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What role does the palate play in speech motor control? Insights from tongue kinematics for German alveolar obstruents

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Abstract

By means of simultaneous EMMA and EPG recordings we investigated tongue tip kinematics and tongue palate contact patterns for four German speakers in order to compare production strategies of alveolar stops with fricatives. We assumed that the central nervous system integrates the palate in the speech motor control process and that tongue palate contact patterns influence the kinematic properties of the tongue movement. For stops versus fricatives two different control strategies were supposed: a target location above the contact location for /t/ resulting in a collision of the tongue tip at the palate and a precise positioning of the tongue at the lateral margins at the palate for /z/. Additionally, we suspected differences with respect to anterior and lateral palate contacts and their influence on tongue kinematics.

Results of this study confirmed two different control strategies for alveolar stops and fricatives by means of differences in movement amplitude, velocity, and duration of the closing gesture, the amplitude of deceleration peaks, tongue tip movement during acoustically defined closure and constriction, and maximal anterior contact during closure. Additionally, speaker dependent mechanisms seem to occur depending on the coronal palatal shape.

1. Introduction

A particular characteristic of speech production compared to other human motor systems is that the tongue moves in a narrow space delimited by the pharyngeal walls, cheeks, teeth, lips and palate. Hence, even if the basic principles that govern arm or limb motor control might also apply to speech, it seems reasonable to assume that in speech production specific strategies are used to deal with these additional constraints. In this paper we will further concentrate on the upper limit of the vocal tract, the palate. Since tongue movements for oral consonants are most of the time produced in the presence of palatal contacts it is hypothesized that: 1) the palate passively influences kinematic properties of speech movements, and 2) tongue palate interactions are taken into account in the speech motor control process as limitations of the degrees of freedom for tongue movement or as potential help to achieve the relevant articulatory objectives. Both hypotheses are discussed in the following paragraph supported by findings from the literature.

Concerning consonant production, Stone (1991) suggested that some tongue shapes, particularly in the production of alveolars could not be produced by a free-standing tongue position, i.e. the palate is a spatial reference for the tongue and it can be used to provide tactile feedback information in order to learn and/or control specific tongue shapes. Additional evidence was provided by perturbation studies. In 1978, Hamlet and Stone recorded tongue-palate contact patterns for ten speakers wearing a dental prosthesis of 4 mm thickness in the alveolar region. Data were observed in two sessions: immediately after the insertion of the prosthesis, when subjects were still unfamiliar with it, and two weeks after adaptation. Results for the first session provide evidence for a tongue overshoot in /s,z,t,d,n/. Results for the second session showed compensatory movements with a similar variability as in the first session. The authors suggested that:

> ”The way sensory feedback is used in learning a compensatory form of speech is qualitatively similar to its use routinely. That is, all sensory information (from audition, proprioception, touch etc.) by which the status of the oral environment and relative positions of the articulators can be assessed, is continuously monitored, and planning the speech act” (Hamlet and Stone 1978, p.246).

Baum and McFarland (1997) investigated acoustic and perceptual changes for /s/ production after structural modifications of the alveolar ridge using an artificial palate. Seven subjects were analyzed. They found that /s/ was acoustically and perceptually highly susceptible to perturbing effects in the beginning of the session. After one hour practicing, a significant improvement of acoustic and perceptual characteristics were observed, although compensation was not complete. The authors propose that an adaptation to articulatory perturbations could be achieved in a relatively short time period due to a recalibration of the speech motor control system taking into account the new spatial reference at the alveolar ridge. Honda et al. (2002) and Honda and Murano (2003) used another experimental paradigm, dynamic (time varying) perturbations. They examined compensatory tongue movement for unexpected perturbations due to an inflatable artificial palate, which thickness can suddenly be increased or reduced, and combined it with or without auditory masking. Their findings suggest that compensatory movements are actively and immediately produced due to tactile feedback information, and that auditory feedback is used in precise articulatory adjustment, but with a longer time delay in comparison to tactile feedback.

The influence of tongue palate interaction onto tongue kinematics was discussed in Hoole (1996) who found for German /aCa/-sequences differences with respect to the deceleration peak of the closing gesture in the following order: /t/>/d/>/n/>/s/. He assumed that in alveolar stop production the relatively high deceleration peak of the tongue tip is mainly passive and a result of tongue interaction with the palate whereas in alveolar fricatives the deceleration phase is actively controlled. Fuchs et al. (2001) showed that the onset of oral closure, defined by EPG data, coincided with the time point of the high deceleration peak for the tongue tip sensor. It was proposed that a collision of the tongue tip against the palate could be responsible for the abrupt deceleration and the strength of the deceleration peak. These findings support the hypothesis of Löfqvist and Gracco (1997) for bilabial stops that articulatory gestures could be directed toward a target that is beyond the contact location. Thus, stops are not controlled via a fine positioning of the tongue at the palate, but by the use of the palate as a reference which stops the tongue automatically at the required location in the vocal tract. In terms of stability and simplicity such a control strategy seems to be extremely efficient in comparison with the control of a fine positioning of the tongue at the palate. The effects of target variations in stop production on tongue kinematics (a precise positioning of the tongue without the palate and a collision between tongue and palate) were modeled in Perrier et. al (2003) using a 2D biomechanical tongue model. It has been shown that the tongue-palate interaction combined with the relative target positions of the surrounding phonemes could explain some of the direction of the counter-clockwise trajectories (so called loops) in /VkV/-sequences.

Contrasting stops with fricatives, a more precise positioning of tongue and jaw has been observed (e.g. Mooshammer et al. 2003). Fricatives are also often described as being difficult to produce, and more complex. They are acquired later in the children's speech development in comparison to less complex sounds, cause most problems in patients who suffer from sensori-motor coordination impairments and they seem to occur more frequently in tongue slips, especially regarding place of articulation (Boomer and Laver 1968).

The aims of our study are twofold: first, to compare alveolar stops with fricatives, because fricatives should be based on a fine positioning of the tongue at the lateral margins of the palate as well as tongue grooving which is not required in stop production. Thus, we suppose two different control strategies. Second, tongue-palate interaction in the anterior and lateral parts of the palate were investigated separately in order to interpret their potential influence onto tongue kinematics. Lateral contacts could potentially cause damping, and they might explain speaker dependent differences in tongue kinematics based on the shape of the palate (Tiede 1998, Mooshammer et al. in press).

2. Method

Tongue tip movements and tongue-palate contact patterns of four German speakers were recorded simultaneously by means of EPG (Reading EPG3) and EMMA (AG100, Carstens Medizinelektronik) systems. Tongue tip movement was associated with the movement of a sensor placed mid-sagittally approximately 1 cm behind the tip. Two sensors served as reference points to compensate for helmet movements, one at the bridge of the nose and one at the upper incisors. All other sensors at the tongue and the jaw were not taken into account here. Speech signals were synchronously recorded on DAT. Sampling frequencies were 16 kHz for the acoustic data, 100 Hz for EPG and 200 Hz for EMMA data respectively. Four German subjects were recorded, three males (CG, DF, JD) and one female (SF). The speech material consisted of the nonsense words *geCVCe* and *geCVC*, where C was always either /t/ or /z/. In *geCVC* the word final /z/ becomes devoiced since the phonological rule of final devoicing applies in German. In this paper we were interested in the second C of each target word, following one of the stressed vowels /ɑː/ or /uː/. Different positions of the consonant were considered: C in word medial position (hereafter med), e.g. in *getah**t**e* and C in word final position (hereafter fin) as in *getah**t***. All target words were embedded in the carrier phrase ”Ich habe geCVCe nicht geCVC erwähnt.” (I said geCVCe not geCVC.) and each sentence was repeated ten times in a randomized order. The tongue tip closing gesture from the stressed V to C was taken into account. The on- and offsets of the closing gesture were defined on the tangential velocity signal of the tongue tip sensor using a 20 per cent threshold criterion (see figure 1).

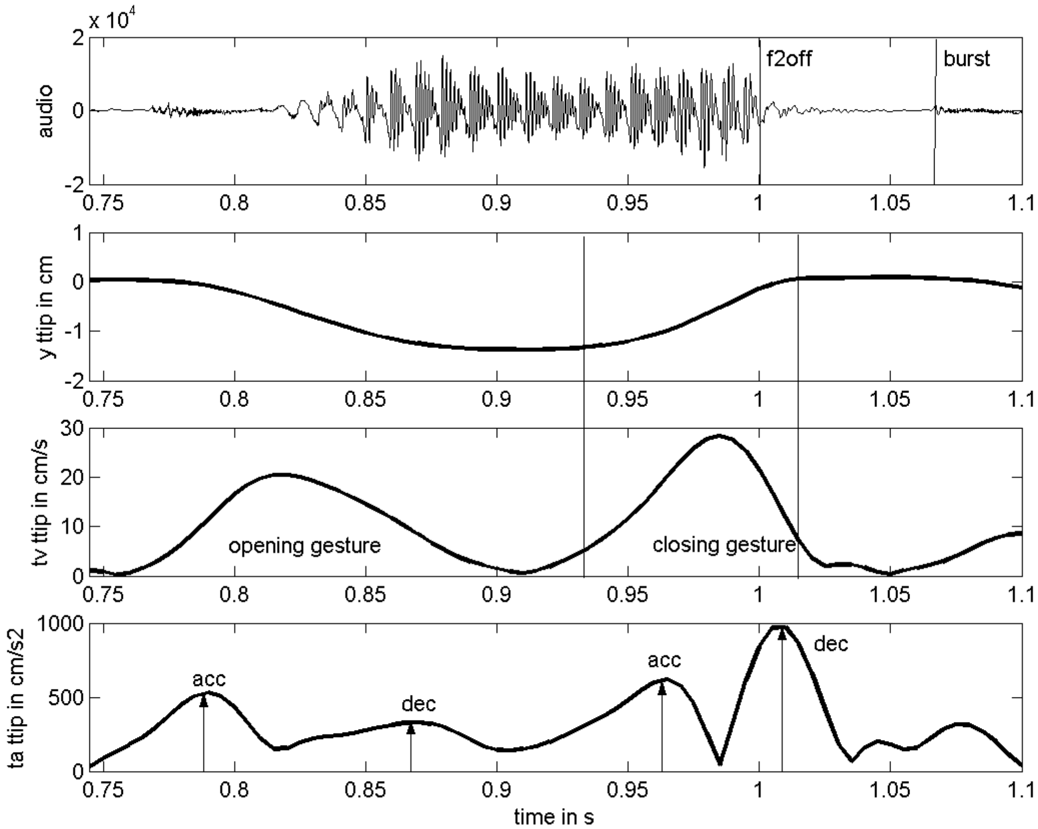

Figure 1: Articulatory and acoustic labeling criteria from CG's medial /t/ production in /a/-context: 1st track: audio signal with f2 offset and the burst, 2nd track: tongue tip vertical movement in cm, 3rd track: tongue tip tangential velocity signal in cm/s with closing gesture onset and offset, 4th track: tongue tip tangential acceleration signal in cm/s2 with acceleration (acc) and deceleration peaks (dec); x-axis: time in s

Starting from the landmarks defining the closing gesture, the velocity peak vel_peak, the duration of the closing gesture clg_dur and the movement amplitude ampl (as the integral from onset to offset of the closing gesture in the tangential velocity signal) were considered. In order to compare stop production with fricative production in relation to previous findings in Fuchs et al. (2001) and Hoole (1996), the acceleration and deceleration peaks of the closing gesture (VC-sequence) as well as of the preceding opening gesture (CV-sequence) were labeled. The latter was taken as a reference.

From the acoustics two landmarks for each obstruent were analyzed. For stops, closure onset was defined as the offset of the second formant. The burst was labeled too. For fricatives, on- and offset of high frequency noise were taken into account.

From each EPG pattern the percentage of contact in the anterior region (4 most front rows) = ANT, in the posterior region (4 most back rows) = POST and in the lateral region (2 most peripheral columns on the left and right side of the palate) = LAT were computed in order to quantify tongue palate contact in time. Onsets of lateral and anterior contact of the closing gesture were labeled as the landmarks where the relevant contact increases after the preceding vowel. The increase of contact was most of the time rather abrupt and thus, we did not use a threshold criterion as for the EMMA data. Additionally, the landmarks of maximal lateral and anterior contact during oral closure/constriction were defined. In order to get an impression of subject dependent palatal shapes the x, y, and z coordinates for each of the 62 electrodes of the custom made artificial palate were measured using a method described in Fitzpatrick and Ní Chasaide (2002).

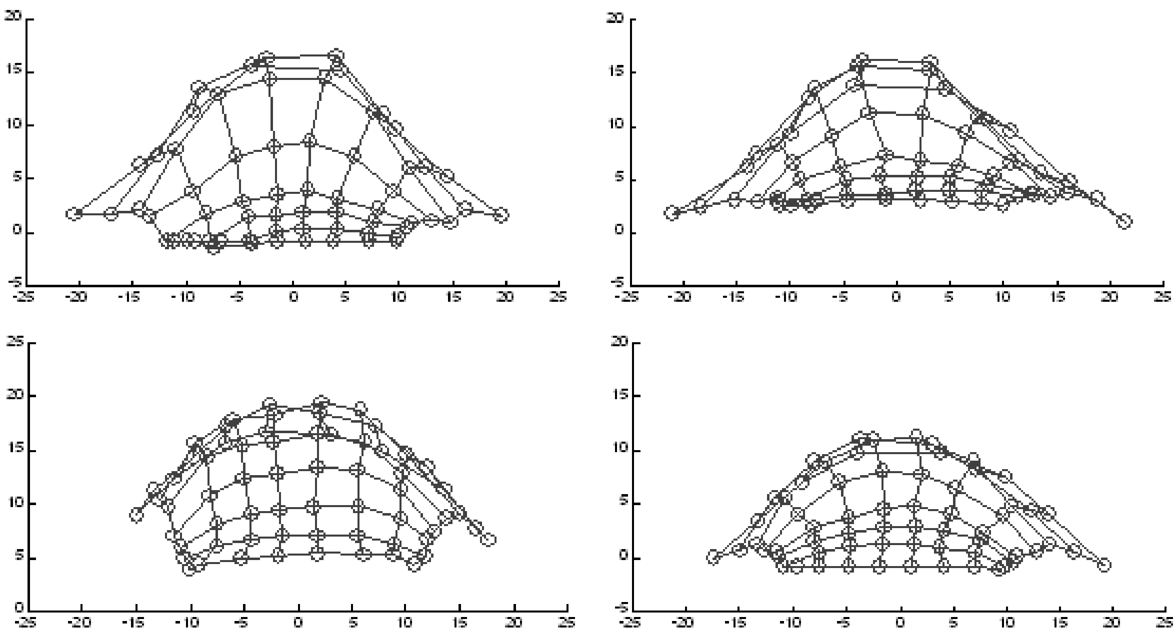

Figure 2: Coronal shapes of the artificial palates (anterior to posterior view), dots correspond to the 62 electrode positions at the speaker specific EPG palates, left 1st row: CG, right 1st row: DF, left 2nd row: JD, right 2nd row: SF, x and y-axis in mm

Figure 2 exhibits the palatal shapes for all subjects. Two subjects (upper row) showed coronal shapes similar to a dome and the two other subjects (lower row) a rather flat palate shape in the coronal plane.

3. Results

3.1. Closing gesture amplitude and its duration

A number of variance analyses were calculated using the General Linear Model in SPSS 11.5. Closing gesture amplitude, its duration and velocity peak were taken as the dependent variables and consonant (/z/ versus /t/) as the independent variable. Data were split by vowel (/a/ versus /u/) and position in word (med versus fin). Results provide evidence that movement amplitudes in /t/ are significantly larger for all subjects in all conditions (all $p<0.001$, except JD med /a/-context $p<0.05$ at a 95 per cent confidence interval). The same was true for the velocity peaks (all highly significant).

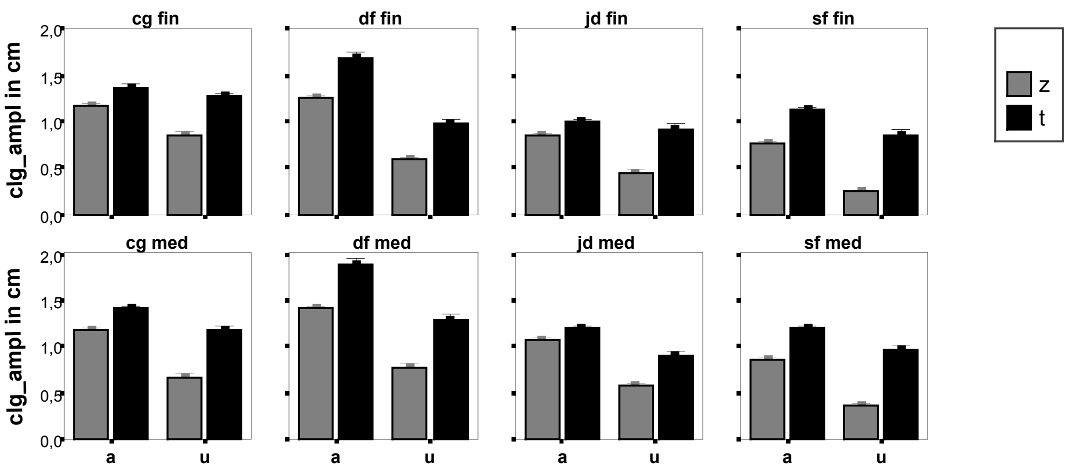

Figure 3: Bar plots showing means of closing gesture movement amplitudes in cm with +/- 1 std. error; gray bars = /z/, black bars = /t/; upper row = word final position, lower row = word medial position; graphs correspond to different subjects (CG, DF, JD, SF) from left to right; x-axis: /a/ versus /u/-context

Similar findings have been presented by Geumann (2001) who showed a smaller movement amplitude due to a lower tongue tip target position in /s/ and a higher tongue target position in /t/. The smaller movement amplitude for the fricative may also be a result of tongue grooving as described in Narayanan et al. (1995), and knowing that the tongue tip sensor is placed within the mid-sagittal groove. The latter can be confirmed by means of maximal anterior contact during oral closure/constriction from EPG data. Results for stop production showed generally significant more per cent of maximal ANT contact than in fricative production (all /a/-contexts p<0.001, except DF fin p<0.05, /u/-context med CG, SF p<0.001, JD p<0.05, fin CG, SF p<0.001, JD p<0.05).

If alveolar fricatives and stops were controlled in the same way, movement duration should be similar for both consonants and larger movement amplitudes coincide with greater velocity peaks whereas smaller movement amplitudes with smaller velocity peaks. Such results are generally found for the alveolars realized in /u/-context. However, in all speakers' production concerning the /a/-context, the movement amplitude and the velocity peak are larger in /t/ compared to /z/, but the closing gesture is shorter for /t/ than /z/ (med: CG p<0.001, DF/JD/SF p<0.01; fin: CG/DF p<0.001, SF p<0.01, JD p<0.05).

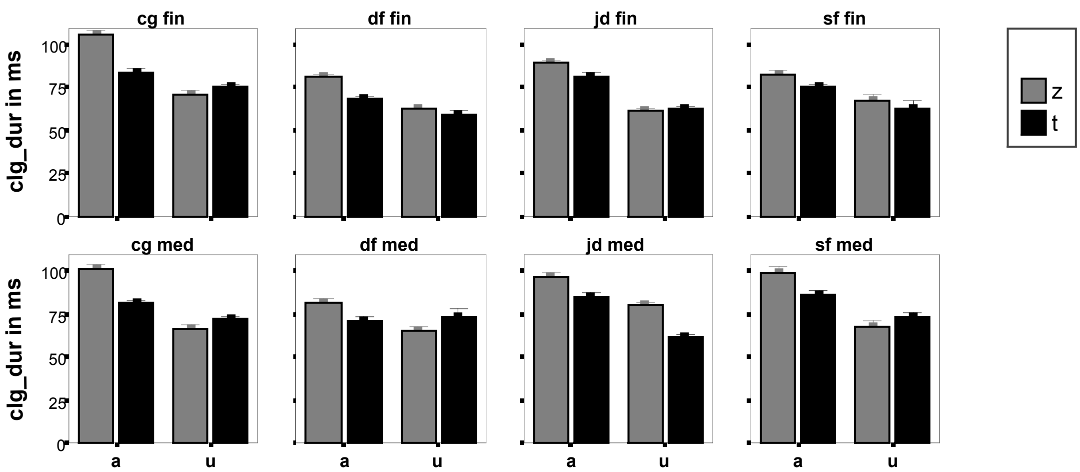

Figure 4: Bar plots showing means of closing gesture duration in ms with +/- 1 std. error; gray bars = /z/, black bars = /t/; upper row = word final position, lower row = word medial position; graphs correspond to different subjects (CG, DF, JD, SF) from left to right; x-axis: /a/ versus /u/-context

3.2. Deceleration of tongue tip movement and movement during closure/constriction

In order to further assess strategies used in stop and fricative production two different measurements were carried out: first, acceleration and deceleration peaks in the opening and closing gestures were compared and second, tongue tip movements (movement amplitude, vertical and horizontal movements) during oral closure or constriction were observed.

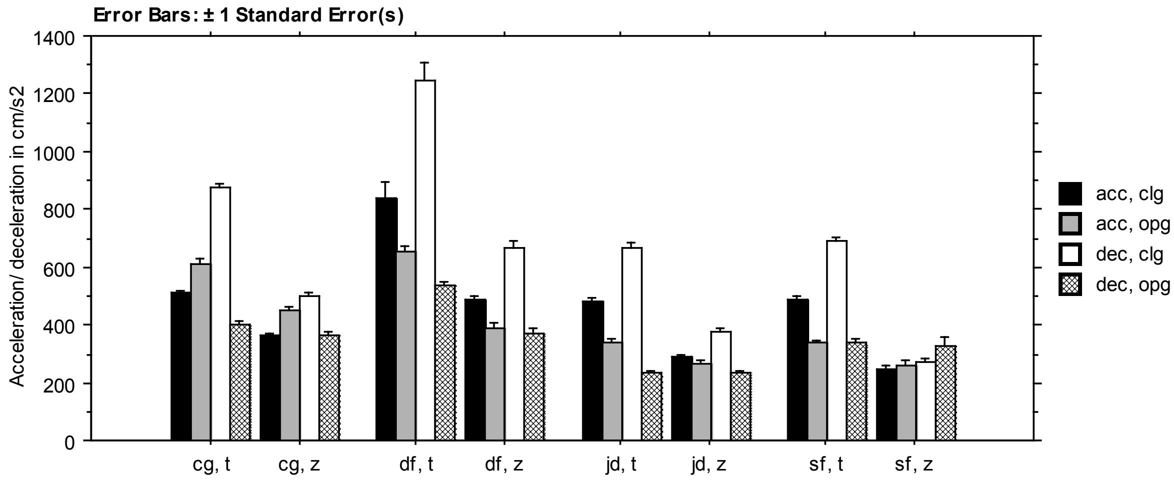

Figure 5: Bar plots showing means of acceleration (acc) and deceleration peaks (dec) in cm/s2 with +/- 1 std. error, averaged over vowel context and word position; back and white bars = closing gesture, gray and structured bars = opening gesture; x-axis: subjects: CG, DF, JD, SF (first 4 bars for /s/, second for /t/) from left to right

As predicted from the hypothesis that palatal collision strongly affects movement kinematics for stops, a consistently higher deceleration peak during the closing gesture was found in comparison to the opening gesture for /t/ (see figure 5). This is also true for /z/ (except from SF). Additionally, the relative differences between deceleration peaks in the opening and closing gestures are always greater for /t/ than /z/, e.g. for CG - the deceleration peak in the closing gesture for /t/ is 2.2 times greater than in the opening gesture whereas in /z/ it is only 1.4 times greater. Acceleration peaks do not exhibit comparable relations and vary rather speaker dependently. In order to rule out a possible influence of the larger movement amplitude in /t/ onto the deceleration peak (larger amplitudes coincide with greater velocity peaks, the deceleration is a derivative of the velocity and could therefore be influenced by the larger amplitude) a covariance analysis was calculated with deceleration peak in the closing gesture as the dependent variable, movement amplitude as the covariate and consonant (/t/ versus /z/) as the independent variable. Data were split by position (med versus fin) and vowel context (/a/ versus /u/). Significant results for the deceleration peaks between /t/ and /z/ were found in all /a/-context (med: CG, JD $p<0.001$, DF $p<0.01$, SF $p<0.05$, fin: CG, DF, SF $p<0.001$, JD $p<0.001$). In /u/-context differences are less consistent (med: JD, SF $p<0.001$, DF $p<0.01$, fin: SF $p<0.001$, DF $p<0.05$). These findings are interpreted with respect to the hypothesis that the tongue does not stop its movement due to an active deceleration for alveolar stops, but due to an impact at the palate. It is in general agreement with Hoole's proposal (1996) and Löfqvist's and Gracco's suggestion (1997) for a planned target position beyond the contact location.

Additional evidence was derived from the results concerning tongue tip movement during acoustically defined closure and constriction. If a target is planned beyond a contact location the global force at the origin of the movement is reoriented by the abrupt apparition of the palatal reaction forces and gets redirected depending on the angle of incidence and the target positions of the surrounding phonemes (see also Brunner et al. 2004). For a target planned at the contact location, less damping effects should occur due to the missing impact, and less movement should be produced in order to precisely place the articulator at the target location.

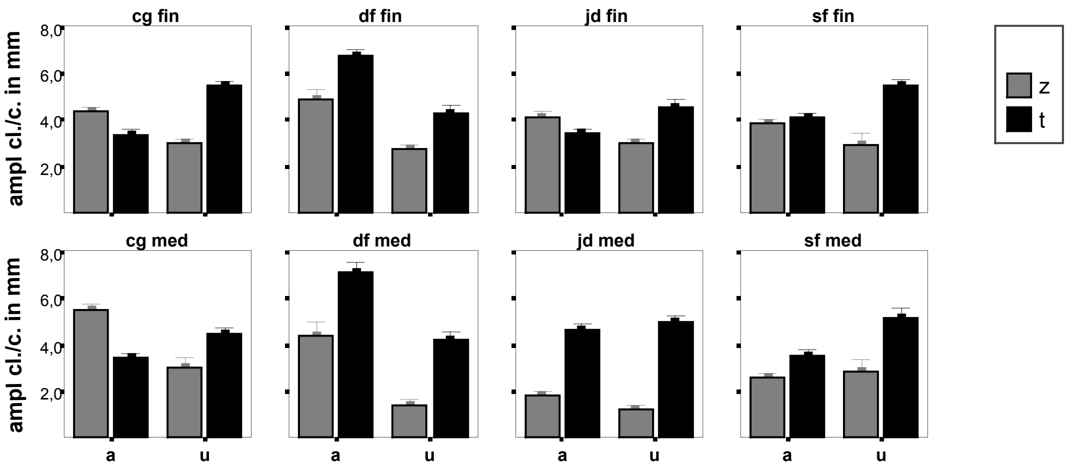

Figure 6: Bar plots showing means of movement amplitude during acoustically defined closure/constriction in mm with +/- 1 std. error; gray bars = /z/, black bars = /t/; upper row = word final position, lower row = word medial position; graphs correspond to different subjects (CG, DF, JD, SF) from left to right; x-axis: /a/ versus /u/-context

Figure 6 exhibits larger movement amplitudes during /t/ closure compared to /z/ constriction in all cases for /u/-context (highly significant). In /a/-context significant differences occur particularly in the word medial position (DF, JD, SF). In word final position similar distinct pattern were only found for DF. Subject CG shows generally the reverse pattern in /a/-context with larger amplitudes for /z/ than for /t/. The differences in movement amplitude are interpreted with respect to the differences in target planning.

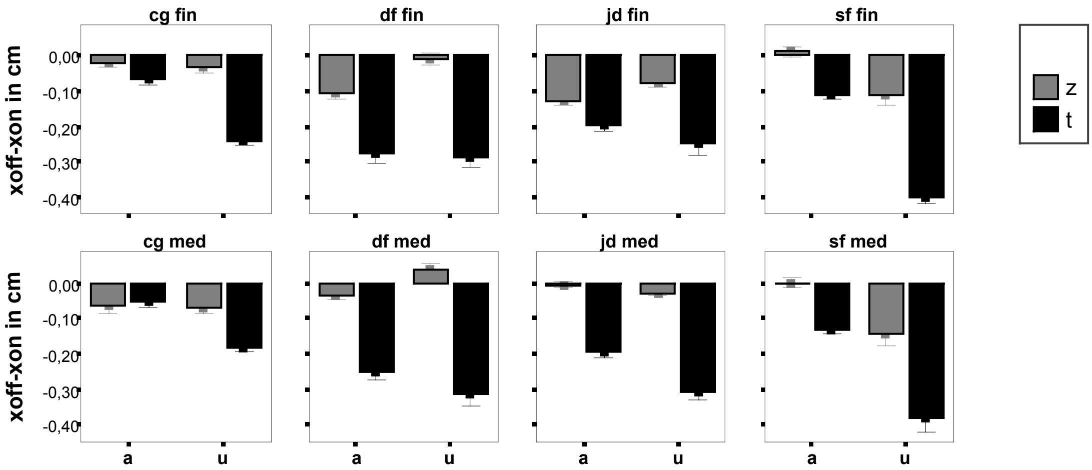

Figure 7: Bar plots showing means of the difference in horizontal position from closure/constriction onset to closure/constriction offset in cm with +/- 1 std. error; negative values correspond to a forward movement; gray bars = /z/, black bars = /t/; upper row = word final position, lower row = word medial position; graphs correspond to different subjects (CG, DF, JD, SF) from left to right; x-axis: /a/ versus /u/-context

The larger movement amplitudes during oral closure for /t/ are mainly a result of a forward movement of the tongue tip as shown in figure 7 (except for CG in /a/ context for whom differences in amplitude correspond to vertical tongue movement). Forward movements during /t/ closure are more pronounced in /u/ than in /a/-context, confirming the idea that a redirection of the movement depends on the planning of the target and on the angle of incidence. Brunner et al. (2004) suggested the greater the size of the angle of incidence, determined by the target positions of the surrounding environment, the larger the movement amplitude of the sliding tongue. Although the exact angle of incidence was not calculated here, it seems reasonable to assume that the angle of incidence in /u/-context is more obtuse than in /a/-context since the tongue moves from a back high vowel towards the front.

3.3. Duration from onset of lateral contacts and velocity peak

In a previous pilot study we observed for one subject that in /t/ the velocity peak was well synchronized in time with an increase in lateral contacts, corresponding to the onset of stop occlusion. This observation raised the question whether for stop production the deceleration phase could be a result of tongue-palate interaction only. In order to generally test the reliability of these preliminary findings, the temporal difference between the velocity peak and the onset of lateral contact was calculated. In /u/-context (all speakers, all conditions) lateral contacts start already during the vowel, i.e. they precede the velocity peak. Tongue and palate are always in contact with each other since /u/ is a high vowel. Results obtained for the /a/-context are shown in figure 8 and exhibit a speaker dependent picture.

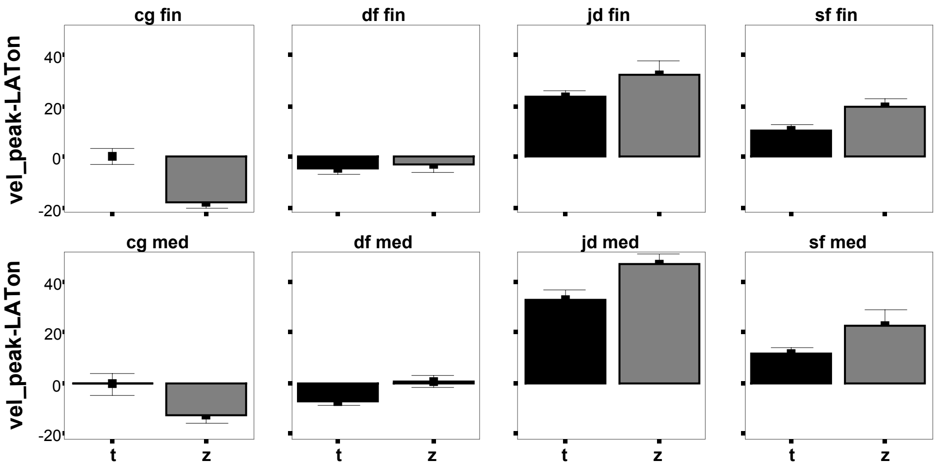

Figure 8: Barplots with means of the difference between velocity peak and beginning of LAT in ms with +/- 1 std. error; negative values correspond to lateral contact after the occurrence of velocity peak; positive values to lateral contacts before velocity peak; gray bars = /z/, black bars = /t/; upper row = word final position, lower row = word medial position; graphs correspond to different subjects (CG, DF, JD, SF) from left to right, /a/-context

Differences between /z/ and /t/ are relatively small keeping in mind that the frame rate of EPG is 100 Hz. However, results clearly reveal specific patterns for speakers with a dome shaped palate versus speakers with a flat palatal shape. For the latter, tongue contact with the lateral margins of the palate occur already within the /a/-context (between 15-30 per cent LAT) and increases for the relevant consonant. Speakers with a dome shaped palate don't indicate such patterns. Their results show roughly a simultaneous timing of the velocity peak with the onset of lateral contacts. If the tongue is in contact with the palate already during vowel production as for speakers with a flat palatal shape, the impact between tongue and palate in stop production seems to be smaller in its strength. The interpretation of differences between the two groups of speakers is consistent with the results for the deceleration peaks in /t/ production. For speaker DF and CG deceleration peaks are larger than for JD and SF, which suggests that in case of dome shaped palate the damping induced by the palatal contacts is stronger. Thus, tongue palate contact patterns realized in the preceding vowel are different and therefore, affect tongue kinematics to a different degree. Since lateral contacts were already produced during the acceleration phase, they cannot induce the deceleration phase alone. However, a combination of lateral and anterior contacts may cause the beginning of the deceleration, at least for stop production.

In opposition to what we expected that lateral contacts start earlier with respect to anterior contacts in /z/ production, we did not find reliable differences between /t/ and /z/. If differences occurred than they were often 10 ms and therefore close to the reliability range of EPG. It means that either lateral contacts always co-occur with anterior contacts in alveolar obstruent production or that differences between the onsets of such contacts are very tiny and should be investigated by means of a higher time resolution technique.

4. Discussion

By means of simultaneous EMMA and EPG recordings we investigated tongue tip kinematics and tongue palate contact patterns for four German speakers in order to compare production strategies of alveolar stops with fricatives. We assume that the central nervous system integrates the palate in the speech motor control process and that tongue palate contact patterns influence the kinematics of the tongue movement. For stops versus fricatives two different control strategies are supposed: In stop production the alveolar target is planned beyond the contact location (see Löfqvist and Gracco 1997). In terms of stability and simplicity such a control strategy would be efficient, since it can tolerate quite a large amount of variability in the motor commands without endangering the final tongue positioning. In opposition, we suppose that fricatives are planned with a target at the lateral margins of the palate in order to create a narrow mid-sagittal constriction as a prerequisite in the production of turbulent noise. To do so, a more precise tongue and jaw position is required.

Results for both strategies are evident in tongue tip kinematics and tongue palate contact patterns. The larger deceleration peak in /t/ production provides evidence for a collision of the tongue tip at the palate(in agreement with Hoole 1996 and Fuchs et al. 2001). Additionally, the movement amplitude and the velocity peak of the closing gesture are larger in /t/ whereas the duration of the closing gesture is significantly shorter, at least in /a/-context. Movement amplitudes for /z/ are smaller in size, slower in speed, and are produced with a longer duration. Findings from maximal anterior contact during closure or constriction exhibit significantly more percent of contacts for /t/ than for /z/, supporting two ideas: First, alveolar fricatives are produced with tongue grooving and have therefore less contact with the palate. Second, an impact always produces a high amount of contacts whereas fine positioning can potentially produce both - a small or a large amount of contact.

By observing the movement amplitude during the acoustically defined oral closure for stops and the oral constriction for fricatives, a larger tongue tip movement amplitude was found for /t/ than for /z/. The tip generally moves in a forward direction which is particularly pronounced in /u/-context and confirms earlier work from Brunner et al. (2004). Brunner et al. suggested that the target location beyond the palate as well as the size of the angle of incidence play a major role for the amplitude of the sliding tongue. The more obtuse the angle of incidence during the impact, the larger the movement amplitude. In /z/ production less movement is produced during oral constriction, speaking for a more precise tongue positioning.

Concerning the role of lateral tongue palate contacts, differences are less consistent for the two consonants. However, speaker dependent variations are found and interpreted with respect to differences in palate shape. Speakers with a flat palate shape exhibit lateral contact already during /a/- production whereas for speakers with a dome shaped palate such contact does not occur. Concerning the /a/-context we suggest that for speakers with a flat palate shape the impact between tongue and palate is less pronounced since the tongue is already in contact with the palate during the preceding vowel. A previous study of the token-to-token variability of all German vowels (Mooshammer et al. in press), including the same male speakers recorded here, provided evidence for a smaller variability of tongue positioning in general, comparing JD with CG and DF. We interpreted this result partly due to differences in palate shape, since small tongue movements have larger effects on the area function for speakers with a flat palate. Thus, speakers with a flat palate may have learnt a more precise tongue positioning. Whether this holds also true for consonant production and to what extent differences in the precision of vowel production affect consonant production needs further investigation.

Johnson et al. (1993) proposed that palatal doming has an impact on articulatory organization, in particular on tongue and jaw co-ordination. In a next step we will also observe jaw movements, since preliminary inspections showed differences in vertical jaw movements for the two groups of speakers with smaller movement amplitudes for speakers with the flat palate (JD, SF) and larger amplitudes for the speaker with a dome shaped palate (CG, DF).

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