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Supralaryngeal control in Korean velar stops

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Abstract

The aim of this study was to investigate the supralaryngeal control of the production of the Korean three-way contrast in velar stops. First, an EMA-experiment with three Korean speakers was carried out, and the kinematic properties of the tongue back were analyzed (length of the deceleration phase of the movement, peak velocity, peak acceleration, amplitude and duration of the looping movement during consonantal closure, and angle of incidence between tongue and palate at contact onset). To understand the potential motor control mechanisms underlying the production of the three-way contrast, the target hypothesis which suggests that articulator movements in stops are directed towards a target at or beyond the palate, was evaluated by comparing its predictions with our experimental findings. Evidence was found in support of this hypothesis. Hence, the hypothesis was further explored in a modeling study. The results suggest that variability in the articulatory parameters can be explained by a single control parameter, namely the target position of the tongue. In a third step the Korean velar stops were simulated by varying the target position. The results show that the main trends of the simulated consonants are in good agreement with the experimental findings.

Key words: motor control, Korean velar stops, loops, electromagnetic articulography, speech production modeling, articulatory target, virtual target

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1 Introduction

Looking at the languages of the world, most languages with more than one velar stop exhibit a two-way contrast, which is mainly based on a laryngeal mechanism, either voicing or aspiration (Maddieson (1984)). However, a few languages, such as Korean, exhibit a three-way contrast. From a motor control perspective the rarity of these languages could be explained by the great accuracy in laryngeal control required for a three-way contrast to be maintained. The fact that these languages have been able to maintain this contrast throughout their diachronic evolution suggests that their native speakers were able to develop robust motor control strategies that ensure the production of a three-way contrast in all phonetic contexts and under all speaking conditions. Speakers of these languages can be assumed to have elaborated supralaryngeal control strategies that are concomitant with the laryngeal control strategy.

One such control strategy could be *target control*, a strategy that requires speakers to use just one control parameter, in this case a certain target position of the tongue during the production of the consonant. According to this control model speakers would plan to move the tongue to this target position without specifying any other kinematic properties, such as velocity or movement duration. The aim of the present study was to test this control model using articulatory data of tongue movements. Therefore, an experimental study of the supralaryngeal correlates of the three-way contrast in velar stops in Korean was carried out. Three native speakers of Korean were recorded by means of 2D electromagnetic articulography when pronouncing V1CV2 sequences, where C is one of the three velar stops. Kinematic characteristics of the articulatory movements of the tongue dorsum such as movement amplitude, velocity and acceleration were analyzed and compared to the predictions of the target control model.

Since the experimental data were found to be largely in agreement with target control, the target hypothesis was quantitatively tested with the help of the speech production model GEPPETO (Perrier & Ma (2008)). This model comprises a biomechanical model of the tongue and a motor control model based on a target-to-target movement control hypothesis. Simulations generated with the model were analyzed with the same approach as the experimental data, and the experimental and modeling results were compared to each other.

1.1 The three-way contrast in Korean velar stops

One of the Korean velar stops is unaspirated and, although underlyingly voiceless, is voiced intervocalically (Jun (1993)). Korean also has an aspirated stop and an unaspirated voiceless *tense* stop, /k'/. Previous studies use a number of different labels and symbols for these sounds. In the current study the labels *lax*, *aspirated* and *tense* and the symbols /k/, /kh/ and /k'/ are used.

The three Korean velar stops differ both laryngeally and supralaryngeally. Laryngeally the stops differ in VOT, voicing during closure and the degree of glottal closure. VOT is the acoustic measure that has most consistently demonstrated differences among the Korean stops. In initial and medial position the tense stop /k'/ has the shortest VOT, the VOT of the lax stop /k/ is a little longer, and the aspirated stop /kh/ has the longest VOT (Lisker & Abramson (1964), Han & Weitzman (1970), Kagaya (1971), Abramson & Lisker (1972), Shimizu (1996), Silva (1992), Hardcastle (1973), Cho et al. (2002)). However, a number of authors have found that even if there is a difference in the mean values, there are overlaps between variation ranges, so that categories are not always distinct (Kim (1965), Han & Weitzman (1970)). Voicing during closure is characteristic for medial /k/ only (Cho & Keating (2001)). Observation of laryngeal activity has shown that during the tense stop the glottis is closed, during the aspirated stop it is wide open, and during the lax stop it is slightly open (Kim (1967), Kim (1970), Kagaya (1974), Sawashima & Park (1979), Hirose et al. (1974)).

The supralaryngeal differences in the Korean stops have often been subsumed under the term "tenseness" of the articulation (e.g. Kim (1965)). Tenseness has been measured in a number of ways. For the alveolar stops (which also exhibit a three-way contrast in Korean), one such measure is the amount of palatal contact: palatographic investigations have shown that there is less palatal contact in the lax stop as compared to the aspirated and the tense stops (Kim (1965), Cho & Keating (2001)). For velar stops the higher tenseness of /k'/ has been measured as higher burst energy, higher intra-oral air pressure and less airflow after release (Kim (1965)). A further nonlaryngeal mechanism differentiating the stops is closure duration. The tense stop has an extremely long closure. The lax stop has the shortest closure (Silva (1992) and Cho & Keating (2001) for initial and medial stops).

Kim et al. (2005) carried out a stroboscopic-cine MRI study of Korean alveolar stops and affricates and suggest that there are two independent control mechanisms in those sounds, a laryngeal one and a supralaryngeal one, which are temporally coordinated in order to produce a three-way contrast. Their results show that laryngeally the aspirated stop differs from the two others due to wide glottal opening during closure. Supralaryngeally, the lax stop forms an apical closure with a relatively low tongue body whereas the two other stops rather have an apico-laminal closure with a higher tongue body. The larynx has a higher position in the tense and aspirated stop than the lax stop. Kim et al. (2010) carried out a similar study on bilabial, alveolar and velar stops. The earlier finding that there is more glottal opening in the tense stop was confirmed for the other places of articulation. Also, a higher larynx was found for all tense and aspirated stops as compared to the respective lax stops. A higher tongue position was found for the tense and aspirated velar and alveolar stops but not for the bilabial ones, suggesting that, contrary to the tongue pull theory, the observed differences in tongue position are controlled independently from the larynx position.

1.2 Target control

The target control hypothesis supposes that the central nervous system generates movement by specifying changes in the posture of the motor system (Feldman (1966), Bizzi (1980), Feldman (1986), Bizzi et al. (1992)). This hypothesis has been shown to be in agreement with measurements of kinematic data of arm movements under normal (Shadmehr et al. (1993), Flanagan et al. (1993)) and perturbed conditions (Gribble & Ostry (2000)) as well as for eye (Levin & Feldman (1995)), jaw (Laboissière et al. (1996)) and tongue movements (Perrier et al. (2003)). According to this hypothesis, movement is generated to carry the motor system from an initial to an intended final posture.

A number of researchers have used target-based models to study speech production. In this framework the discrete phonemic input of speech production is transformed into a discrete sequence of intended postures, which can in turn generate continuous articulatory movements and, as a result, acoustic signals (see among others MacNeilage (1970), Saltzman (1986), Kelso et al. (1986), Perrier et al. (1996)).

In some of these studies stops are assumed to have what is called a *virtual target* either beyond the palate (for the tongue in lingual stops) or within the upper lip (for the lower lip in bilabial stops). This means that the muscle activation levels are changed towards a state associated with a position beyond the palate or within the upper lip. While moving towards this configuration, however, the moving articulator is stopped at the contact location and the target is not reached. The virtual target was first proposed by Löfqvist & Gracco (1997) for labial stops based on the observation that (1) just before the onset of the consonantal closure the lips are moving at high velocity and (2) during the consonantal closure, the lower lip continues to move, pushing against the upper lip, which results in tissue compression of both lips. These findings are consistent with the hypothesis that the lower (or the upper) lip moves towards a target that is located above (or below) the actual position of the upper (or the lower) lip and that contact happens on the way towards these targets, which in the end will not be reached (hence the term *virtual target*). Based on this interpretation of their experimental data, Löfqvist &

Gracco suggest that speakers control the production of the airtight seal necessary for the generation of the consonantal burst by planning a negative lip aperture. This would be a robust strategy to achieve this objective regardless of any contextual variability in the articulatory positions. Löfqvist (2000) adds that the virtual target strategy would also enable the control of closure duration. Different closure durations would then be a byproduct of different target positions. A longer stop would be produced with a higher target of the lower lip.

The virtual target hypothesis has since been adopted by a number of authors. Studying German lingual stops Fuchs et al. (2001) found higher deceleration peaks and more linguo-palatal contact in voiceless alveolar stops than in voiced ones. More contact can mean that there is more tissue compression of the tongue. For movements of equal amplitude, this and the observed deceleration at closure onset are consistent with a higher target beyond the palate.

Löfqvist & Gracco (2002) further investigated lingual stops with the hypothesis of a virtual target beyond the contact location. They state that high movement velocities at the onset of the oral closure are compatible with the notion of a virtual target for the tongue. A movement that is planned to reach the actual tongue position at closure onset would have a low velocity before the contact happens. In their study VCV sequences with V=/a, i, u/ and C=/t, d, k/ and /g/ were recorded via electromagnetic articulography. The results show that the tongue is moving at high velocity at closure onset. In the context of a target-based model, this suggests that the movement is planned to go further beyond the palate.

Perkell et al. (2002) investigated tongue release and closing gestures in V1CV2 sequences. The authors found that, while the beginning of the closing gesture in C was normally identical with the end of the preceding opening gesture in V1, the beginning of the opening gesture in V2 was often preceded by an ”intermovement interval”(p.1631), separating it from the end of the preceding closing gesture. Perkell et al. state that ”the actual beginning of the opening movement occurs during the closure and is obscured by it” (p. 1639) and they suggest that this is consistent with Löfqvist and Gracco's view that the consonantal target is virtual. From this perspective, the ”intermovement interval” would correspond to the virtual part of the movement towards and from the virtual target.

Mooshammer et al. (2006) compared the closing gestures of the jaw and tongue and found that the offset of the closing gesture for the jaw is later than the offset of the closing gesture for the tongue relative to the acoustically measured end of the consonant. Among a variety of possible explanations the authors consider that of a virtual consonantal target of the tongue located beyond the palate which cannot be reached. The jaw continues the movement towards the target whereas the tongue cannot continue the movement since the target beyond the palate is virtual.

The target of a stop can vary horizontally and vertically. The horizontal position is likely to be influenced by the surrounding vowels, which is consistent with the observation that velar stops are produced at a more anterior position if they are surrounded by front vowels and at a more posterior one if they are in a back vowel environment (e.g. Alfonso & Baer (1982), Parush et al. (1983), Geng et al. (2003)). The vertical position can vary with manner of articulation. For fully voiced stops in intervocalic position for example, often no burst can be measured. The absence of a burst can be explained by the absence of complete vocal tract closure, which in turn could be evidence for the fact that the target position is lower than for other stops with a burst.

The virtual target theory assumes that there is a constant peak velocity / distance relationship for different stops. This assumption is based on the finding that velocity and distance are correlated (Ostry & Munhall (1985), Keller & Ostry (1983)). The virtual target theory also assumes that the velocity profiles of planned movements from one virtual target to the next are symmetrical. This assumption is based on the fact that speech movements have to be planned all at once and cannot be corrected after movement onset. The reason for this is that these movements are so short that online cortical feedback cannot be used to carry out corrections of the movement after movement onset, and only corrections (or external perturbations, e.g. linguo-palatal contact) would lead to unsymmetrical velocity profiles.

Taking into consideration what has been found so far for Korean velar stops, one can assume that the tense stop should have the highest target since it has the longest closure duration; the lax stop should have a target at or even just below the palate since its closure is very short and sometimes there is only an approximation of tongue and palate. The aspirated stop should have a target somewhere in between. This is because the planned movement to a higher target should take longer than the planned movement to a lower target. Even if the target cannot be reached (because it is virtual), the muscle commands which should have led the articulator to the target stay active during the rest of the planned movement towards the virtual target. In reality this results in a longer closure. In front vowel contexts, all the stops should have a more fronted target whereas in back vowel contexts they should all have a more retracted target.

A number of kinematic properties of articulatory movements are likely to be affected by the target position: the length of the deceleration phase, peak velocity and acceleration, the movement during closure, closure duration, and the angle of incidence of the tongue at the palate.

Deceleration phase. If a movement directed towards a target is not perturbed by any external influences its velocity profile is essentially bell-shaped (cf. Ostry & Munhall (1985)): in the first half of the movement the velocity increases (acceleration phase) and in the second half it decreases (deceleration phase) to reach the intended target with zero velocity. An idealized representation of such a bell-shaped velocity profile is given in figure 1 (bold solid curve in the upper subplot).

INSERT FIGURE 1 ABOUT HERE

If the movement is planned towards a point located above the palate, the tongue will be stopped at the palate (see dotted and dash-dotted lines in figure 1). If the collision occurs during the deceleration phase of the virtual movement, the deceleration phase of the actual movement will be shortened as compared to the virtual one (figure 1, dotted curve). If the impact occurs around the velocity peak of the virtual movement (dash-dotted line), the actual velocity at collision will be equal to the peak velocity of the virtual movement and the movement will be stopped very shortly after the velocity peak. In this case the deceleration phase is shortened while the acceleration phase is unchanged (the profile becomes slanted to the right). Thus, if a movement is stopped due to an impact with the palate, one usually observes an increase in the relative timing of the velocity peak due to a reduction in the deceleration phase.

If one assumes different targets for different stops, one can therefore expect differences in the lengths of the deceleration phases for different stops since for virtual targets the bell-shaped profiles are cut off at some point.

Velocity and acceleration peaks. Assuming a higher target for the tense stop than for the lax one and the same vocalic starting position, the maximal velocity and acceleration of the tongue should be higher for the tense stop than for the lax stop since the planned movement is larger for the tense stop and the tongue will therefore develop higher velocities (see e.g. Ostry & Munhall (1985), Keller & Ostry (1983) for the relationship between velocity and distance).

Looping patterns. Further expectations are related to a phenomenon called the looping pattern. Previous investigations have shown that in velar stops (and to a lesser extent in other stops as well) the tongue does not stay at the same place during closure, but moves forwards or sometimes backwards. From a target control perspective this movement can be seen as a continuation of the movement towards a virtual target after the tongue has been redirected at the palate. Perrier et al. (2003) show in a modeling study that the horizontal position of the target influences the direction of the movement during closure. Mooshammer et al. (1995) found that the loops are greater for voiceless than for voiced stops. This could be due to a higher target for voiceless stops resulting in a larger redirected movement of the tongue. For Korean stops the loop should therefore be greatest for the tense stop (with the highest target), smaller for the aspirated stop (with a lower but still virtual target) and smallest for the lax stop (with a target at the palate).

Closure duration. Closure duration could be a further correlate of the target location: if the target is higher above the palate, the redirected movement towards it should take longer so that the closure duration becomes longer. However, it is equally possible that differences in closure duration are the result of a time control strategy which is independent of target control. Thus, if differences in closure duration correlate with differences in loop size one can assume that the two are the result of the same mechanism, namely the height of the target. From this perspective closure duration should be longer for stops with a higher target than for stops with a lower target.

Angle of incidence. The angle of incidence is the angle at which the tongue hits the palate. Figure 2 shows two examples. In the left panel one can see a case with a large angle of incidence. The palate is schematized as a thick black horizontal line. Front is left. The tongue comes from the vocalic target (small circle in the lower right) and moves towards the consonantal target beyond the palate (small circle in the upper left). When the tongue hits the palate the angle of incidence is large. In the right panel one can see an example of a small angle of incidence. The tongue moves towards a retracted consonantal target. When it hits the palate the angle of incidence is small. Thus, according to the target theory the angle of incidence should be seen as an indicator of the horizontal target position relative to the vowel target. If the angle is large (i.e. the tongue moves towards a more anterior position), the target is fronted. If the angle is smaller (the tongue moves towards a more retracted position), the target is retracted.

INSERT FIGURE 2 ABOUT HERE

From a motor control perspective, it is useful to know whether the movement along the palate belongs to the movement up to the palate (i.e. both movements are controlled together) or whether they are two independently controlled movements. Target control would assume that the movement along the palate is part of the movement up to the palate. The angle of incidence could help distinguish between two separately controlled movements (one up to the palate and another one along the palate) and a single movement which is redirected at the palate. In the first case there should be no correlation between the angle and the amplitude of the looping movement since the tongue movement stops at the palate and a new movement with entirely different characteristics starts. In the second case there should be a correlation between the angle and the looping movement. This is because the redirected movement is dependent on the degree of damping carried out at the palate. If the angle is great, the movement is not damped very much. If the angle is small, the damping is considerable and the movement amplitude should be decreased.

In summary, the following expectations are set up for target control: from what has been stated in the literature one can assume that the lax stop /k/ should have a target at the palate, the aspirated stop /kh/ one slightly above the palate and the tense stop /k'/ one high above the palate. As a consequence of this one can expect that:

- the velocity profile should differ for different stops. For targets above the palate it should be skewed to the right. Thus, the deceleration phase should be shorter for higher targets than for lower targets;
- assuming quasi-constant movement duration, the peak velocity and acceleration should be higher for targets which are higher above the palate;
- the closure duration should be longer for higher targets;
- the loops should be greater for higher targets;
- there should be a correlation between angle size and loop size.

The aim of this study was to test these hypotheses for the three Korean velar stops. The possible correlates mentioned above were first measured on experimental data. Since the experimental results were largely in agreement with the target approach we decided to further test the plausibility of our approach with a target-based speech production model. In a first series of simulations with this model the influence of the target position on a number of possible supralaryngeal correlates of the three-way contrast was evaluated and compared with the results of the experimental data. In a second series of simulations we tried to reproduce the measured articulatory patterns of the three Korean velar stops with the model by manipulating the target position.

2 Experimental study

2.1 Methods: EMA-experiment

Three Korean speakers, two females and one male, were recorded via electromagnetic articulography (Carstens AG100).[1] Three sensors were attached midsagittally to the tongue. The most anterior sensor was located at about 1 cm from the tongue tip, and the most posterior one at the tongue back, about 5 cm from the tongue tip sensor. The tongue dorsum sensor was placed in between the two so that the sensors were evenly spaced on the tongue. For the purposes of the present study only the data of the tongue back sensor have been analyzed because this part of the tongue is most representative for the production of velar stops. Two sensors, which were attached to the upper incisors and the bridge of the nose, served as references. The sampling rate was 500 Hz. Preprocessing included 20 Hz lowpass filtering, correction for head movement, translation and rotation of the articulatory data to the occlusal plane coordinates, and calculation of velocities and accelerations. The stimuli were Korean words with VCV sequences where V1=/a/, C=/k, kh, k'/ and V2=/a, i, u/. Table 1 lists the words. Each word was repeated 10 times in sequence.

INSERT TABLE 1 AROUND HERE

A number of acoustic landmarks were labeled on the acoustic signal: onset and offset of the vowels (onset and offset of F2), voice offset (the point where periodicity in the oscillogram stopped), and the release burst of the consonant.

A number of articulatory landmarks were labeled on the articulatory signal: the vocalic target positions of V1 and V2 (minima in the vertical movement), the turning points (beginning and end of the looping movement along the palate during the consonantal closure), and the velocity and acceleration peaks during the movement up to the palate. The articulatory landmarks are illustrated in figures 3 and 4. Figure 3 shows kinematic parameters over time. Figure 4 shows xy-plots of /k', kh/ and /k/ in the /a/-context.

The points called turning point 1 and turning point 2 in figure 4 mark the beginning and end of the looping movement of the tongue along the palate. They were labeled on these xy-plots as the points with the highest curvature. The first turning point is the point where the tongue starts moving forwards (or sometimes backwards, especially if V2=/u/). The second turning point is the point where the tongue changes direction and moves downwards towards

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[1] The data were originally recorded for another project by Hyeon-Zoo Kim and Pascal Perrier at the GIPSA-lab in Grenoble in 2001.

the second vowel. In some productions of /k/ there was no complete closure and the curvature remained fairly constant over a certain time interval. In these cases, turning point 1 was taken as the mid-point of this time interval with constant curvature, while turning point 2 was defined as the highest point on the trajectory. Turning point 1 and turning point 2 are usually close to the acoustically measureable closure onset and offset. However, they are not always identical with them. Whereas they are identical in figure 4a, in figure 4b closure onset is somewhat later than turning point 1 amd closure offset is somewhat earlier than turning point 2. The reason for not taking the acoustically measureable closure onset and offset was that the turning points were used to measure the size of the loop which is better characterized by those points than by the acoustic closure onset and offset.

INSERT FIGURE 3 ABOUT HERE

INSERT FIGURE 4 ABOUT HERE

As a next step the possible correlates of the target position listed in section 1.3 were calculated.

Deceleration phase. The deceleration phase was measured as the duration between the velocity peak during the closing movement and the acoustically measured closure onset (offset of F2 of V1).

Peak velocity. Peak velocity was calculated as the maximal tangential velocity during the movement from V1 to turning point 1.

Peak acceleration. Peak acceleration was measured as the maximal tangential acceleration between V1 and the velocity peak.

Size of the loop. The size of the loop was measured as the movement amplitude (distance traveled by the tongue back sensor) during the sliding movement from turning point 1 to turning point 2.

Closure duration. Closure duration was measured as the duration of the looping movement from turning point 1 to turning point 2 and is the temporal equivalent of the loop size.

Angle of incidence. The angle of incidence of the tongue at the palate was calculated between three points on the trajectory: velocity peak, turning point 1 and turning point 2 (cf. figure 4a). If the tongue comes from a V1-target posterior to turning point 1, i.e. the tongue moves in an upward and forward direction, the angle will be greater than 90 degrees. If, on the other hand, the tongue comes from a position anterior to turning point 1, the angle will be less than 90 degrees. For backward loops the angle is greater than 90 degrees if the tongue comes from a position anterior to turning point 1 and less than

90 degrees if it comes from a position posterior to turning point 1. In order to differentiate between forward and backward loops the angles of backward loops are given with a negative sign.

Statistics. All statistical analyses were carried out in the script language R. Table 2 gives a list of all analyses. All variance analyses were first calculated with *speaker*, *context* and *consonant* as factors. If a significant effect of *speaker* and *context* was found, data were split by speaker and context and the analysis was repeated (i.e. separate ANOVAs or ANCOVAs were calculated for each speaker and context). Tukey post-hoc tests were calculated for the differences in peak acceleration, size of the loop, closure duration and angle of incidence for different consonants and possibly different contexts. In order to assess the relation between angle and size of the loop Pearson correlations were calculated.

Since velocity and movement amplitude are correlated, ANCOVAs (rather than ANOVAs) were calculated for the variables *deceleration phase* and *peak velocity* (factor: *consonant*, covariate: *movement amplitude* from V1 to turning point 1).

INSERT TABLE 2 ABOUT HERE

2.2 Results of measurements on experimental data

2.2.1 Velocity and acceleration during the closing and looping movements

INSERT FIGURE 5 ABOUT HERE

INSERT FIGURE 6 ABOUT HERE

Figures 5 to 7 show kinematic data for the three stops in the /a/-context for each subject. The upper plots present means and standard deviations of the tangential velocity computed for the temporally normalized repetitions of each sequence. The lower plots show the first derivative of the mean tangential velocity. The data in the left panels show velocity and acceleration during the closing movement (from the velocity peak up to turning point 1). The right panels show these variables for the looping movement (from turning point 1 to closure offset). Each color or line style corresponds to one of the three stops (/k'/: grey, /k/: thin black, /kh/: thick black).

Looking at the upper left panel for speakers HS (figure 5) and SH (figure 6) one can see that in /k/ (thin line) the velocity has a slightly steeper downward slope than in the other stops. This observation is consistent with the hypothesis that during the production of /k/ the movement is planned to end at the palate, so that the the velocity profile is nearly bell-shaped, while during the other stops the movement is planned to continue beyond the palate, so that the velocity profile is cut off. Looking at the figures on the right one can see that after turning point 1 the acceleration is below 0 for all stops, corresponding to a deceleration. This deceleration is much stronger for /k'/ and /kh/ than for /k/. Again this is consistent with the assumption that the movement reaches its planned end in /k/ while in /kh/ and /k'/ it is stopped by the palate so that much of the deceleration occurs after closure onset. For speaker HZ (figure 7) the steeper fall of the velocity during the closing movement was not observed. The lower deceleration in /kh/ and /k'/, however, was found for this speaker as well.

INSERT FIGURE 7 ABOUT HERE

What else one could expect in these data is that absolute values of velocity and acceleration of /akha/ would be in between the ones for /aka/ and /ak'a/. This was not observed. Rather, the trajectory for /akha/ is usually higher than the ones for the other two sequences. The reason for that was that there were differences in position of V1. In /ak'a/ this vowel was somewhat higher leading to a shorter distance to the palate and consequently to a smaller movement amplitude and, since velocity and acceleration are dependent on the movement amplitude, to lower velocities and accelerations.

2.2.2 Deceleration phase

Table 3 shows the results of an ANCOVA calculated for the influence of *consonant* on the length of the deceleration phase with *movement amplitude* as covariate. The normalized means in columns 3 to 5 show that in most cases the deceleration phase is shorter for /k'/ than for the other stops. The deceleration phase of /kh/ is usually shorter than that of /k/.

INSERT TABLE 3 ABOUT HERE

The final two columns in the table give F and p values for the factor *consonant* and the covariate *movement amplitude*. One can see that the influence of the factor is significant in all cases. The influence of the covariate does not reach significance. This result is broadly consistent with the target hypothesis according to which the movement is planned to go to a point higher above the palate for /k'/ than for /kh/ and /k/.

2.2.3 Peak velocity

Table 4 gives the results of an ANCOVA calculated with *consonant* as factor, *peak velocity* as dependent variable and *movement amplitude* of the closing movement as covariate. Looking at the mean values (columns 3 to 5) there is a slight tendency for /k<kh<k'/. The influence of *consonant* on *peak velocity* is significant in all cases. In the majority of cases /k'/ had a higher mean velocity than the other two stops, consistent with the target hypothesis. There are a few exceptions, though, for HZ in /aCi/ and SH in /aCa/, where the aspirated stop had a higher velocity than the tense stop, and for SH in /aCu/, where the lax stop had a higher peak velocity than the tense stop.

INSERT TABLE 4 ABOUT HERE

2.2.4 Peak acceleration

Figure 8a presents the results of the measurements of peak acceleration. Each subplot shows the results for one speaker and one context. Each boxplot gives the results for one consonant. In the /a/- and /i/-contexts, the tense stop has the highest acceleration, the acceleration for the aspirated stop is a little lower, and the lax stop has the lowest acceleration, consistent with the target hypothesis. This trend is not observed in /aCu/ of speakers HZ and SH, and the difference between /k/ and /kh/ is often not significant (tables .1-.3 in the appendix).

INSERT FIGURE 8 ABOUT HERE

2.2.5 Size of the loop

Figure 8b presents the results for the measurements of the size of the loop (the distance traveled from turning point 1 to turning point 2). For speaker HS no reliable conclusions can be drawn, mainly because this subject produced very small loops which are variable in direction (forwards vs. backwards). The differences in loop size for this subject (all smaller than 1 mm) are below or equal to the EMA measurement accuracy.

For speakers SH and HZ the loops are usually greatest for the tense stop, and they tend to be a little smaller for the aspirated stop and smallest for the lax stop (tables .4 and .5 in the appendix), consistent with the target hypothesis. Note, however, that for speaker HZ in the /a/-context the values for the tense stop are lower than expected.

The factor *consonant* had a significant main effect on the variable *size of the loop* (cf. tables .4 to .6 in the appendix). Tukey post-hoc tests (carried out between consonants with *size of the loop* as dependent variable) showed that the differences between two consonants are not significant in all cases. However, the vowel context has an influence on the loop size: for speakers HZ and SH the loops tend to be greater in the /i/-context than in the other contexts.

2.2.6 Closure duration

For closure duration (the time the tongue moves along the palate) the same tendency can be found as for the size of the loop (/k<kh<k'/), but the tendency is more pronounced. A statistically significant three-way contrast was found in six out of the nine pairwise comparisons. In all other cases at least the contrast between the lax and the tense stop is significant (cf. figure 8c, tables .7-.9). In contrast to the results for the size of the loop there is no obvious difference between the /i/-context and the other contexts.

2.2.7 Correlation between angle size and loop size

For speakers SH and HZ a significant positive correlation between the angle of incidence and the size of the loop was observed. For speaker HS, however, there was a nonsignificant negative correlation (figure 9, table 5). In part this could be the result of the backward loops observed for this speaker. Figure 9 shows that the angle of incidence data for speaker HS are bimodally distributed. Splitting the data into positive and negative angles (forward and backward loops) does not yield significant correlations in either subset.

INSERT FIGURE 9 ABOUT HERE

There are clear differences in angle size with respect to the vocalic context: the angle and the size of the loop are greater for /aCi/ (asterisks in figure 9) than for the other contexts. The influence of the context on the angle is significant whereas the influence of the consonant is not (tables .10-.12 in the appendix). Although for speakers HZ and SH there is a significant positive correlation if the data are pooled, there often is none if the data are split by context.

INSERT TABLE 5 ABOUT HERE

The data are therefore consistent with the initial assumption that the movement along the palate is a continuation of the movement up to the palate which is damped at the palate.

2.2.8 Conclusion

For most parameters (deceleration phase, peak velocity and acceleration, loop size and closure duration) a dependence on the consonant identity was found. The tense stop usually has a short deceleration phase; it tends to have the highest peak velocity and acceleration, the largest loop and the longest closure duration. The aspirated stop also has a rather short deceleration phase; it tends to have a lower peak velocity and acceleration than the tense stop, a lower velocity at closure onset, a smaller loop and a shorter closure duration. The lax stop usually has a rather bell-shaped velocity profile; it tends to have the lowest peak velocity and acceleration, the lowest velocity at closure onset, the shortest closure duration and the smallest loop. While the tense stop can usually be well distinguished from the other stops, the difference between the aspirated and the lax stop is less clear. The correlation between angle of incidence and loop size suggests that the looping movement is not externally controlled but is a part of the movement up to the palate. The results are clearer in the /aCa/-context than in the other contexts.[2]

The results are broadly in line with the predictions made in the framework of target theory. The three stops can be assumed to have different target locations at or beyond the palate. The higher the target the longer the closure duration, the higher the velocity and acceleration, and the greater the looping movement.

Interestingly, independently of the consonant identity, the loops and angles are greater in the /i/-context than in the other contexts. An explanation could be that the differences in horizontal target locations in different contexts lead to different Euclidean distances between contact location and consonantal target. If one compares two virtual consonantal targets, a more fronted one and a less fronted one, the Euclidean distance from the point of collision with the palate (turning point 1) to the target is greater for the more fronted target than for the more retracted target. Consequently, the movement towards the more fronted target should be longer and the movement amplitude (the size of the loop) greater.

Target control is a very efficient way to control stop production since only one control parameter is needed. The target model is compatible with well-known motor control theories such as the Equilibrium Point Hypothesis (Feldman (1986)) or the VITE model (Bullock & Grossberg (1988)), and it has also been adopted by many scientists such as Cooke (1980) and Bizzi et al. (1982). In the field of speech production it has been adopted in the task dynamics model (e.g. Saltzman & Munhall (1989)), where a movement is calculated from the difference between a *present tract variable vector* and a *target tract variable vector*. These vectors give the constriction locations and degrees for the vocal tract. Higher or lower targets beyond the palate would be related to different values of the tract variable *constriction degree*. According to the formula for the second-order mass spring model characterizing the movement of each gesture in the model, the average and peak velocity of the articulator would be higher

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[2] A more in-depth analysis showed that this could be due to prosodic differences in the utterances in the /i/- and /u/-contexts.

for a target higher above the palate (see formula A1 in Saltzman & Munhall (1989)). At the palate the articulator movement would be stopped, even if muscle forces stay active.

The results are also in agreement with τ-theory (Lee (1998), Lee et al. (1999)), a theory which has been applied intensively to the investigation of many kinds of movements such as hand-mouth movements, braking or playing the piano. This theory assumes that the most important control variable in human or animal movements is the gap to closure (τ). Applied to tongue movements in velar stops speakers would define different τ parameters for each stop with the largest τ for /k'/ and the smallest for /k/. For /k'/ and /kh/ the movement would then be planned to continue even if contact is produced.

3 Correlates of the target position: A modeling study

The observations made on experimental data are broadly consistent with the hypothesis that the supralaryngeal correlates of the three-way contrast in Korean are controlled by different target positions. In the simulation part of the study the problem was approached from the opposite perspective. Different targets were assumed for different stops and it was investigated whether the corresponding results in closure durations, loop sizes and accelerations are comparable to those measured in the experimental study.

Simulations of velar stops with different target positions were carried out and the resulting loop sizes, closure durations, accelerations and angles of incidence were measured.

Since some measured variables showed a parallel behavior (e.g. acceleration and velocity), we concentrated on four of them, namely acceleration, closure duration, loop size and angle of incidence.

3.1 Methods: Simulations

For the simulations the GEPPETO model of speech production (Payan & Perrier (1997), Perrier et al. (1998), Perrier et al. (2003), Perrier & Ma (2008)) was used. It includes a 2D biomechanical tongue model. This tongue model has been shown to generate realistic movement patterns such as complex articulatory looping trajectories (Perrier et al. (2003)) and relations between speed and trajectory curvature (Perrier & Fuchs (2008)). Since the model has been described extensively in the literature cited, the description here will be limited to force generation, tongue-palate interaction and time control.

Very basically, the model of the vocal apparatus consists of models of hard structures (palate, teeth, bones) and a soft body representing the tongue, in which seven muscles are modeled. Movements of the tongue can be simulated for selected sequences of phonemes specified by target positions. The tongue model then moves from the configuration of one phoneme to that of the next. Changes of the target position can be carried out by changing the muscle commands.

The modeling of muscle recruitment is based on the Equilibrium Point Hypothesis (Feldman (1986)). According to this hypothesis the muscles of a body at rest are in an equilibrium defined by a set of λ-commands which specify the threshold length of each muscle above which active muscle force is generated. Movement occurs when the muscles shift into the equilibrium position specified by new λ-commands. Muscle force is generated as soon as the actual length l of a muscle is longer than the corresponding threshold length.

Muscle force varies as a function of the difference between the current muscle length and the threshold length, as well as of the muscle length change rate. The movement trajectory results from the interaction between this muscle force and the biomechanical properties of the tongue soft tissues.

For a movement from one configuration to the next the λ-value is shifted linearly over the transition time. When the transition time is longer, the rates of shift are smaller. This results in less force so that for the same movement distance the velocity is lower for longer transition times than for shorter ones.

The temporal characteristics of the simulations are the result of, on the one hand, extrinsic control and, on the other hand, intrinsic factors such as the biomechanical and dynamical characteristics of the vocal apparatus. The two extrinsic control parameters are transition time and hold duration. The transition time is the time taken in order to change the motor control variables from one sound target to the next one. The transition time largely influences important kinematic characteristics of the movement, for example the peak velocity. For a movement between two constant targets the velocity is higher if the transition time is short. This may of course be different if external factors such as a collision with the palate perturb the normal course of the movement.

The second temporal parameter which can be externally controlled is hold duration. This is the time between two transition times during which the muscle commands for the sound stay constant. During this time interval, different movement patterns can be expected. If the target can be reached but has not been reached during transition time (NOT the case with a virtual target), the tongue continues to move towards the target during the hold time. If the target cannot be reached, for example because it is virtual, muscle forces stay active and the tongue continues to be attracted towards the virtual target. As long as the tongue can move towards the target, it will do so. However, when collision with the palate occurs, the movement will depend on a combination of external factors acting on the tongue, such as the location of the collision relative to the virtual target. Depending on the external circumstances the tongue might continue to move towards another direction, or it might not move, for example if it hits the palate perpendicularly.

The timing of the movement which is observed for a simulated movement is furthermore influenced by the biomechanical characteristics of the motor system. Like the human muscle system the biomechanical model we used has a certain inertia, which causes a certain delay between the onset of a muscle command and the actual movement.

The impact of the interaction between transition duration, hold time and the biomechanical characteristics of the soft tongue on the actual timing of tongue movement is complex and quite different patterns can be observed. We will describe two examples of the model's responses for a simulation vowel-stop-vowel. The lag between muscle command and the system's response is here set to 30 ms.

(1) *Transition time V-C: 50 ms, hold time: 50 ms, transition time C-V: 50 ms, with realistic target.* 30 ms after transition time onset the system starts to move. The target is reached after 80 ms. The movement towards the second vowel starts after 130 ms.

(2) *Transition time V-C: 50 ms, hold time: 50 ms, transition time C-V: 50 ms, with virtual target, with looping movement at the palate.* 30 ms after transition time onset the system starts to move. The target is not reached because it is beyond the palate. A closure is produced earlier than in example (1) before the end of the transition time. Since the muscle length is not beyond the threshold length, forces stay active throughout the rest of the transition time and the hold duration. The movement continues towards the target under the constraints imposed by palatal contact. The movement might continue until the end of the hold time. Under certain circumstances, namely when forces are acting in a way such that they permit no further movement, the movement might stop. The movement towards the second vowel starts after 130 ms.

The examples show that there is a relation between target and closure duration, but the relation is not linear. If the target is beyond the palate, contact might start before the onset of the hold time. The resulting closure duration is then longer than it would have been if the target had been at the palate.

Linguo-palatal contact is modeled according to the penalty method (Marhefka & Orin (1996)). This means that as soon as the line marking the upper tongue contour goes beyond the line marking the palate a force is generated which pushes the tongue back below the line. The force increases nonlinearly with the distance the tongue has moved beyond the line. The palate can also be removed in the model so that the tongue can reach a target that would otherwise be virtual.

Simulations of different consonantal targets. Each set of λ-commands is related to a target. By changing one of these commands the target might (but does not necessarily have to) change. For a target at or beyond the palate, manipulations of the commands for styloglossus (SG) and genioglossus posterior (GGP) lead to different targets. While more styloglossus activity moves the target to a higher and more posterior position, more activity of the genioglossus posterior moves it to a higher and more anterior position.

For the first series of simulations, different consonantal targets are simulated for the sequence /aka/, where /k/ is just any velar stop, the exact kind of which is specified by the target. Different λ-commands for SG (between 58 and 68) and GGP (between 26 and 36) for the consonant were chosen in order to get different velar stops. For the surrounding vowels GGP=63 and SG=105 were chosen. The resulting values of the three correlates of the target position, size of the loop, closure duration and peak acceleration, were measured as described in the data.

In order to assess the potential influence of linguo-palatal contact the simulations were carried out first with the palate and then without it. In the simulations without the palate the otherwise virtual consonantal target can be reached.

Simulations of different hold durations. In order to test whether target and hold duration are independently controlled, the influence of the hold duration (the time during which the motor commands for the consonant stay constant) on the loop size was investigated by carrying out simulations with hold durations from 50 to 275 ms (in steps of 25 ms).

3.2 Results: Simulations

The first four sections present the influence of the target position on the articulatory properties of the stop. They serve to shed light on the question of whether loop size, closure duration and acceleration are indeed correlates of the target position. The first subsection describes general aspects of providing local changes to the target position in the model. Then the influence of a target variation on three parameters, (1) the size of the loop, (2) the closure duration and (3) the peak acceleration, is discussed. Afterwards, the results for the investigation of hold duration are discussed.

Figure 10 shows two examples of different targets created by choosing different

λ-values for a 150 ms hold duration of the consonantal commands. The simulations were carried out without the palate. The figure shows the trajectory of a node of the tongue which is approximately at the place where a tongue back sensor would be placed in an EMA-experiment. The left subplot shows a trajectory with a high contraction level of the genioglossus posterior and consequently a low λ-value (λ=26, dotted line) and one with a low contraction level and consequently a high λ-value (λ=36, solid line). The right plot shows trajectories for the variation of the SG. For the high contraction levels the tongue moves to a higher position. This movement is greater for variation of the GGP than for variation of the SG. Additionally, the figure shows that genioglossus posterior activity moves the target to the front while higher styloglossus activity moves it backwards (right subplot). This is important for the horizontal location of the target.

INSERT FIGURE 10 ABOUT HERE

We hypothesized that the size of the loop would be influenced by the target position. Figure 11 shows that the loop becomes greater for higher contraction levels (lower λ-values) of the genioglossus posterior up to a certain level (λ GGP=37). Afterwards it stays rather constant. If the target is midsagittally below the palate (up to λ GGP=39), results for simulations with palate (circles) and without (asterisks) are of course equal. For higher targets palatal contact reduces the size of the loop. For higher contraction levels of the styloglossus the loop decreases (up to λ SG=62 with palate, λ SG=60 without), then it stays constant. As one can see from the figure, the size changes a little more for differences in GGP activity than for differences in SG activity. The results can easily be explained. Since the GGP pulls the tongue to the front, higher activity results in greater loops. The SG pulls the tongue to the back, which results in smaller loops. For both muscles, there is a saturation effect. For normal speech one can assume that the extreme values do not occur and that GGP activity therefore enlarges the loop up to a certain value, after which it no longer influences loop size. SG activity reduces the size of the loop.

INSERT FIGURE 11 ABOUT HERE

A problem when looking at the experimental data was that we could not say whether the differences in closure duration (as compared to the loop size) are due to differences in hold duration or to differences in the target position leading to differences in closure duration. In contrast to the experimental data, the model allows the investigation of the influence of a single parameter while keeping the other parameters constant. We were thus able to test the influence of different targets on closure duration while keeping hold duration constant.

Figure 12 shows the results for this relationship. For a higher target produced by more activity of either muscle (lower λ-values) closure duration increases.

There is a saturation effect for very low levels of the SG (λ between 75 and 70), where closure duration stays constant. The duration of the forward movement is in general longer if there is palatal contact than if there is not.

INSERT FIGURE 12 ABOUT HERE

If the target is higher above the palate and the planned movement amplitude is therefore larger, the tongue can develop higher velocities. Figure 13 shows that both ways of influencing the target, by shortening either the threshold length of the GGP or that of the SG, increase the peak acceleration.

INSERT FIGURE 13 ABOUT HERE

Hold time does not influence the loop size except if this time is so short that the loop cannot develop (target undershoot, figure 14). From 100 ms onwards it stays constant. The loop is marginally larger if there is no palatal contact than if there is.

INSERT FIGURE 14 ABOUT HERE

In general, the simulations without the palate led to slightly greater loops and shorter closure durations. However, the differences are always very small in comparison to the changes induced by the other factors tested.

3.3 Comparison of experimental data and simulations

In the experimental data loop size, closure duration and acceleration differed for the three stops. They tended to be highest for /k'/ and lowest for /k/. It was hypothesized that this could be due to differences in the vertical target position. In the simulations this parallel behavior of closure duration and acceleration could also be found. Acceleration and closure duration increased for higher targets. If the higher target was set up by more activation of the GGP, this also resulted in greater loops. The simulations are therefore in line with the target hypothesis. Closure duration, size of the loop and acceleration are correlates of the vertical target position.

Another pattern observed in the experimental data was that the loops are greater if V2 is /i/. An explanation for this is that there are differences in the horizontal position of the target resulting in greater Euclidean distances from closure onset to the virtual target and therefore in greater redirected movements. The Euclidean distance between closure onset and target is greater for a more fronted target, consequently the movement amplitude of the loop is greater.

In the remainder of the paper we will try to answer one remaining question: Can the target alone be held responsible for all the differences found in the data? The simulations have shown that each correlate of the target behaves in a way that is consistent with the experimental data. It is therefore more a question of the magnitude of the influences. Do differences in targets indeed lead to the observed differences in loop size and at the same time in acceleration and closure duration? In particular, it is possible that the clear results measured for closure duration are due to an independent control of hold duration.

The last step in this study is therefore a simulation of the three Korean velar stops by varying only one parameter: the target. If we succeed in producing similar patterns as were found in the experimental data, we can conclude that target control alone is sufficient to explain the supralaryngeal variability among the stops observed in the experimental data.

4 Simulations of the Korean velar stops

Building on the analyses of the control mechanisms set up so far, the Korean velar stops were simulated by varying the target position. The highest target was assumed for the tense stop. A lower target was assumed for the aspirated stop and the lowest one for the lax stop.

The vertical position of the target has been assumed to be a control mechanism for differentiating among the stops. The horizontal position has been assumed to be a control parameter related to the production of the vowel due to planned coarticulation strategies.

For the correlates of the target height we calculated mean values over all speakers in an attempt to reduce the speaker dependent influences. These means served as target values for the simulations (cf. table 6). Since a systematic difference in loop size between the /i/-context and the other contexts was found, a more fronted horizontal position of the consonantal target was chosen for those simulations where V2=/i/.

The model was originally designed for French sounds. In order to get the muscle commands for the Korean sounds we took the commands for the French /k/ and changed the values slightly until the trajectories were similar to the ones we found in the Korean data. For the vowels we took the values for French /i/, /a/ and /u/.

For V2=/i/ λ GGP=43, 40 and 36 were chosen for the different stops (instead of 44, 41 and 37 in the other contexts) and λ SG=73 was chosen instead of

72. This means that for /i/ there is more activity of the GGP and less of the SG so that the target is more fronted.

The vertical position of the target was varied by choosing different λ GGP since this muscle is strongly involved in the control of the anterior-posterior positioning of the tongue, which is in turn a major factor influencing loop size. Most activity was assumed for the tense stop, less for the aspirated stop and the least for the lax stop. The exact values as well as the resulting loop size, closure duration and acceleration can be found in table 7. Values in parentheses give the difference between simulated and experimentally measured results.

INSERT TABLE 6 ABOUT HERE

INSERT TABLE 7 ABOUT HERE

Even though the simulated values differ somewhat from the measured ones, the two sets of values are rather close, and, most importantly, show the same hierarchy: Largest loops, longest closure durations and highest peak accelerations were found for the simulations with the highest activation level (lowest λ) of the GGP. The smallest loops, shortest closure durations and lowest peak accelerations were found for the simulations with the lowest GGP activity.

By changing the target position only, similar patterns to the experimental data were found. Thus, there was no need to manipulate the hold duration. This means that only one parameter is needed in order to produce the supralaryngeal differences between the stops, but it does not mean that speakers do not control hold duration independently. Independent control is possible and under certain circumstances (e.g. perturbations) it might be necessary. Under normal conditions, however, our results suggest that it is superfluous.

As discussed in the introduction, Kim et al. (2005 and 2010) found for that speakers produced the closure of the lax stops with a lower tongue body than for the other two stops, assumingly in order to ensure a safe closure to enable pressure built-up behind the closure (Kim et al. (2010, p.104)). Following our modelling results one can suggest that this might be a result of differences in GGP and SG activity in these sounds.

5 Conclusions

The aim of the study presented here was to investigate a possible control mechanism, i.e. target control, during the production of velar stops by three Korean speakers. Korean was chosen because it has a three-way contrast in stops. Such a variety in velar stops is very rare in the languages of the world and is therefore especially challenging with regard to speech motor control. For two of the stops target control would predict movements which are planned to go beyond the palate and are interrupted by the palate. The movement along the palate is, from a target control perspective, a continuation of the closing movement.

In this study, the properties of the Korean velar stops were first investigated by means of EMA-recordings of three speakers. As predicted in the target control model, supralaryngeal differences in stop identity (deceleration phase, velocity, acceleration, loop size, closure duration) were found: The tense stop tended to have the shortest deceleration phase, the highest acceleration and velocity, the greatest loop and the longest closure. The lax stop tended to have the longest deceleration phase, the lowest velocity and acceleration, the smallest loop and the shortest closure. For the aspirated stop values in between the values of the tense and the lax stop were measured. The angle of incidence correlated with the loop size. In the /i/-context both the angle and the loop size were greater than in the other contexts, suggesting that the target is more fronted in the /i/-context than in the other contexts.

In the second part of the study some of the correlates of the target, i.e. size of the loop, closure duration and acceleration, were tested for their relation to the target with a speech production model. It turned out that size of the loop, closure duration and acceleration can be interpreted as correlates of the hypothesized vertical target position. Hold duration was found to have no influence on the size of the loop, except with very short hold durations.

In a second series of simulations we tested whether the target on its own succeeds in explaining the observed patterns. We simulated the Korean velar stops by simply changing the vertical target position for different consonants and the horizontal position for different V2s. The results are rather close to the values found in the data. Target control is a very efficient control strategy which could, in synergy with the laryngeal control, determine the three-way contrast for Korean velar stop production.

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Table 1
Stimuli.

transcription	analyzed segment	English translation
pakaci	/aka/	gourd
kak’ai	/ak’a/	near
akhasia	/akha/	acacia
sakilo	/aki/	made of chinaware
ak’ita	/ak’i/	to save money
sakhita	/akhi/	to grow
pakuni	/aku/	basket
pak’uta	/ak’u/	to change
sakhula	/akhu/	cherry flower

Table 2

Statistical analyses. Column 1: analysis, column 2: factors and possibly covariates, column 3: dependent variable, column 4: data subsets (i.e. ”speaker” means that there was a separate analysis for each speaker), column 5: table in which the results of the analysis can be found.

analysis	factor(s)/covariate(s)	dependent variable	data split by	results in table
ANCOVA	consonant/ movement amplitude	deceleration phase	speaker, context	3
ANCOVA	consonant/ movement amplitude	peak velocity	speaker, context	4
ANOVA	speaker, context, consonant	peak acceleration		.1
ANOVA	consonant	peak acceleration	speaker, context	.2 and .3
correlation	angle	size of the loop	speaker	5
ANOVA	speaker, context, consonant	size of the loop		.4
ANOVA	consonant	size of the loop	speaker, context	.5 and .6
ANOVA	speaker, context, consonant	closure duration		.7
ANOVA	consonant	closure duration	speaker, context	.8 and .9
ANOVA	speaker, context, consonant	angle of incidence		.10
ANOVA	context	angle of incidence	speaker	.11 and .12

Table 3

Results of ANCOVA with *deceleration phase* as dependent variable, *consonant* as factor and *movement amplitude* as covariate. Column 1: speaker, column 2: context, columns 3 to 5: normalized mean duration of the deceleration phase, column 6: F and p for consonant, column 7: F and p for movement amplitude.

speaker	context	/k/	/kh/	/k'/	consonant	movement amplitude
HS	/aCa/	18	10	5	F(2, 20)=28.899, p=.000	F(1, 20)=1.196, p=.287
	/aCi/	14	5	6	F(2, 25)=7.346, p=.003	F(1, 25)=0.075, p=.787
	/aCu/	16	16	6	F(2, 26)=17.955, p=.000	F(1, 26)=0.071, p=.792
HZ	/aCa/	38	24	18	F(2, 26)=10.889, p=.000	F(1, 26)=0.504, p=.484
	/aCi/	31	25	23	F(2, 26)=9.814, p=.000	F(1, 26)=2.545, p=.123
	/aCu/	27	26	21	F(2, 26)=11.107, p=.000	F(1, 26)=0.379, p=.543
SH	/aCa/	23	3	2	F(2, 26)=27.030, p=.000	F(1, 26)=0.280, p=.601
	/aCi/	17	5	9	F(2, 26)=11.900, p=.000	F(1, 26)=0.229, p=.637
	/aCu/	15	8	5	F(2, 25)=32.675, p=.000	F(1, 25)=1.009, p=.325

Table 4
Results of ANCOVA with *consonant* as factor, *peak velocity* as dependent variable and *movement amplitude of the closing movement* as covariate. Column 1: speaker, column 2: context, columns 3 to 5: mean velocity, column 6: F and p for peak velocity, column 7: F and p for movement amplitude.

speaker	context	/k/	/kh/	/k'/	peak velocity	movement amplitude
HS	/aCa/	20	18	22	F(2, 20)=12.424, p=.000	F(1, 20)=55.115, p=.000
	/aCi/	19	20	23	F(2, 25)=15.690, p=.000	F(1, 25)=2.786, p=.108
	/aCu/	18	15	19	F(2, 26)=79.565, p=.000	F(1, 26)=21.928, p=.000
HZ	/aCa/	14	17	19	F(2, 26)=58.414, p=.000	F(1, 26)=50.821, p=.000
	/aCi/	16	21	20	F(2, 26)=11.770, p=.000	F(1, 26)=7.775, p=.010
	/aCu/	17	14	18	F(2, 40)=36.037, p=.000	F(1, 40)=47.201, p=.000
SH	/aCa/	17	20	19	F(2, 26)=209.225, p=.000	F(1, 26)=38.685, p=.000
	/aCi/	20	21	24	F(2, 26)=20.597, p=.000	F(1, 26)=0.700, p=.410
	/aCu/	24	22	23	F(2, 25)=4.333, p=.024	F(1, 25)=9.700, p=.004

Table 5
Correlation coefficients and significances for the relation between angle of incidence and size of the loop. Data have been split by speaker. Column 1: speaker, column 2: V2, column 3: correlation coefficient, column 4: p-value. Bold: significant results.

speaker	V2	r	p
HS	all	-0.136	0.219
HZ	all	**0.720**	<0.001
SH	all	**0.457**	<0.001
HS	/a/	**-0.641**	0.001
HS	/i/	0.184	0.341
HS	/u/	-0.144	0.448
HZ	/a/	**0.580**	0.001
HZ	/i/	0.029	0.878
HZ	/u/	**0.602**	<0.001
SH	/a/	**0.714**	<0.001
SH	/i/	-0.175	0.354
SH	/u/	0.338	0.068

Table 6
Average values of the physical correlates of the three-way contrast to be reached in the simulations of the Korean velar stops. Column 1: consonant, column 2: V2, column 3: loop size in mm, column 4: closure duration in ms, column 5: peak acceleration in cm/s^2

consonant	V2	loop size	clos. dur.	acc.
/k/	/a/	1.1	73	446
/kh/	/a/	2.5	78	591
/k'/	/a/	2.6	102	757
/k/	/i/	3.6	80	481
/kh/	/i/	3.6	94	522
/k'/	/i/	4.5	126	662
/k/	/u/	1.8	70	552
/kh/	/u/	2.0	100	495
/k'/	/u/	2.7	125	566

Table 7

Parameters used for the simulations of the Korean velar stops. Column 1: simulated sequence, column 2: λ-values of the GGP, column 3: λ-values of the SG, columns 4 to 6 give values measured on the simulated stops. Differences between simulated and measured values are given in parentheses. Negative values signify that the value from the simulations is lower than the mean experimental value.

	Parameters varied		Correlates measured		
Item	λ GGP	λ SG	loop size (mm)	clos. dur. (ms)	peak acc. (cm/s^2)
/aka/	44	72	1.4 (-0.3)	66 (7)	550 (-104)
/akha/	41	72	3.4 (-0.9)	81 (-3)	640 (-49)
/ak’a/	37	72	4.5 (-1.9)	97 (5)	700 (57)
/aki/	43	73	4.1 (-0.5)	73 (7)	531 (-50)
/akhi/	40	73	4.5 (-0.9)	113 (-19)	593 (-71)
/ak’i/	36	73	5.0 (-0.5)	131 (19)	633 (37)
/aku/	44	72	1.6 (0.2)	73 (-3)	550 (2)
/akhu/	41	72	3.4 (-1.4)	77 (23)	640 (-145)
/ak’u/	37	72	4.5 (-1.8)	121 (4)	700 (-134)

Table .1
Results of ANOVAs with factors *speaker*, *context*, *consonant* and dependent variable *peak acceleration*

Effect	F and p
speaker	F(2, 236)=70.054, p=.000***
context	F(2, 236)=13.983, p=.000***
consonant	F(2, 236)=65.119, p=.000***
speaker*context	F(4, 236)=10.592, p=.000***
speaker*consonant	F(4, 236)=4.816, p=.000***
context*consonant	F(4, 236)=15.675, p=.000***
speaker*context*consonant	F(8, 236)=1.955, p=.053

.

Table .2
Results of ANOVAs for each speaker and context with factor *consonant* and dependent variable *peak acceleration*.

speaker	context	F and p
HS	/aCa/	F(2, 21)=6.316, p=.007**
HS	/aCi/	F(2, 26)=12.910, p=.000***
HS	/aCu/	F(2, 27)=12.306, p=.000***
HZ	/aCa/	F(2, 27)=27.514, p=.000***
HZ	/aCi/	F(2, 27)=15.718, p=.000***
HZ	/aCu/	F(2, 27)=1.288, p=.292
SH	/aCa/	F(2, 27)=37.161, p=.000***
SH	/aCi/	F(2, 26)=9.466, p=.000***
SH	/aCu/	F(2, 27)=3.269, p=.053

Table .3
Results of Tukey post-hoc tests for effect of factor *consonant* on dependent variable *peak acceleration*.

speaker	context	/k'/-/k/	/kh/-/k/	/kh/-/k'/
HS	/aCa/	p=.000***	p=.590	p=.001**
HS	/aCi/	p=.000***	p=.023*	p=.111
HS	/aCu/	p=.854	p=.001**	p=.000***
HZ	/aCa/	p=.000***	p=.004**	p=.002**
HZ	/aCi/	p=.000***	p=.152	p=.003**
HZ	/aCu/	p=.397	p=.991	p=.330
SH	/aCa/	p=.000***	p=.001**	p=.000***
SH	/aCi/	p=.003**	p=.982	p=.002**
SH	/aCu/	p=.448	p=.042*	p=.391

Table .4
Results of ANOVAs with factors *speaker*, *context*, *consonant* and dependent variable *size of the loop*.

Effect	size of the loop
speaker	F(2, 236)=135.461, p=.000***
context	F(2, 236)=198.492, p=.000***
consonant	F(2, 236)=77.710, p=.000***
speaker*context	F(4, 236)=57.661, p=.000***
speaker*consonant	F(4, 236)=15.836, p=.000***
context*consonant	F(4, 236)=7.943, p=.000***
speaker*context*consonant	F(8, 236)=6.368, p=.000***

Table .5
Results of ANOVAs for each speaker and context with factor *consonant* and dependent variable *size of loop*.

speaker	context	size of the loop
HS	/aCa/	F(2, 21)=10.646, p=.000***
HS	/aCi/	F(2, 26)=3.556, p=.000***
HS	/aCu/	F(2, 27)=3.093, p=.000***
HZ	/aCa/	F(2, 27)=34.834, p=.000***
HZ	/aCi/	F(2, 27)=5.406, p=.011*
HZ	/aCu/	F(2, 27)=12.285, p=.000***
SH	/aCa/	F(2, 27)=70.320, p=.000***
SH	/aCi/	F(2, 26)=12.631, p=.000***
SH	/aCu/	F(2, 27)=13.884, p=.000***

Table .6

Results of Tukey post-hoc tests for effect of *consonant* on *size of the loop*.

speaker	context	/k'/-/k/	/kh/-/k/	/kh/-/k'/
HS	/aCa/	p=.001**	p=.203	p=.015*
HS	/aCi/	p=.679	p=.190	p=.037*
HS	/aCu/	p=.162	p=.066	p=.891
HZ	/aCa/	p=.211	p=.000***	p=.000***
HZ	/aCi/	p=.009**	p=.081	p=.611
HZ	/aCu/	p=.000***	p=.260	p=.008**
SH	/aCa/	p=.000***	p=.000***	p=.000***
SH	/aCi/	p=.000***	p=.741	p=.001**
SH	ak'u-aku	p=.005**	p=.231	p=.000***

Table .7
Results of ANOVAs with factors *speaker*, *context*, *consonant* and dependent variable *closure duration*.

Effect	closure duration
speaker	F(2, 236)=156.225, p=.000***
context	F(2, 236)=54.986, p=.000***
consonant	F(2, 236)=208.432, p=.000***
speaker*context	F(4, 236)=3.871, p=.005**
speaker*consonant	F(4, 236)=3.696, p=.006**
context*consonant	F(4, 236)=4.900, p=.001**
speaker*context*consonant	F(8, 236)=4.247, p=.000***

Table .8
Results of ANOVAs for each speaker and context with factor *consonant* and dependent variable *closure duration*.

speaker	context	F and p
HS	/aCa/	F(2, 21)=42.267, p=.000***
HS	/aCi/	F(2, 26)=12.022, p=.000***
HS	/aCu/	F(2, 27)=8.398, p=.001**
HZ	/aCa/	F(2, 27)=65.494, p=.000***
HZ	/aCi/	F(2, 27)=6.329, p=.006**
HZ	/aCu/	F(2, 27)=51.087, p=.000***
SH	/aCa/	F(2, 27)=301.220, p=.000***
SH	/aCi/	F(2, 26)=38.884, p=.000***
SH	/aCu/	F(2, 27)=39.030, p=.000***

Table .9

Results of Tukey post-hoc tests for effect of factor *consonant* on dependent variable *closure duration*. The differences are in most cases highly significant ($p < .001$). The cases in which p is higher are listed below.

speaker	context	/k'/-/k/	/kh/-/k/	/kh/-/k'/
HS	/aCi/	p=.000	p=.963	p=.001**
HS	/aCu/	p=.000	p=.185	p=.076
HZ	/aCi/	p=.004**	p=.204	p=.188

Table .10

Results of ANOVA with factors *speaker*, *context*, *consonant* and dependent variable *angle of incidence.*

Effect	F and p
speaker	F(2, 251)=11.996, p=.000***
context	F(2, 251)=53.768, p=.000***
consonant	F(2, 251)=1.245, p=.290
speaker*context	F(4, 251)=21.882, p=.000***
speaker*consonant	F(4, 251)=1.521, p=.196
context*consonant	F(4, 251)=11.342, p=.000***
speaker*context*consonant	F(8, 251)=4.675, p=.000***

Table .11
Results of ANOVAs for each speaker with factor *context* and dependent variable *angle of incidence.*

speaker	angle of incidence
HS	F(2, 95)=30.806, p=.000***
HZ	F(2, 87)=41.808, p=.000***
SH	F(2, 88)=3.651, p=.030*

Table .12
Results of Tukey post-hoc tests for effect of factor *context* on dependent variable *angle of incidence.*

speaker	pair	p
HS	/aCi/-/aCa/	p=.063
HS	/aCu/-/aCa/	p=.000***
HS	/aCu/-/aCi/	p=.000***
HZ	/aCi/-/aCa/	p=.000***
HZ	/aCu/-/aCa/	p=.917
HZ	/aCu/-/aCi/	p=.000***
SH	/aCi/-/aCa/	p=.105
SH	/aCu/-/aCa/	p=.878
SH	/aCu/-/aCi/	p=.034*

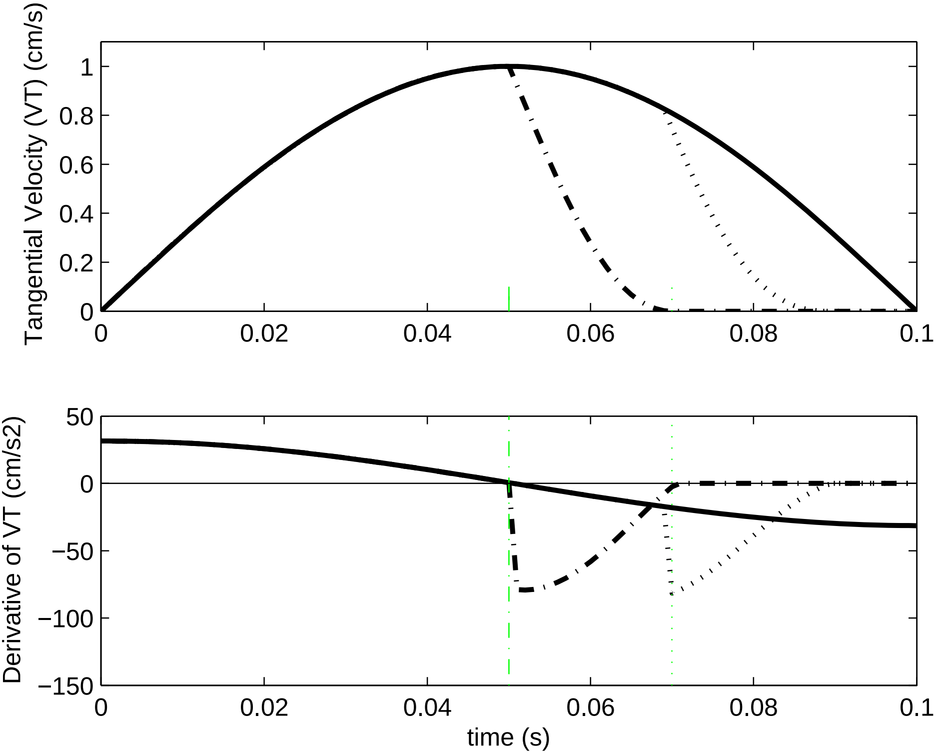


Fig. 1. Schematized kinematic properties of movements with impacts occurring at various stages of the movement. Upper track: tangential velocity versus time. Lower track: derivative of the tangential velocity versus time. Bold solid curve: movement without impact; bold dotted curve: movement with contact in the deceleration phase; bold dash-dotted line: movement with contact around the peak velocity. The light grey vertical lines mark the impact time in the different cases.

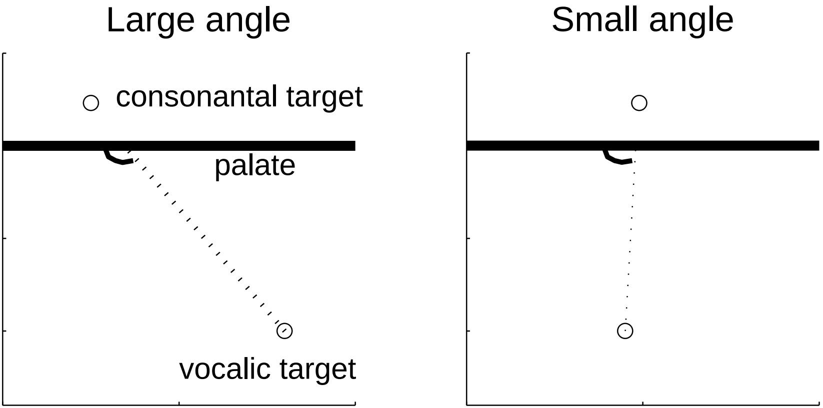


Fig. 2. Schematized example of a tongue movement from a vocalic target towards a consonantal target. Left: with a large angle of incidence. Right: with a small angle of incidence. Front is left.

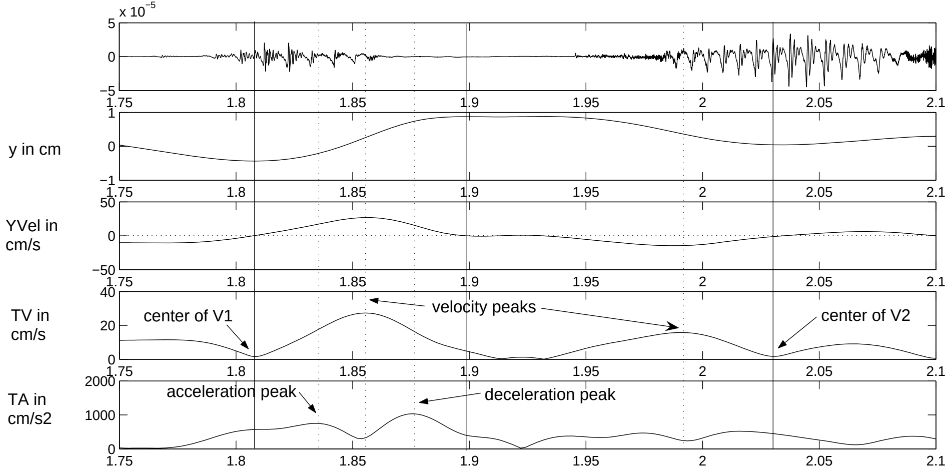
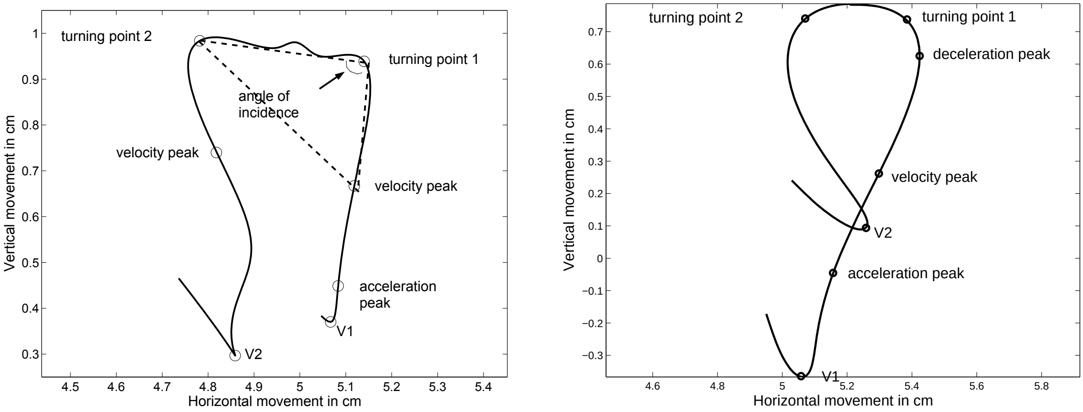
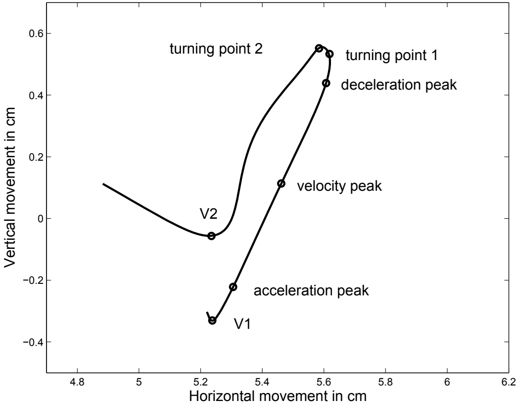


Fig. 3. Articulatory labeling for the sequence /akha/. First track: acoustic signal, second track: vertical movement of the tongue back sensor, third track: vertical velocity, fourth track: tangential velocity with velocity peaks during upward and downward movement of the tongue, fifth track: tangential acceleration with acceleration peak. The deceleration peak is marked for reasons of orientation.



(a) /ak'a/ (b) /akha/



(c) /aka/

Fig. 4. Trajectory of the tongue back sensor during a production of /aCa/. Front is left. Coming from the first vowel (V1) the tongue moves up towards the palate, then it slides along the palate and moves down again to the second vowel (V2).

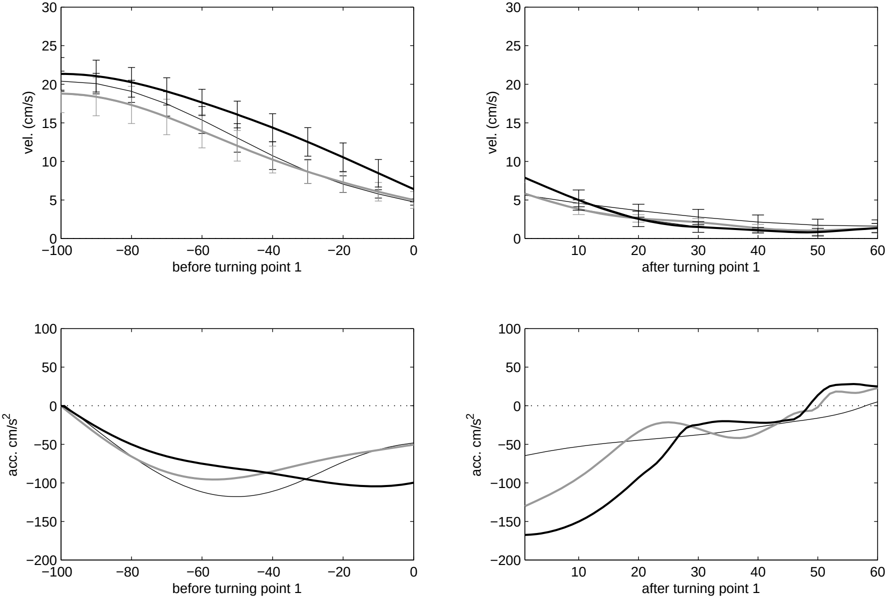


Fig. 5. Time normalized mean tangential velocity and standard deviation in the closing movement (upper left) and the sliding movement (upper right), derivative of the time normalized mean velocity of the closing movement (lower left) and the sliding movement (lower right). /k'/: grey, /kh/: thick black, /k/: thin black. Context: /aCa/, speaker HS.

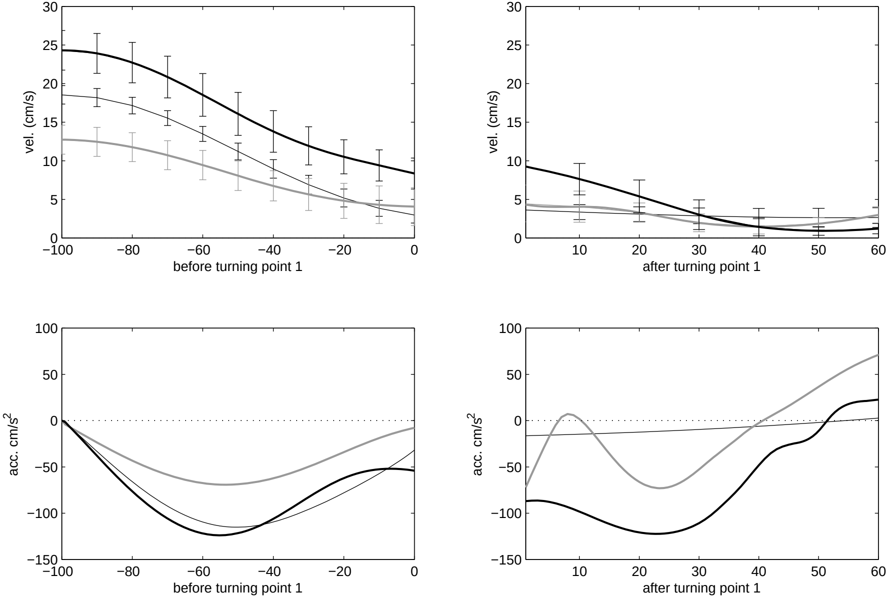


Fig. 6. As in figure 5, but for speaker SH.

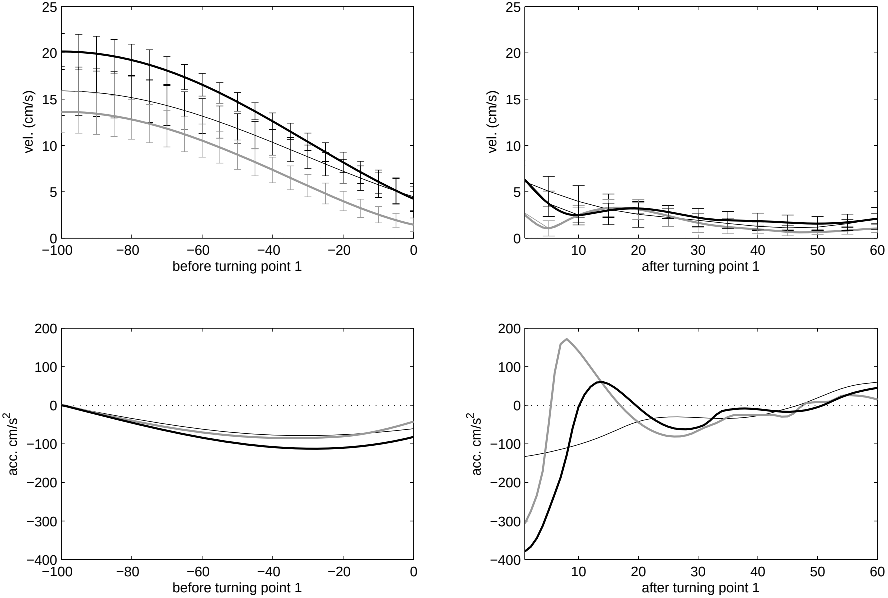
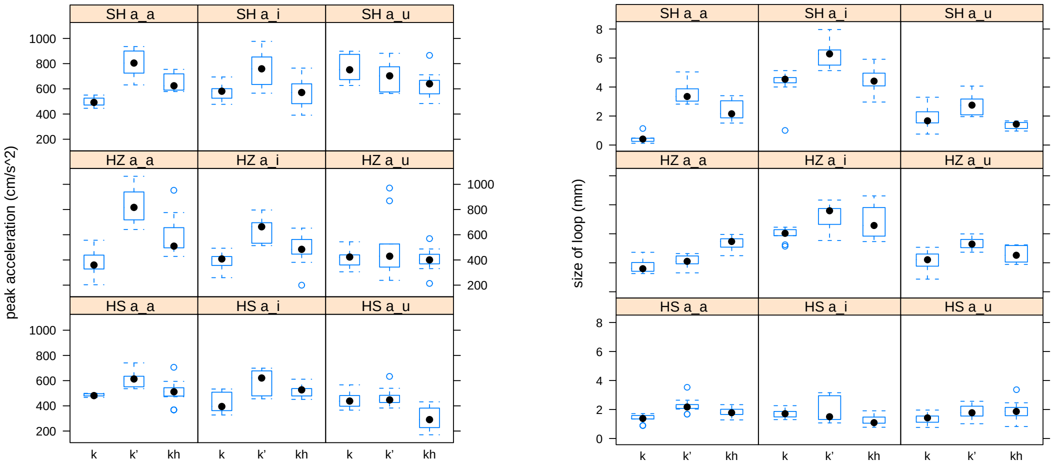
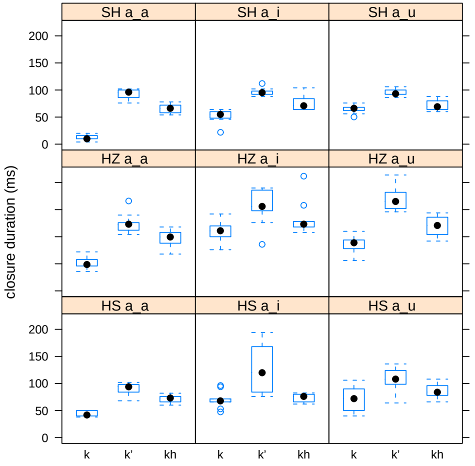


Fig. 7. As in figure 5, but for speaker HZ.



(a) Peak acc.

(b) Size of the loop



(c) Clos. dur.

Fig. 8. Peak acceleration, size of the loop and closure duration for each speaker (rows: SH, HZ and HS, boxplots represent the different consonants) and each vocalic context (columns: /aCa/, /aCi/ and /aCu/).

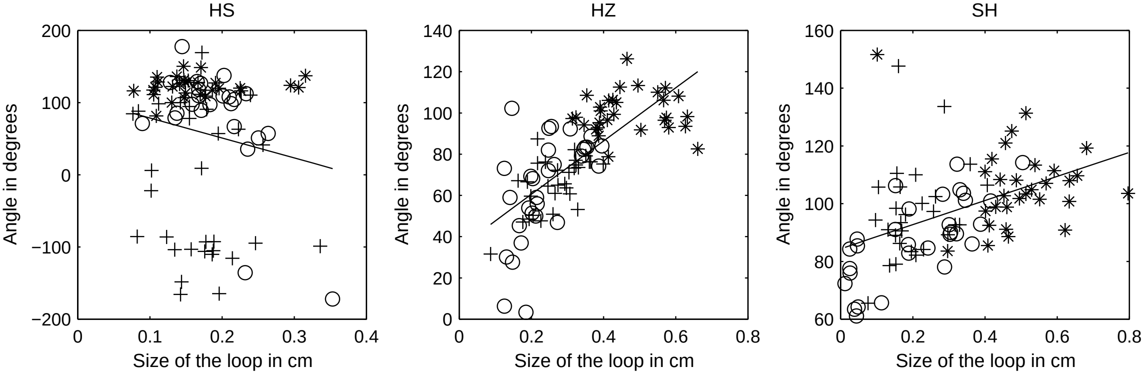


Fig. 9. Relation between angle size (ordinate) and size of the loop (abscissa). /aCa/: 'o', /aCi/: '*', /aCu/: '+'.

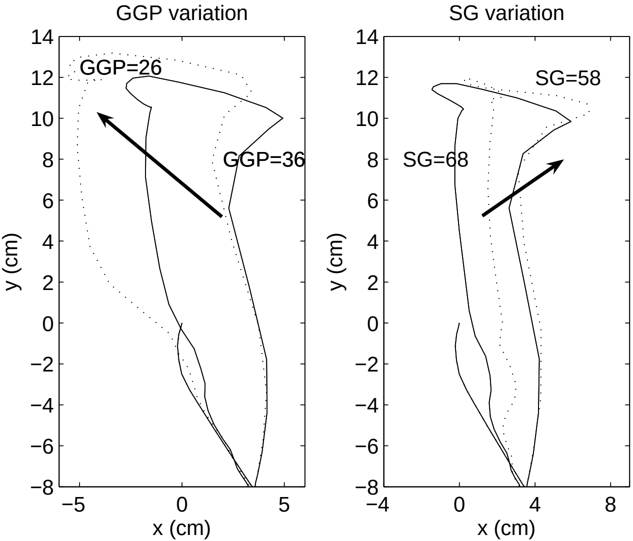


Fig. 10. Trajectories of one node on the suface of the tongue back from the simulations of different targets with the tongue model (without palate). Genioglossus posterior (left subplot) and styloglossus (right subplot) activity was varied. The tongue moves to a higher point for higher activation of both muscles as realized by longer threshold lengths of the muscles. The arrows signal increasing muscle activity. The trajectories are jagged as compared to those of the experimental data because the simulations have a lower sampling rate.

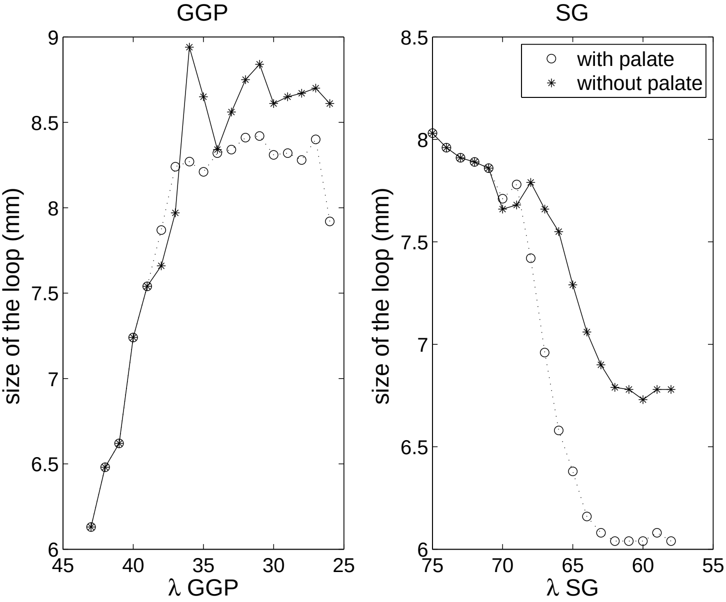


Fig. 11. Size of the loop (movement amplitude from closure onset to closure offset) as a function of the λ-commands of the genioglossus posterior (left) and the styloglossus (right). Asterisks show the results for the simulations without palate, circles the ones for the simulations with palate.

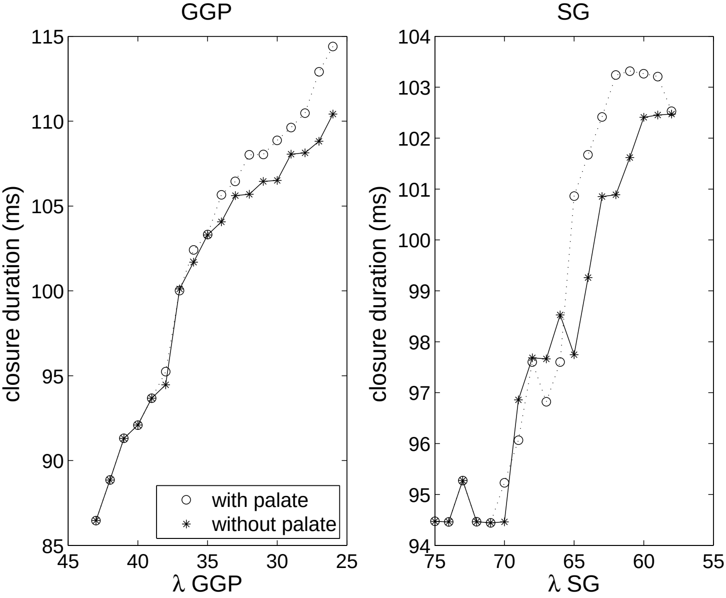


Fig. 12. Influence of the target (defined by λ-commands, abscissa) on the closure duration (ordinate). Asterisks show the results for the simulations without palate, circles those for the simulations with palate.

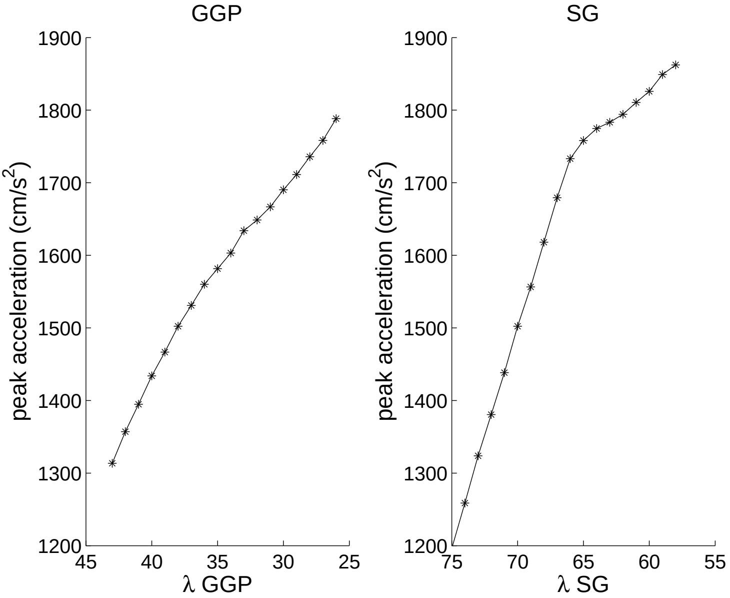


Fig. 13. Peak acceleration variation as a function of the λ-commands of the genioglossus posterior (left) and the styloglossus (right). No simulations with palate were carried out because the acceleration peak occurring during the closing movement is not altered by linguo-palatal contact.

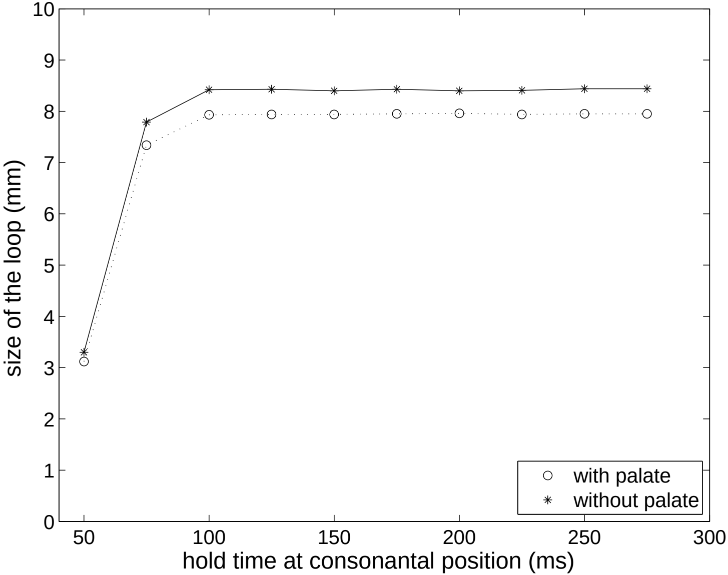


Fig. 14. Influence of the hold time (abscissa) on the size of the loop (ordinate). Asterisks show the results for the simulations without palate, circles those for the simulations with palate.