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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. For alveolar stops versus fricatives, two different control strategies were hypothesized: a target above the contact location for alveolar stops resulting in a collision of the tongue tip at the palate as opposed to a precise positioning of the tongue at the lateral margins at the palate for alveolar fricatives. Additionally, we suspected differences between stops and fricatives 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 significant 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, results for speaker dependent mechanisms were related to the subject's 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. The focus of this paper is on the upper extent the tongue's possible movement, 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) the tongue's action at the palate is taken into account in the speech motor control process in terms of limiting the degrees of freedom for tongue movement and supporting the tongue's shaping. As far as consonant production is concerned, Stone (1991) suggested that some tongue shapes, particularly those in the production of alveolar fricatives, could not be produced by a free-standing tongue position, i.e., with the palate as a spatial reference for the tongue; Stone also suggests that the palate can be used to provide tactile feedback information in order to learn and/or control specific tongue shapes. Additional evidence for the role of the palate 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 from the first session provided evidence for 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 being monitored, and used in 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's practice, a significant improvement of acoustic and perceptual characteristics was 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 whose thickness could suddenly be increased or reduced; this technique was combined with or without auditory masking. Their findings suggest that incomplete compensatory movements are actively and immediately produced due to tactile feedback information, and that auditory feedback is used to complete precise articulatory adjustment, but with a longer time delay in comparison to tactile feedback.

The influence of the tongue's action at the palate on 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's action at 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, coronal 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 automatically blocks the tongue's movement 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. They showed that the tongue's action at the palate combined with the relative articulatory target positions of the surrounding phonemes could explain some of the direction of the anti-clockwise trajectories (so called loops) in /VkV/-sequences.

In contrast to stops, Mooshammer et al. (2003) observed that fricatives have a more precise positioning of tongue and jaw. Fricatives are also often described as being difficult to produce. 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).

Previous studies have mainly focused on tongue kinematics by means of EMMA data and have inferred the corresponding tongue palate contact patterns. We will take the advantage of simultaneous EMMA and EPG recordings. The aims of our study are twofold. First we will compare alveolar stops with fricatives, because fricatives show both 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 for stops versus fricatives. Second, the tongue's action at the anterior and lateral parts of the palate were investigated separately in order to interpret their potential influence on 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. 2004).

2. Method

Tongue tip movements and tongue-palate contact patterns from four German speakers (all colleagues from the lab), three male (CG, DF, JD) and one female (SF, the first author of this paper), 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. The sampling frequencies were 16 kHz for the acoustic data, 100 Hz for EPG and 200 Hz for EMMA data respectively. The speech material consisted of the nonsense words ge/C1VC2/e and ge/C1VC2/, where C was always either /t/ or /z/. The phonologically voiced /z/ has been used instead of /s/ since it coincides most frequently with a preceding tense vowel in the German inventory whereas /s/ occurs with lax vowels. The focus of this paper is on C2 of each target word, following one of the stressed vowels /ɑː/ or /uː/. Different positions of the consonant were considered: word medial C (henceforth med) in e.g., [gəˈtʰɑːtə] corresponding to orthographic 'getahte', and word final position C (henceforth fin) in e.g., [gəˈtʰɑːt], orthographically 'getaht'. All target words were embedded in the carrier phrase "Ich habe geC1VC2e nicht geC1VC2 erwähnt." (= I have geC1VC2e not geC1VC2 said, i.e. I said geC1VC2e not geC1VC2.) with pitch-accents on C1VC2 in both cases to convey contrastive sentence stress. A neutralization process of word final /z/ to the voiceless allophone takes place in German, i.e. word final /z/ was in most cases realized as [s]. As will be seen in the results section, supralaryngeal production mechanisms of word medial phonological /z/ (produced as [z]) and word final /z/ (produced as [s]) did not differ most of the time so that voicing distinction was not likely to be relevant for the interpretation of the tongue kinematics in our data. Thus, we maintained the phoneme description /z/.

Each sentence was repeated ten times in a randomized order. The tongue tip closing gesture from the stressed V to C was measured. The on- and offsets of the closing gesture were defined using a 20 per cent threshold criterion (see figure 1), i.e. closing gesture onset corresponds to the point where the tangential velocity signal of the tongue tip reached 20 per cent by traveling from the velocity minimum to the peak. Closing gesture offset corresponds to the time landmark where the velocity signal reached 80 per cent by traveling from the velocity peak to the next velocity minimum. The advantages of the 20 per cent threshold criterion are described in Kroos et al. (1997).

Insert Figure 1 around here

Starting from the landmarks defining the closing gesture, the velocity peak, the duration of the closing gesture and the movement amplitude were calculated. The latter was calculated as the integral of the tangential velocity signal from onset to offset of the closing gesture which corresponds to the area beyond the velocity signal. The measurement is generally more precise in comparison to calculations of the Euclidian distance, since it takes into account the whole curvature of the trajectory.

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. Peaks in the preceding opening gesture were taken into account in order to have some references for the magnitude of the deceleration peaks.

Two acoustic landmarks were used for analyzing the obstruents. For the stops, the closure and burst were labeled and the closure onset was marked at the offset of F2 in the preceding vowel. The acoustic boundaries for the fricatives were marked at the on- and offset of high frequency noise.

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 contacts of the closing gesture were labeled as the landmarks where the relevant contact increased after the preceding vowel. The increase of contact was most of the time rather abrupt, particularly for stops which showed nearly no contact during the end of the vowel and a sudden rise in the following pattern for closure onset. Additionally, the landmarks of maximal lateral and anterior contact during oral closure/constriction were marked. In order to get an impression of subject’s palatal shape, for each of the 62 electrodes placed in the individual artificial palates, the x, y, and z coordinates were measured using a caliper (for a detailed description of the method see Fitzpatrick and Ní Chasaide 2002).

Insert Figure 2 around here

Figure 2 exhibits the palatal shapes for all subjects based on the coordinates of the 62 electrodes. Two subjects (left column) showed coronal shapes similar to a dome and the two other subjects (right column) a rather flat palate shape in the coronal plane. The classification - flat versus dome shaped palates was based arbitrary on the individual differences in palatal height.

3. Results

3.1. Closing gesture amplitude and its duration

A number of analyses of variance were calculated using the General Linear Model in SPSS 11.5. Closing gesture amplitude, its duration and velocity peak were the dependent variables and consonant (/z/ versus /t/) was the independent variable. The data were split by vowel (/a/ versus /u/) and position in word (med versus fin). The results showed that movement amplitudes in /t/ were significantly larger (see figure 3) 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).

Insert Figure 3 around here

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 e.g. in Narayanan et al. (1995), and because the tongue tip sensor was placed within the mid-sagittal groove. Tongue grooving may also be confirmed by means of maximal anterior contact during oral closure for the stops in comparison to the contacts during oral constriction for the fricatives. Results for stop production showed generally significant more per cent of maximal anterior 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 $p < 0.05$). The smaller amount of anterior contact in /z/ should be due to the missing palatal contacts in the tongue groove.

If alveolar fricatives and stops were controlled in the same way, we would expect movement duration to be similar for both types of consonants. We would also expect larger movement amplitudes to coincide with greater velocity peaks and smaller movement amplitudes with smaller velocity peaks. Such results were generally found for the alveolars realized in /u/-context (see figure 4). However, in all speakers' production of the /a/-context, the movement amplitude and the velocity peak were larger in /t/ compared to /z/, but the closing gesture duration was 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 $p < 0.05$).

The shorter duration observed for /t/ in the /a/-context gives a quantitative information about the consequence of the differences observed in peak velocity and movement amplitude between fricatives and stops. If the movement amplitude is large enough, the tongue can move in a shorter time interval for stops as compared to fricatives. In the case of the /u/-context these differences cannot be observed since the movement amplitude was too small.

Insert Figure 4 around here

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

Two separate measurements were made in order to further assess strategies used in stop and fricative production: 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 the oral closure or constriction were analyzed.

Insert Figure 5 around here

As predicted from the hypothesis that the tongue's collision at the palate 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 was also true for /z/ (except for SF). Additionally, the relative differences between deceleration peaks in the opening and closing gestures were always greater for /t/ than /z/, e.g. for CG - the deceleration peak in the closing gesture for /t/ was 2.2 times greater than in the opening gesture whereas in /z/ it was only 1.4 times greater. Acceleration peaks did not exhibit comparable relations and varied considerably between speakers. In order to rule out a possible influence of the larger movement amplitude in /t/ on the deceleration peak (this could come due to the fact that larger amplitudes are associated with larger peak velocities, and thus, they are necessarily associated with deceleration, because deceleration is the velocity's derivative) 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 differences 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 were less consistent (med: JD, SF $p < 0.001$, DF $p < 0.01$, fin: SF $p < 0.001$, DF $p < 0.05$). These findings suggest that the tongue's movement does not stop due to an active deceleration in alveolar stop production, 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 tongue's movement is reoriented due to the collision at the palate. The reorientation of the movement depends on the angle of incidence the tongue collides at the palate. For example, if the tongue moves against the palate in an obtuse angle coming from the back it should be redirected towards the front and sliding along the palate. If the angle is around 90 degrees the tongue should have the greatest impact on the palate since the force cannot be redirected (for calculation of the angle of incidence by means of tongue kinematics in looping patterns see 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 place the articulator precisely at the target location.

Insert Figure 6 around here

Figure 6 shows that there were larger movement amplitudes during /t/ closure compared to /z/ constriction in all cases for the /u/-context (highly significant). In the /a/-context, significant differences between /t/ and /z/ occurred particularly in the word medial position (DF, JD, SF). In word final position a /t/-/z/ distinction was only found for DF. Results from subject CG showed generally the reverse pattern in /a/-context with larger amplitudes for /z/ than for /t/.

Insert Figure 7 around here

The larger movement amplitudes during oral closure for /t/ were 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 corresponded to vertical tongue movement, which explains the patterns observed for this speaker). Forward movements during /t/ closure (i.e. the tongue tip slides along the palate) were 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 that 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 to velocity peak

In a previous pilot study of one subject, we observed that the velocity peak in /t/ was well synchronized 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's action at the palate only. In order to begin to test the reliability of these preliminary findings, the temporal difference between the velocity peak and the onset of lateral contact was calculated. In the /u/-context (all speakers, all conditions) lateral contacts started already during the vowel, i.e. they preceded the velocity peak. Tongue and palate were always in contact with each other since /u/ is a high vowel. Results obtained for the /a/-context are shown in figure 8. They show considerably inter-speaker variation.

Insert Figure 8 around here

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 (/a/-context) for speakers with a dome shaped palate versus speakers with a flat palatal shape. For the latter (JD and

SF), tongue contact with the lateral margins of the palate occurred already during the preceding /a/ (between 15-30 per cent LAT) and increases during the consonant. This type of pattern did not occur in speakers with a dome shaped palate (CG and DF). Their results showed roughly a simultaneous timing of the velocity peak with the onset of lateral contacts. In contrast, for speakers with a flat palatal shape (JD and SF), the tongue is already in contact with the palate during the vowel. One consequence of this seems to be a weaker impact of the tongue at the palate during stop production, as suggested by comparing the magnitude of the deceleration peaks during /t/ for the two groups of speaker. Those with a flat palate had lower deceleration peaks, suggesting that contact with the palate caused less damping of the tongue movement than it is the case for the speakers with more dome palate shapes. In this way, the variations in the tongue palate contact patterns during the preceding vowel affected tongue kinematics in different ways. 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.

Contrary to our expectation 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, then they were often 10 ms and therefore close to the reliability range of EPG. This means that either lateral contacts always co-occured with anterior contacts in alveolar obstruent production or that differences between the onsets of such contacts were very tiny and should be investigated by means of a higher time resolution technique.

4. Discussion

We investigated tongue tip kinematics and tongue palate contact patterns by means of simultaneous EMMA and EPG recordings for four German speakers in order to compare production strategies of alveolar stops with fricatives. We assumed that the central nervous system incorporates the palate in speech motor control and that tongue palate contact patterns influence the kinematics of the tongue movement. 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 and the corresponding auditory goal. The tongue's collision at the palate guarantees an air tight seal corresponding to a silent closure phase in the acoustics. By contrast, 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 for the production of turbulent noise, the most prominent acoustic characteristic of fricatives. To do so, a more precise tongue and jaw position is required.

Results for both strategies were 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 with the palate (in agreement with Hoole 1996 and Fuchs et al. 2001). Additionally, the movement amplitude and the velocity peak of the closing gesture were larger in /t/ whereas the duration of the closing gesture was significantly shorter, at least in the /a/-context. Movement amplitudes for /z/ were smaller, slower, and were produced with a longer duration. There was a significantly greater percentage of maximal anterior contact during closure or constriction 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 contact whereas fine positioning can potentially produce either 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 the /u/-context and confirms earlier work from Brunner et al. (2004). In /z/ production, less movement was produced during oral constriction, probably because of the more precise tongue positioning that is required in fricatives than in stops. We suppose that the different control strategies are used in order to create the appropriate auditory goals, i.e. a silent closure interval for stops and turbulent noise for fricatives.

Concerning the role of lateral tongue palate contacts, differences were less consistent for the two consonants. However, speaker dependent variations were 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 did not occur. As far as the /a/-context is concerned, we suggest that for speakers with a flat palate shape the impact between tongue and palate was less pronounced since the tongue was 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. 2004), 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 also holds true for consonant production and the extent to which differences in the precision of vowel production affect consonant production need further investigation.

Johnson et al. (1993) proposed that palatal doming affects articulatory organization, in particular tongue and jaw co-ordination. In a subsequent investigation, 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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List of figures

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/s^2 with acceleration (acc) and deceleration peaks (dec)

Figure 2: Coronal shapes of the artificial palates (anterior to posterior view for four speakers), positions of the 62 electrodes are marked by the open circles, lines connect open circles in the relevant row and column, x-axis (mm): left-right axis, y-axis (mm): palatal height

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

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

Figure 5: Bar plots showing means of acceleration (acc) and deceleration peaks (dec) in cm/s^2 with +/- 1 std. error, averaged over vowel context and word position; 1st row = /t/, 2nd row = /z/, CG, DF, JD, SF from left to right, clg = closing gesture, opg = opening gesture, gray bars = acceleration peak, black bars = deceleration peak

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 7: Bar plots showing means of the difference in horizontal tongue tip position from closure/constriction onset to closure/constriction offset in cm with +/- 1 std. error; positive

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

Figure 8: Bar plots with means of the difference between the time points of the velocity peak and the 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

Figure 1

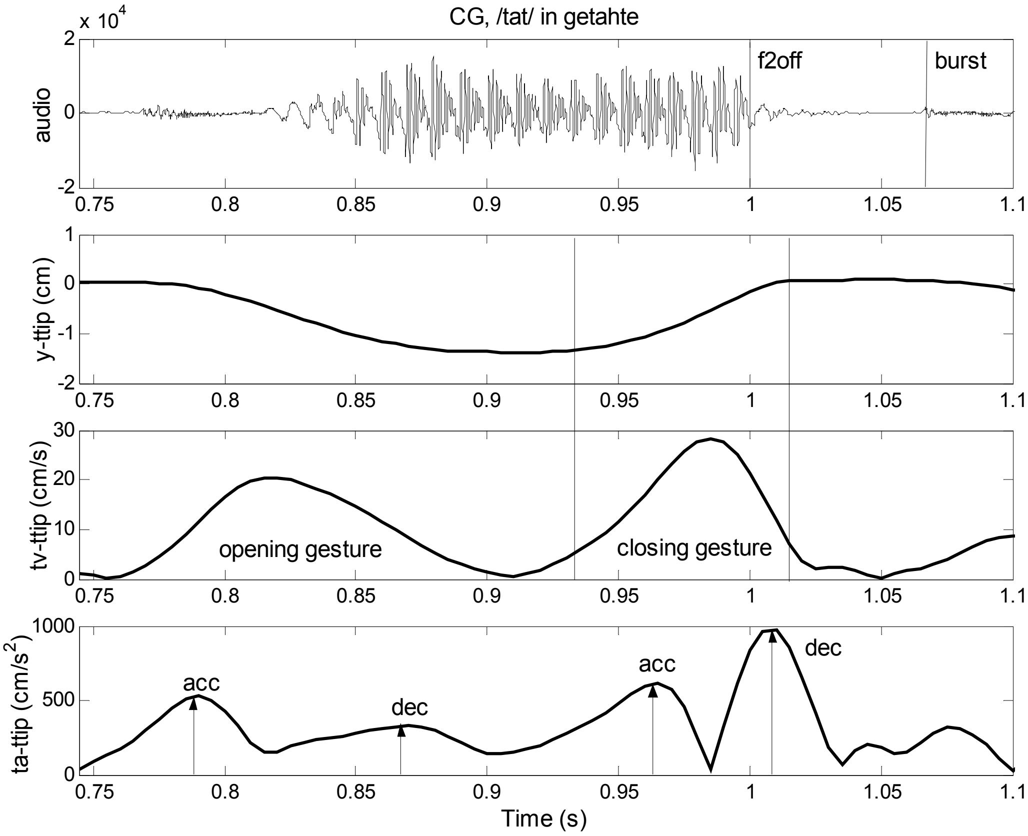

CG, /tat/ in getahte
x 10^4
audio
f2off
burst
2
0
-2
y-ttip (cm)
1
0
-1
-2
tv-ttip (cm/s)
30
20
10
0
opening gesture
closing gesture
ta-ttip (cm/s^2)
1000
500
0
acc
dec
acc
dec
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
Time (s)

Figure 2

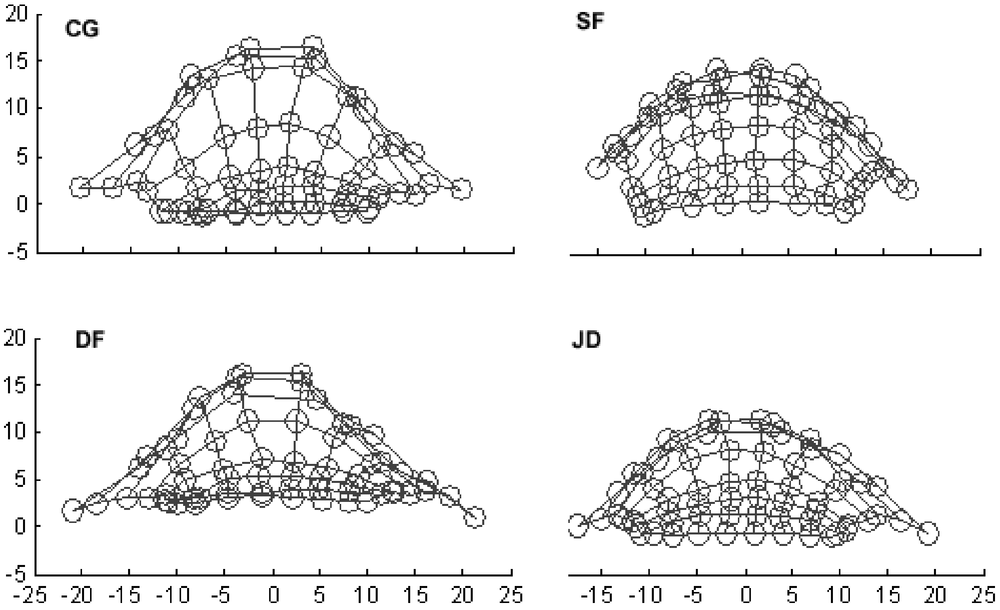


Figure 3

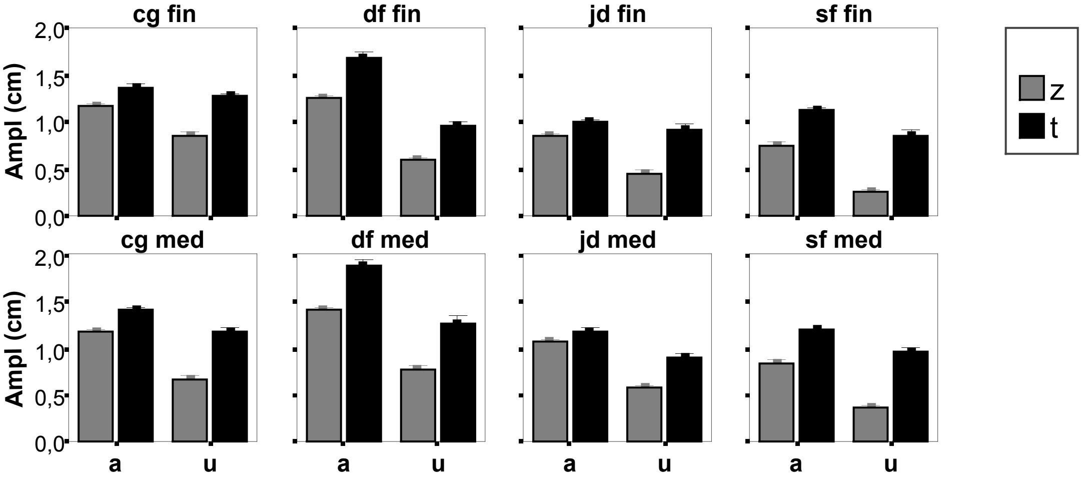

cg fin
df fin
jd fin
sf fin
cg med
df med
jd med
sf med
Ampl (cm)
2,0
1,5
1,0
0,5
0,0
a
u
z
t

Figure 4

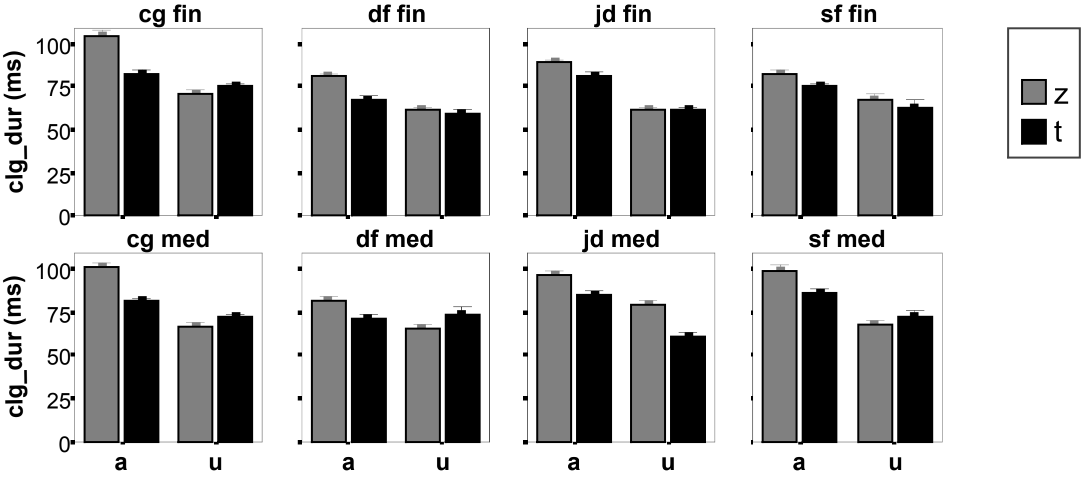

cg fin
df fin
jd fin
sf fin
cg med
df med
jd med
sf med
clg_dur (ms)
100
75
50
25
0
a
u
z
t

Figure 5

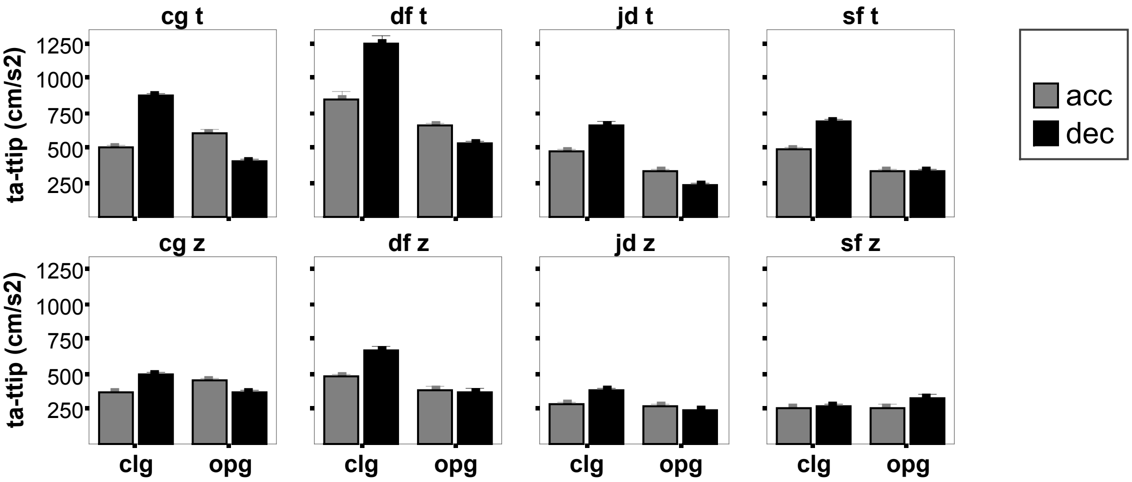

cg t
df t
jd t
sf t
cg z
df z
jd z
sf z
ta-ttip (cm/s2)
1250
1000
750
500
250
clg
opg
acc
dec

Figure 6

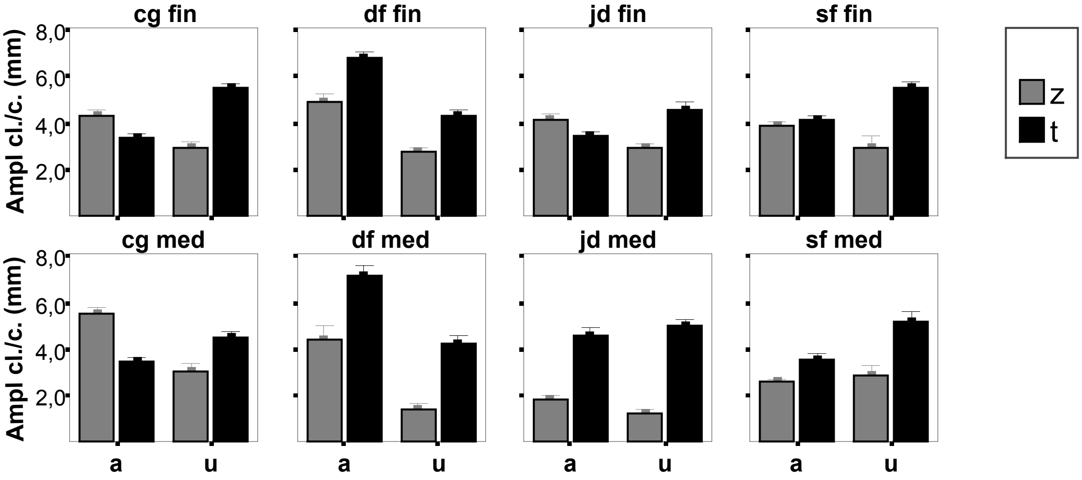

cg fin
df fin
jd fin
sf fin
cg med
df med
jd med
sf med
Ampl cl./c. (mm)
8,0
6,0
4,0
2,0
a
u
z
t

Figure 7

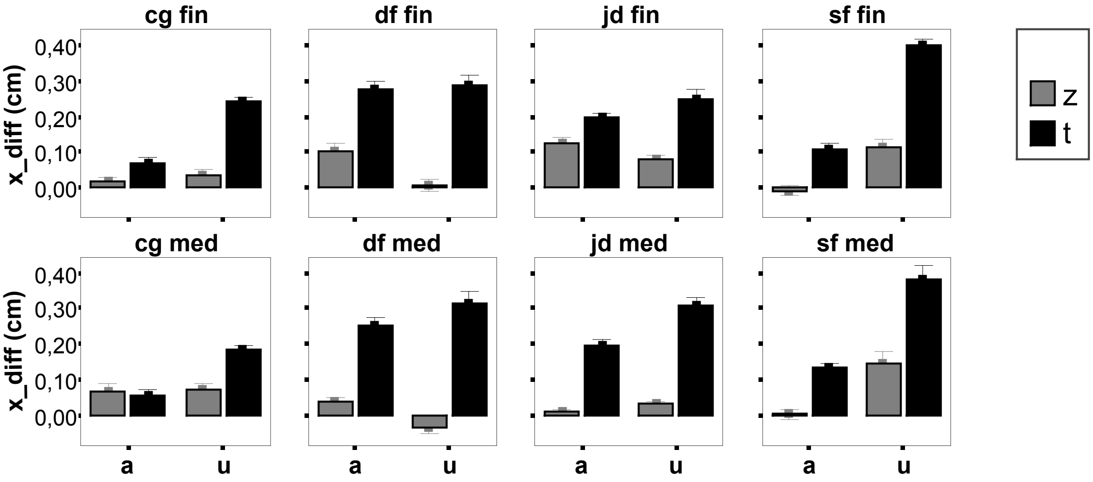
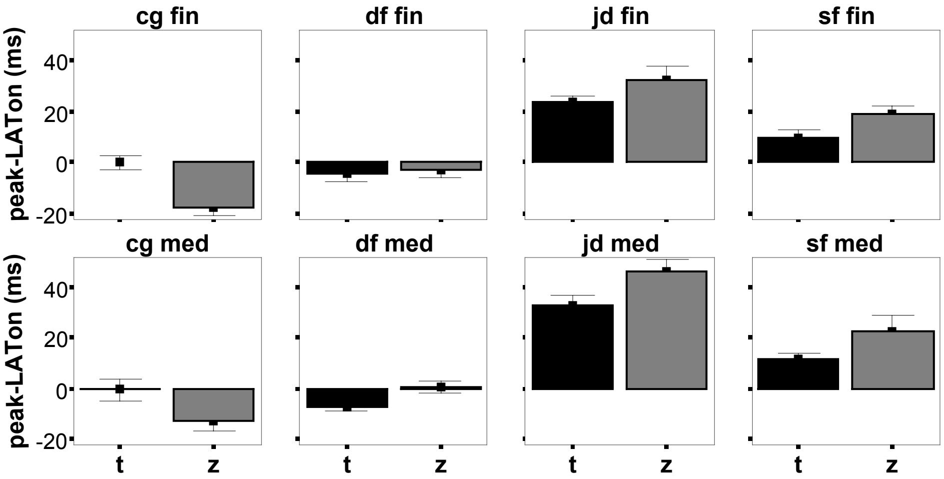

cg fin
df fin
jd fin
sf fin
cg med
df med
jd med
sf med
x_diff (cm)
0,40
0,30
0,20
0,10
0,00
a
u
z
t

Figure 8


cg fin
df fin
jd fin
sf fin
cg med
df med
jd med
sf med
peak-LATon (ms)
40
20
0
-20
t
z