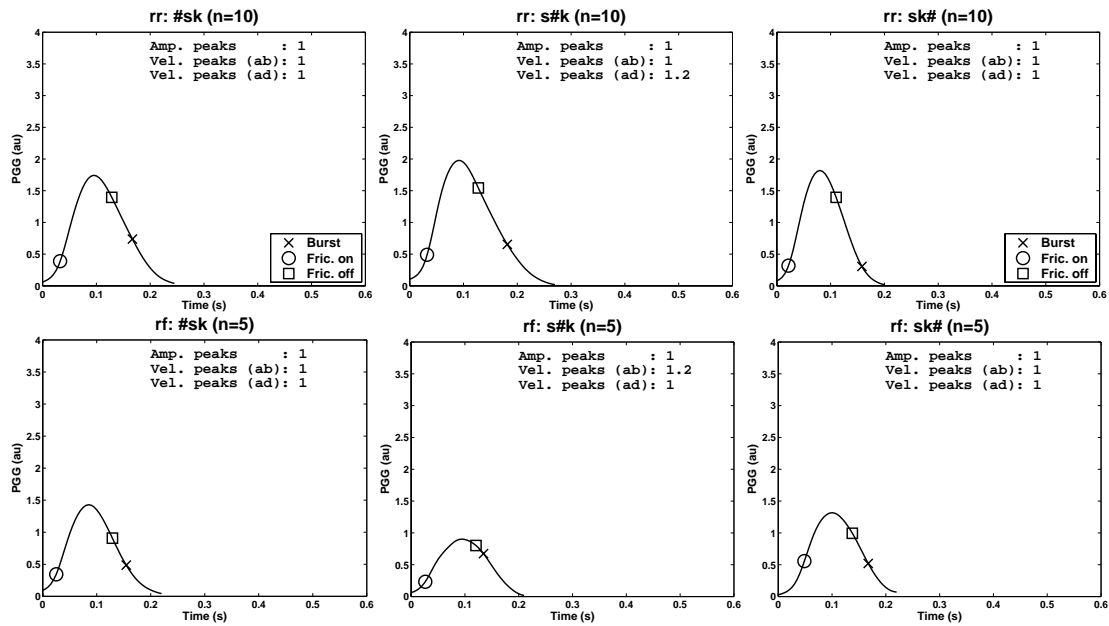


Figure XXX, 2. Averaged glottal abduction pattern for /sk/ clusters with different word boundary locations: #sk (left), s#k (middle), sk# (right). Subject RR (top), subject (RF) bottom. Circles correspond to fricative onset, squares to fricative offset for the fricatives and crosses correspond to stop release. Each figure displays the number of amplitude peaks as well as the number of abduction and adduction velocity peaks. The number of repetitions of each sequence is indicated between brackets.

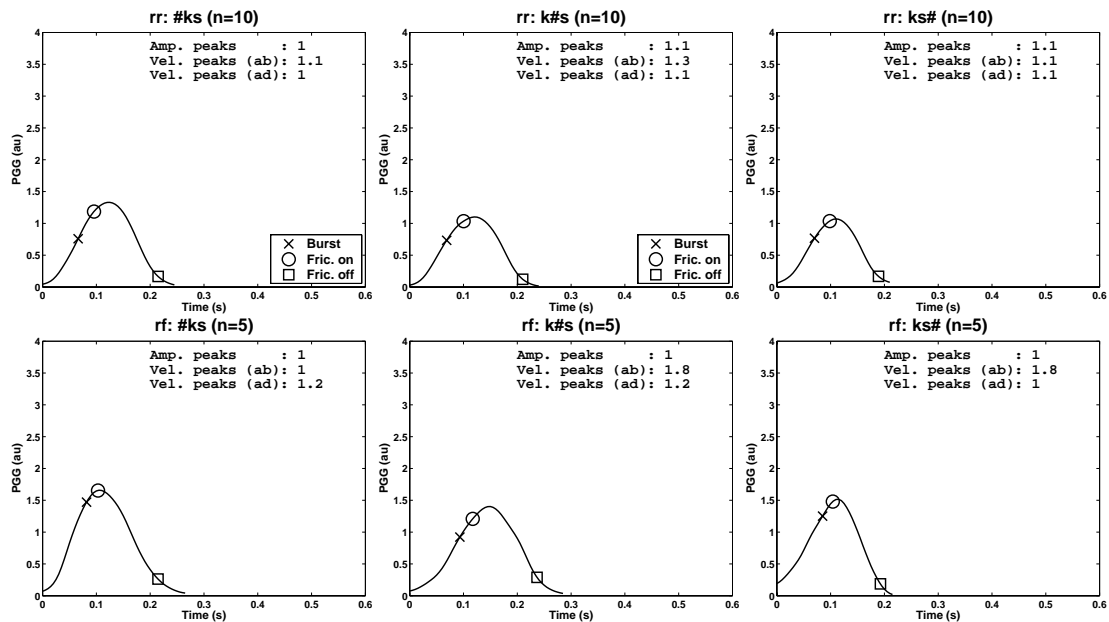


Figure XXX, 3. Averaged glottal abduction pattern for /ks/ clusters with different word boundary locations. Symbols as in Fig. 2.

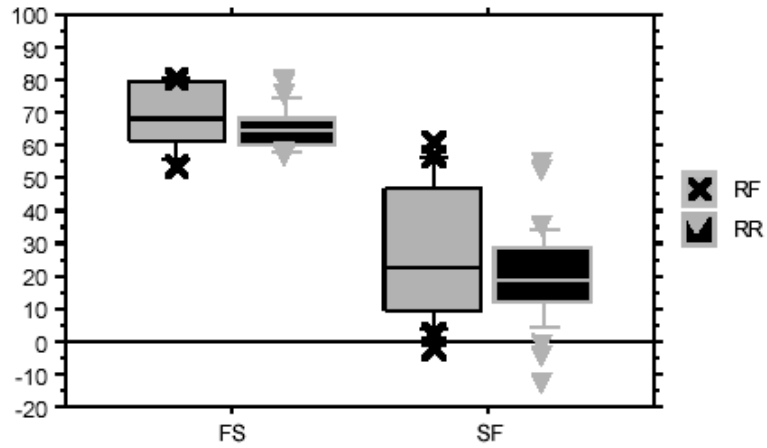


Figure 4. Timing of peak glottal opening during the fricative in two-consonant clusters: fricative+stop (FS) and stop+fricative (SF) sequences

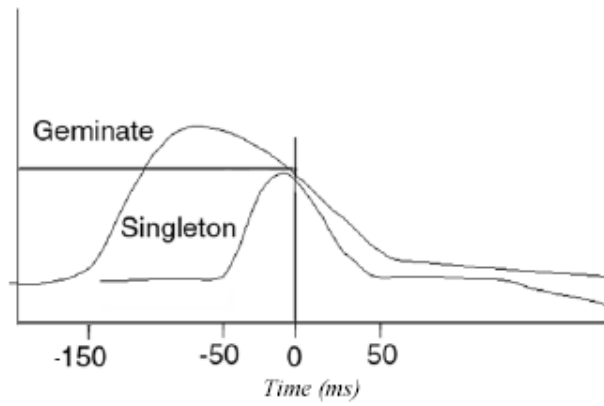


Figure 5. Illustration of the glottal opening during the production of the stops in [itili] and [itili]. The vertical bar indicates the onset of oral release (adapted from Ridouane 2003).

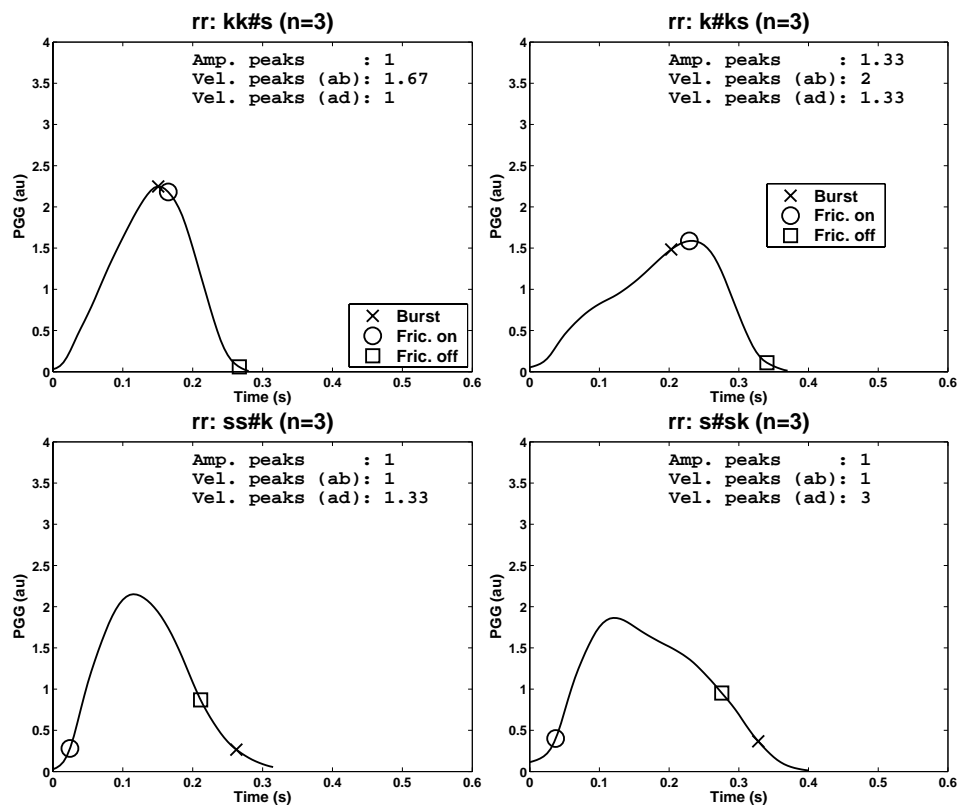


Figure XXX, 6. Averaged glottal abduction pattern for /kk#s/, /k#ks/ (top row) and /ss#k/, /s#sk/ (bottom row) produced by one subject (RR). Symbols as in Fig. 2.

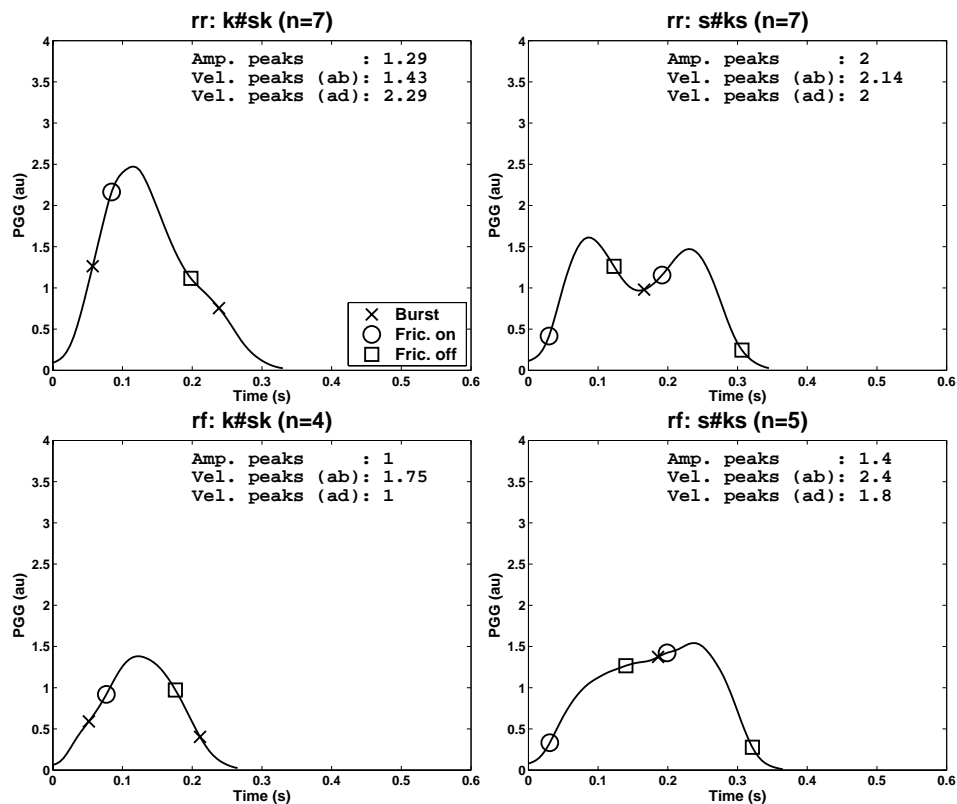


Figure XXX, 7. Averaged glottal abduction pattern for /s#ks/ and /k#sk/. Symbols as in Fig. 2.

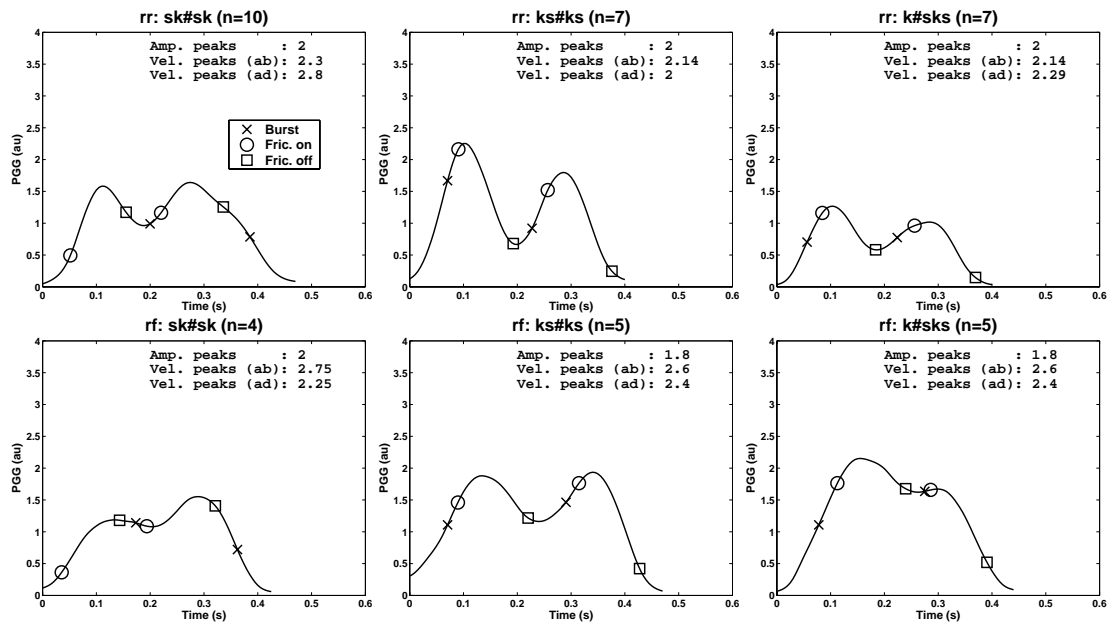


Figure XXX, 8. Averaged glottal abduction pattern for /sk#sk/, /ks#ks/ and /k#sks/. Symbols as in Fig. 2.

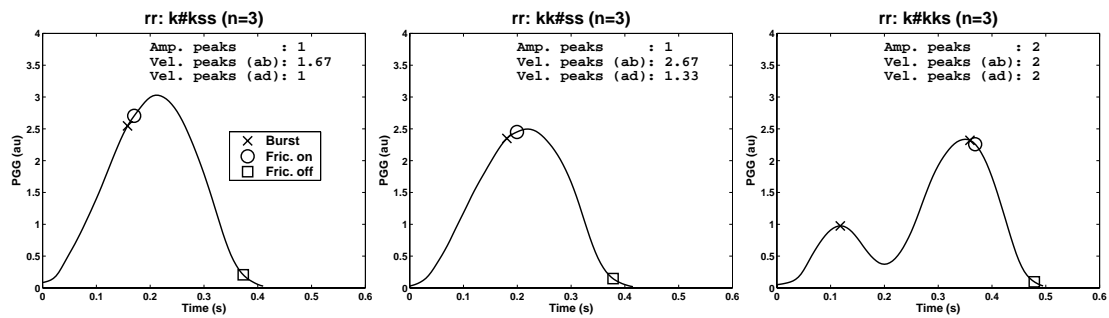


Figure XXX, 9. Averaged glottal abduction pattern for /k#kss/, /kk#ss/ and /k#kks/ produced by one subject (RR). Symbols as in Fig. 2.

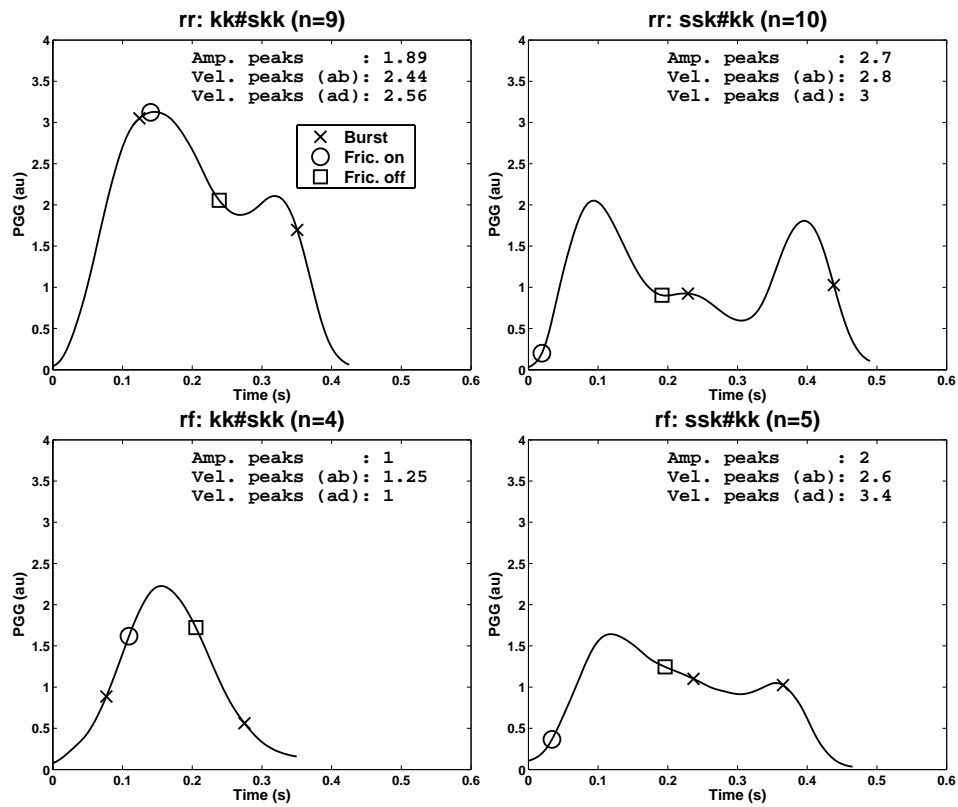


Figure XXX, 10. Averaged glottal abduction pattern for /kk#skk/ and /ssk#kk/. Symbols as in Fig. 2.

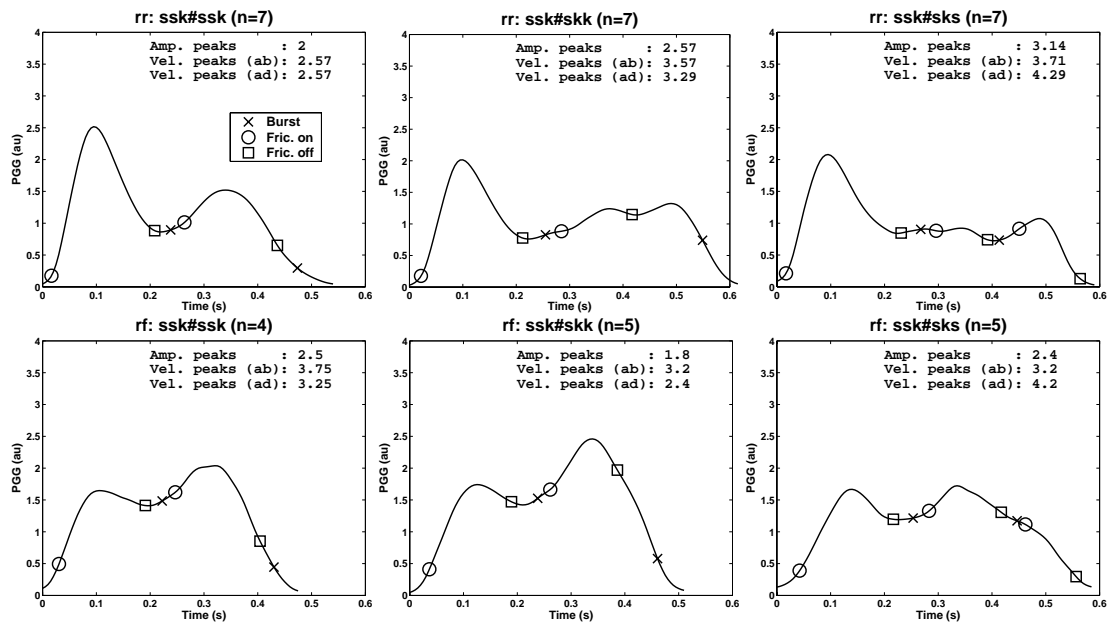


Figure 11

Table 1. The linguistic material: # marks a word boundary, numbers in brackets indicate the number of repetitions, first value for RR and second value for RF.

2 consonants	3 consonants	4 consonants	5 consonants	6 consonants
#ks (10,5)	s#sk (3,-)	sk#sk (10,4)	ssk#kk (10,5)	ssk#ssk (7,4)
k#s (10,5)	ss#k (3,-)	ks#ks (7,5)	kk#skk (10,5)	ssk#skk (7,5)
ks# (10,5)	k#ks (3,-)	k#sks (7,5)		ssk#sks (7,5)
#sk (10,5)	kk#s (3,-)	k#kss (3,-)		
s#k (10,5)	s#ks (7,5)	kk#ss (3,-)		
sk# (10,5)	k#sk (7,4)	k#kks (3,-)		