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Control of oral closure in lingual stop consonant production

Anders Löfqvist[a]
Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511 and
Department of Logopedics & Phoniatrics, Lund University, Lund, Sweden

Vincent L. Gracco
Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511 and
School of Communication Sciences and Disorders, McGill University, Montreal, Canada

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Previous work has shown that the lips are moving at a high velocity when the oral closure occurs for bilabial stop consonants, resulting in tissue compression and mechanical interactions between the lips. The present experiment recorded tongue movements in four subjects during the production of velar and alveolar stop consonants to examine kinematic events before, during, and after the stop closure. The results show that, similar to the lips, the tongue is often moving at a high velocity at the onset of closure. The tongue movements were more complex, with both horizontal and vertical components. Movement velocity at closure and release were influenced by both the preceding and the following vowel. During the period of oral closure, the tongue moved through a trajectory of usually less than 1 cm; again, the magnitude of the movement was context dependent. Overall, the tongue moved in forward–backward curved paths. The results are compatible with the idea that the tongue is free to move during the closure as long as an airtight seal is maintained. A new interpretation of the curved movement paths of the tongue in speech is also proposed. This interpretation is based on the principle of cost minimization that has been successfully applied in the study of hand movements in reaching.
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I. INTRODUCTION

Stop consonants are commonly produced with a complete closure in the vocal tract to allow the build-up of oral air pressure that drives the noise source at the release. The purpose of this study is to make a detailed examination of tongue tip and tongue body kinematics in the production of stop consonants with particular emphasis on events before, during, and after the oral closure. The influences of stop consonant voicing and vowel environment on movement kinematics are evaluated. In addition, we want to extend our previous work on bilabial stop consonant production (Löfqvist and Gracco, 1997; see also Westbury and Hashi, 1997), which has shown that the lips are moving at a high velocity at the onset of the oral closure, resulting in tissue compression and mechanical interactions between the lips, with the lower lip pushing the upper lip upward. These results for the lips suggested that a virtual target for the lips in making the stop closure is a region of negative lip aperture. That is, to reach their virtual targets, the lips would have to move beyond each other. The resulting tissue compression produces the airtight seal for the stop to allow the build-up of oral air pressure. Such a control strategy would ensure that the lips will form an airtight seal regardless of any contextual variability in the onset positions of their closing movements. In addition, this strategy appears to be used in controlling the duration of the closure for a bilabial stop (Löfqvist, 2000). By changing the virtual target for the lower lip, the lips will stay in contact for a longer or shorter period. More specifically, a stop with a longer closure duration is produced with the lower lip reaching a higher vertical position, reflecting a higher virtual target position. Given these findings for labial stop consonants, it is of interest to examine if a similar view of virtual targets is also viable for the tongue, i.e., a virtual target that would effectively require the tongue to move into the nasal cavity. Data on tongue movements and tongue–palate contact patterns presented by Fuchs *et al.* (2001) support such a view of a virtual target for the tongue. They noted that the magnitude of the deceleration of the tongue movement into the closure was highly correlated with the tongue–palate contact pattern, thus suggesting that the tongue is moving towards a virtual target at the onset of the oral closure. Also, the material presented by Mooshammer *et al.* (1995) clearly indicates that the tongue body is moving at the onset of the oral closure for a velar stop consonant, and that the velocity at closure is influenced by the quality of the preceding vowel. In addition, their results also showed that the tongue body is moving during the closure for a velar stop (see also Houde, 1968; Perkell, 1969). The amount of tongue movement during the closure varied with vowel context. Thus, the tongue-body movement during the closure was about 1 mm when the preceding vowel was /i/, and between 4 and 10 mm when the preceding vowel was /u/ or /a/.

Studies of tongue movements during velar stop consonant production have shown that the tongue tends to move in curved paths (Houde, 1968; Perkell, 1969; Kent and Moll, 1972; Schönle, 1988; Munhall *et al.*, 1991; Löfqvist and Gracco, 1994; Mooshammer *et al.*, 1995). In the production

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[a] Electronic mail: lofquist@haskins.yale.edu

of velar stops, the tongue movement trajectory into the stop closure is usually going forward, and the location of the point of contact between the tongue body and the palate at stop closure is influenced by the phonetic context of the stop (cf. Dembowski *et al.*, 1998). There are two properties of the tongue movement kinematics in speech that need to be addressed—the direction of the movement, i.e., forward or backward, and the nature of the path, i.e., straight or curved. Some of the proposed explanations to account for the tongue movement trajectories in velar stop consonants have been based on aerodynamic factors, such as an increase in cavity size to maintain voicing, or the increase in oral air pressure behind the closure (e.g., Coker, 1976; Hoole *et al.*, 1998). Alternatively, tongue movement kinematics has been explained in terms of the biomechanics of the tongue and the jaw (Perrier *et al.*, 1998). None of these explanations has been generally accepted, however. We should also note that in a vowel–consonant–vowel sequence with a bilabial stop, the tongue movement from the first to the second vowel tends to follow a curved path (Löfqvist and Gracco, 1999). Less information on movement kinematics (ignoring for the moment tongue–palate contact patterns obtained by electropalatography) is available for stops produced with the tongue tip and tongue blade, /t, d/, although the data published by Kent and Moll (1972) show that the location of the point of contact between the tongue tip and the palate, or alveolar ridge, is influenced by phonetic context.

In a recent study (Löfqvist and Gracco, 1999), we showed that in a vowel–bilabial stop-vowel sequence, more than 50% of the tongue movement trajectory from the first to the second vowel tends to occur during the stop closure for the consonant. The most likely explanation is that if a large part of the tongue movement trajectory occurred before or after the oral closure, an "extra" vowel sound might be perceived. In a vowel–consonant–vowel (VCV) sequence where the stop is alveolar or velar, one would expect a different pattern, however. The reason is that the tongue is not actively involved in making the labial closure in a VCV sequence with a bilabial stop consonant, but rather in making the vowel-to-vowel gesture. However, in the VCV sequences with the alveolar and velar stops, the tongue is actively involved both in making the stop closure and in the vowel-related gestures. One would thus expect that less than 50% of the tongue movement trajectory from the first to the second vowel occurs during the stop closure. The tongue is constrained in its freedom to move since it has to stay in contact with the palate to maintain the airtight seal.

Kinematic recordings of tongue movements were made in four subjects producing vowel–consonant–vowel sequences. To examine the specific hypothesis about virtual targets for the tongue in stop consonant production, measurements were made of the horizontal and vertical velocity at the onset of the oral closure for the stop. High movement velocities at the onset of the oral closure would be compatible with the notion of a virtual target for the tongue. In addition, the magnitude of tongue movement during the stop closure was evaluated. Finally, a calculation was made of the percentage of the tongue movement from the first to the second vowel that occurred during different intervals of the VCV sequence, such as during the first vowel, during the stop closure, and during the second vowel. We also present detailed analyses of tongue movement trajectories for a small number of tokens produced by two of the subjects. Our rationale for doing this is that such a presentation is useful for constraining the behavior of tongue models (e.g., Payan and Perrier, 1997; Sanguineti *et al.*, 1998).

II. METHOD

A. Subjects

Two female (LK, DR) and two male subjects (VG, AL) participated. All subjects had normal speech and hearing and no history of speech or hearing disorders. Three of the subjects (LK, DR, VG) are native speakers of American English. Subjects LK and DR grew up in the Midwest, while subject VG grew up in Florida; they all currently live in the Northeast. Speaker AL is a native speaker of Swedish who is also fluent in English. Subjects VG and AL are the two authors.

B. Linguistic material

The linguistic material consisted of 36 V_1CV_2 sequences, where the first vowel (V_1) was one of /i, a, u/, the consonant (C) one of /t, d, k, g/, and the second vowel (V_2) one of /i, a, u/. The sequences were placed in the carrier phrase "Say ... again," with sentential stress occurring on the second vowel (V_2) of the sequence. Ten repetitions of each sequence were recorded.

C. Procedure

The movements of the tongue were recorded using a three-transmitter magnetometer system (Perkell *et al.*, 1992). Receivers were placed on four positions on the tongue; these positions will be referred to, from front to back, as tip, blade, body, and rear. Although an attempt was made to position the receivers equidistantly on the tongue, there was some variability in the positions of the tongue receivers between subjects (this can be seen in Figs. 6 and 9 below). Two additional receivers placed on the nose and the upper incisors were used for the correction of head movements. All tongue receivers were attached using Ketac-Bond (ESPE). Care was taken during each receiver placement to ensure that it was positioned at the midline with its long axis perpendicular to the sagittal plane. Two receivers attached to a plate were used to record the occlusal plane by having the subject bite on the plate during recording. All data were subsequently corrected for head movements and rotated to bring the occlusal plane into coincidence with the x axis. This rotation was performed to obtain a uniform coordinate system for all subjects (cf. Westbury, 1994).

The articulatory movement signals (induced voltages from the receiver coils) were sampled at 625 Hz after low-pass filtering at 200 Hz. The resolution for all signals was 12 bits. After voltage-to-distance conversion, the movement signals were low-pass filtered using a 25-point triangular window with a 3-dB cutoff at 17 Hz; this was done forwards and backwards to maintain phase. To obtain instantaneous velocity, the first derivative of the position signals was calculated

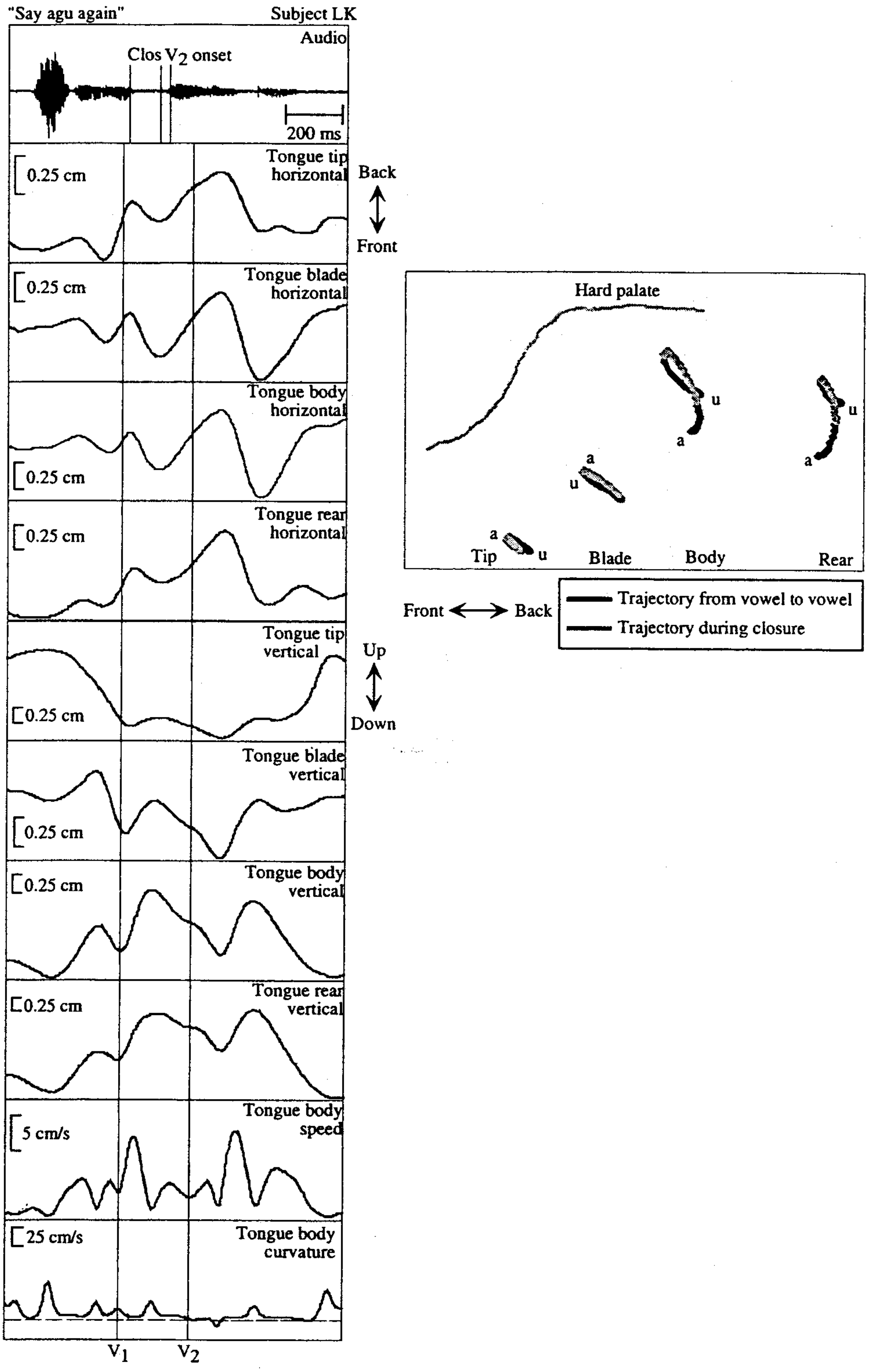

FIG. 1. Acoustic and movement signals recorded during the production of the utterance "Say agu again" by subject LK. The labels in the audio signal correspond to the onset and release of the oral closure for the consonant, and the onset of the second vowel in /agu/. The vertical lines labeled V1 and V2 were defined in the speed signal of the tongue body to identify the onset and offset of the tongue movement from the first to the second vowel in /agu/. The right panel shows the receiver trajectories from the first to the second vowel and also the part of the trajectory made during the oral closure for the consonant.

using a three-point central difference algorithm. The velocity signals were smoothed using the same triangular window. The speed [$v=\sqrt{(\dot{x}^2+\dot{y}^2)}$] was calculated for each receiver. In addition, the curvature [$c=(\dot{x}\ddot{y}-\ddot{x}\dot{y})/v^3$] was obtained. The sign of the curvature shows the direction of the movement, negative for clockwise movement and positive for counterclockwise movement (cf. Löfqvist *et al.*, 1993); in the coordinate system used in the present study, a positive sign of curvature indicates that the movement is going forward–backward; see Fig. 1. The magnitude of the curvature is a measure of how "curved" a movement trajectory is. Tongue movement onsets and offsets were defined algorithmically in the tongue body speed signal as minima during the first and second vowel. We should note that at these points in time, the horizontal and vertical velocity of the tongue is usually not zero. All the signal processing was made using the Haskins Analysis Display and Experiment System (HADES) (Rubin and Löfqvist, 1996).

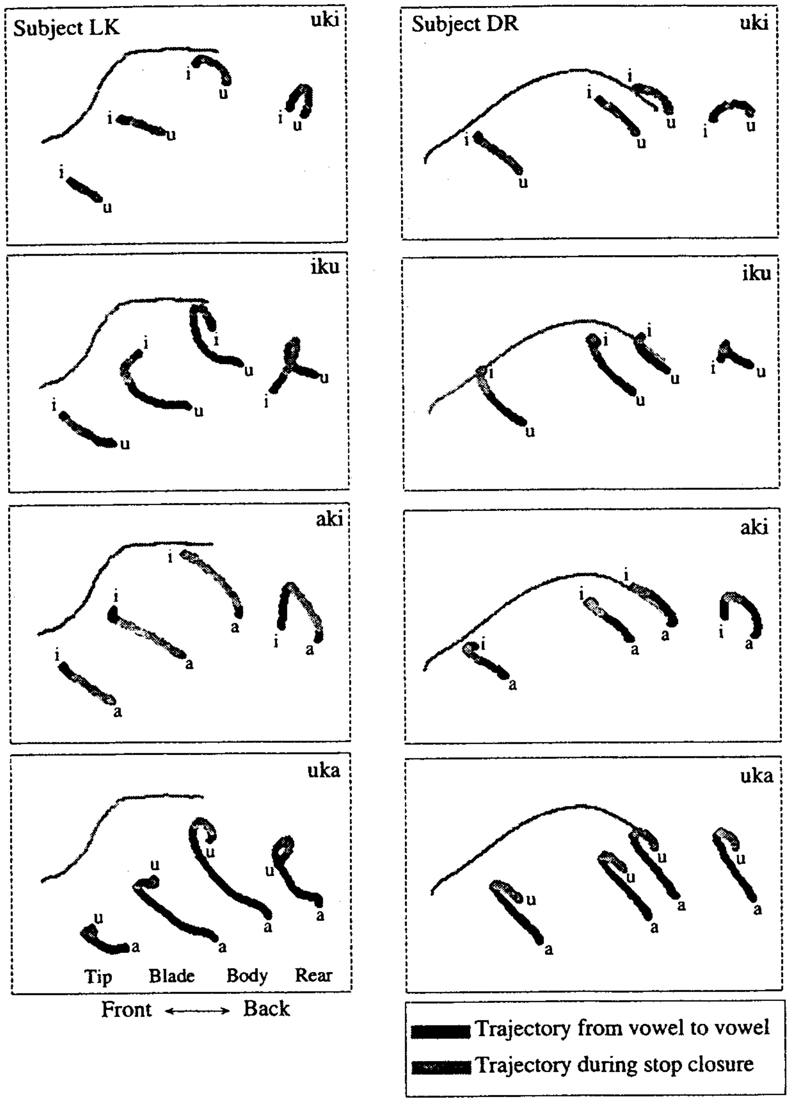

FIG. 2. Plots of receiver trajectories during single productions of sequences with a voiceless velar stop /k/ for subjects LK and DR. The trajectory from the first to the second vowel is shown and also the part of the trajectory that occurred during the oral closure for the consonant.

The acoustic signal was pre-emphasized, low-pass filtered at 9.5 kHz, and sampled at 20 kHz. The onset and release of the oral closure were identified in waveform and spectrogram displays of the acoustic signal. The onset of the closure was identified by the decrease in the amplitude of the acoustic waveform, and by the disappearance of spectral energy at higher frequencies. The release was identified by the burst and the onset of the second vowel in the VCV sequence by the beginning of regular glottal vibrations.

Figure 1 provides an example of tongue movements in one production of the sequence /agu/ by subject LK and also an overview of the labeling and measurement procedures. It presents the acoustic signal, the horizontal and vertical positions of each receiver, the tongue body speed, and the tongue body curvature signals. The following labels were placed in the acoustic and tongue body speed signals and used for measurements. In the acoustic signal, the labels from left to right correspond to the onset of the oral closure, the release of the oral closure, and the onset of the second vowel /u/. The first two of these labels were used for measuring the velocity of the tongue at the onset and release of the oral closure. They were also used to measure the movement of the tongue during the oral closure. The second and third of these acoustic labels, placed at the release and the acoustic onset of the second vowel, respectively, were used to examine the amount of movement between the release and the onset of the second vowel. In the tongue body speed signal, labels were placed at the speed minimum during the first and second vowels, respectively, and used to identify the onset and offset of the tongue movement in the first and second vowels. Thus, the two vertical lines running across the nine lower panels in Fig. 1 correspond to the onset of the closing movement from the first vowel /a/ and the offset of the opening movement into the second vowel /u/, defined in the tongue body speed signal. The first label in the tongue body speed signal was used together with the label at oral closure in the audio signal to measure the movement from the first vowel to the onset of the oral closure. The second label in the tongue body speed signal was used together with the label at the second vowel onset in the acoustic signal to measure the tongue movement during the second vowel. Note that these movement onset and offset in the two vowels were always defined in the tongue body speed signal. That is, they also served as onsets and offsets for the tongue tip movements in sequences with an alveolar stop. The reason is that the tongue body is more directly associated with the production of the vowels than the tongue tip. An examination of the location of the left vertical line in the movement signals in Fig. 1, marking the onset of the movement towards consonant closure, shows that it corresponds to instances of very small vertical movement for all the tongue receivers. However, all the receivers move backwards at this point in time. At the second vertical line in Fig. 1, all the receivers are moving down and back.

The right panel in Fig. 1 shows an $x-y$ plot of the trajectories of the tongue receivers from the first to the second vowel and also the part of the trajectory that occurred during the oral closure for the consonant. The temporal extent of this plot corresponds to the interval between the two vertical lines in the left panel, i.e., between the two vowels.

The bottom panel in Fig. 1 shows the curvature of the tongue body receiver. It has a positive sign during the sequence /agu/ defined by the two vertical lines, thus indicating that the movement is counterclockwise. There is only one instance of clockwise movement of the tongue body during the whole utterance, immediately to the right of the label "V_2;" this instance is thus not included in the trajectories shown in the right panel. In order to maintain consistency in labeling the movement and acoustic signals, all the labeling was made by the first author. The labeling of the movement signals was made interactively using both the temporal and $x-y$ plots shown in Fig. 1. Once the proper interval in the signal had been identified, an algorithm was used to place the label at the minimum of speed.

Measurements were made of receiver positions and velocities at the onset and offset of the oral closure. In addition, the path of the receiver during the oral closure were measured. The following movement trajectories were also measured: from the first vowel to the consonant closure, during the closure, between consonant release and the onset of the second vowel, and during the second vowel. The movement magnitude was measured in two different ways, as the Euclidean distance between receiver onset and offset, and as the movement path by summing the Euclidean distances between successive samples from movement onset to movement offset. The ratio of the path length and the Euclidean distance provides a metric to assess how much the trajectory deviates from a straight line, with a ratio of 1 implying a straight line.

Analyses of variance were conducted to assess the influence of consonant type and vowel context on movement properties. Since many comparisons were made, a p value of ≤ 0.0001 was adopted as significant. Given the large number of degrees of freedom, η^2 values showing the variation accounted for are also reported (cf. Young, 1993).

The kinematic signals represent the movements of receivers placed at the midline of the tongue. When presenting the results, we will use the terms "tongue tip receiver" and "tongue tip" interchangeably, while acknowledging that we are only examining the movements of a single point. Thus, we make no claims about asymmetrical movements of the left and right sides of the tongue during closure and release, although such asymmetries are known to exist (e.g., Hamlet *et al.*, 1986; Stone, 1990). Moreover, it is not possible to know the position of a given tongue receiver relative to the point, or region, of the tongue used for making the tongue–palate contact during the stop closure in a given subject. Finally, the tongue movements include the contribution of the jaw, which is proper when the focus is on the tongue as an end effector.

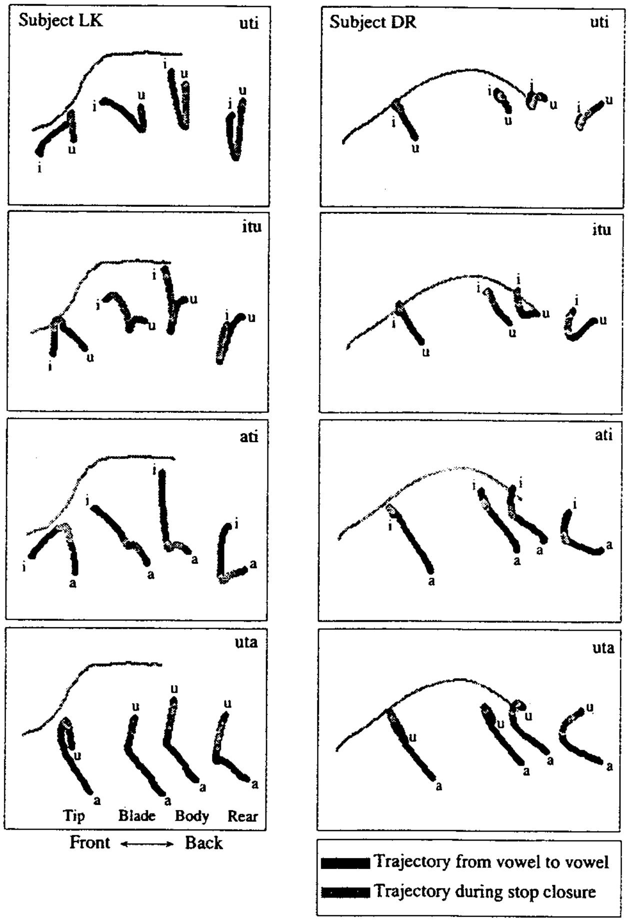

FIG. 3. Plots of receiver trajectories during single productions of sequences with a voiceless alveolar stop /t/ for subjects LK and DR. The trajectory from the first to the second vowel is shown and also the part of the trajectory that occurred during the oral closure for the consonant.

III. RESULTS

We shall first examine some characteristics of tongue movements in selected vowel contexts for two of the speakers. Figure 2 shows receiver movement trajectories from the first to the second vowel for selected sequences with a voiceless velar stop /k/ produced by subjects LK and DR. Figure 3 shows similar sequences with a voiceless alveolar stop /t/. The whole trajectory from vowel to vowel is shown, as well as the part of the trajectory that occurred during the oral closure for the consonant. The letters at the onset/offset of each trajectory identify the receiver positions for the respective vowels. A tracing of the outline of the hard palate is also shown for identification purposes. Since this outline was obtained by having the subject move the tongue tip receiver from the alveolar ridge and as far backwards as possible,

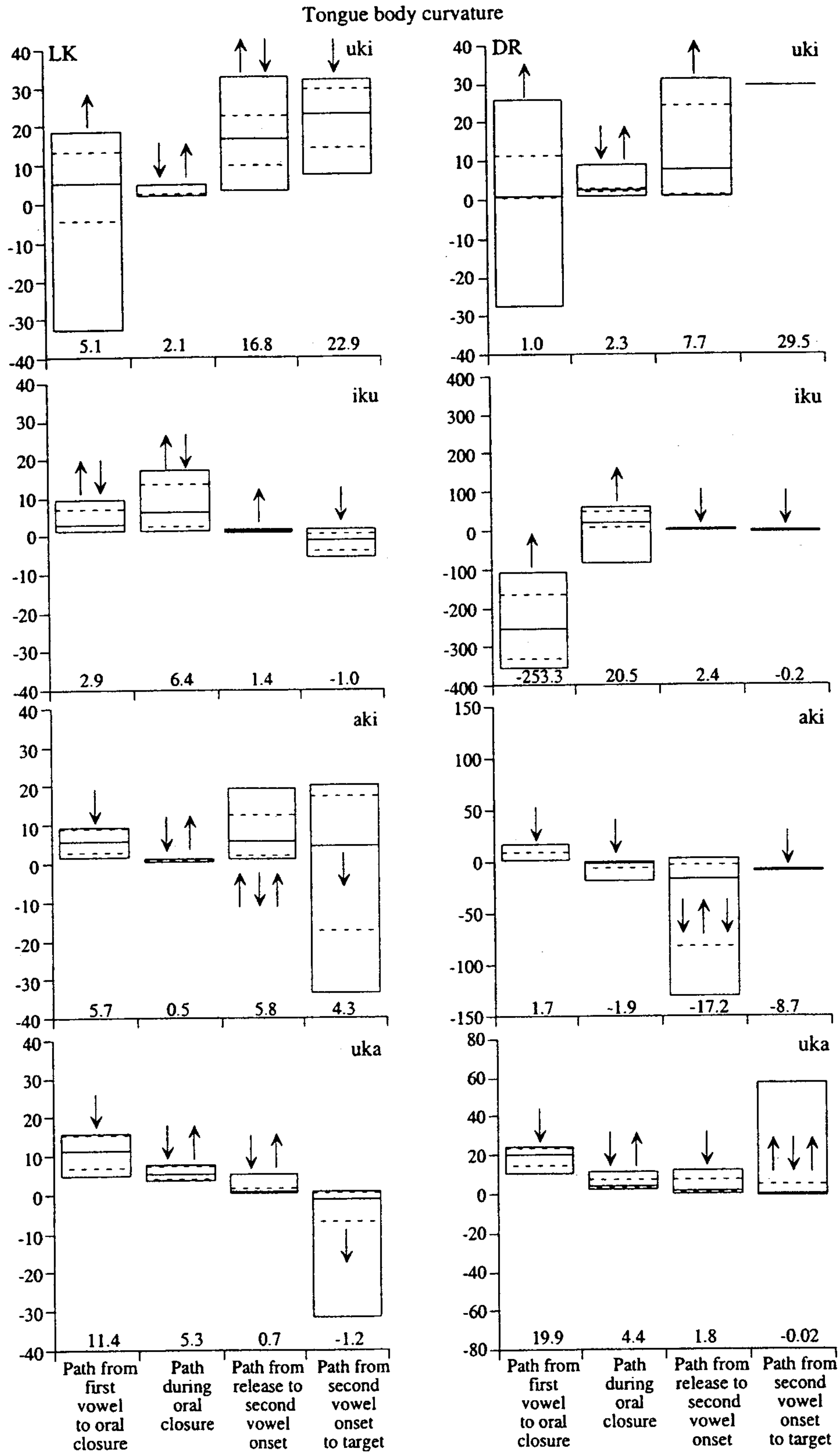

FIG. 4. Percentile plots of tongue body curvature for the productions with a velar stop consonant shown in Fig. 2. The box encloses 90% of the data with the bottom representing 5% and the top 95% of the data. The solid line inside the box is the median value, while the lower and upper two dashed lines in the box represent 25% and 75% of the data, respectively. The numbers below each box show the median curvature for the interval. The arrows above or in each box show the change in curvature for the interval. Two or more arrows indicate several changes occurring in the order from the left to the right arrows.

these tracings do not necessarily give the true outline of the palate in the posterior region (in some cases, a receiver crosses the outline of the palate).

In these figures, several aspects of tongue movements in speech are exemplified. The trajectories of the four tongue receivers show both similarities and differences. In the sequences with a velar stop, shown in Fig. 2, the tongue receivers mostly move in a curved trajectory with a counterclockwise, i.e., forward, movement. There are, however, several instances where this generalization does not hold and also where different receivers move in different directions. Figure 4 shows percentile plots of the curvature of the tongue body for the productions shown in Fig. 2. The box encloses 90% of the data with the bottom representing 5%

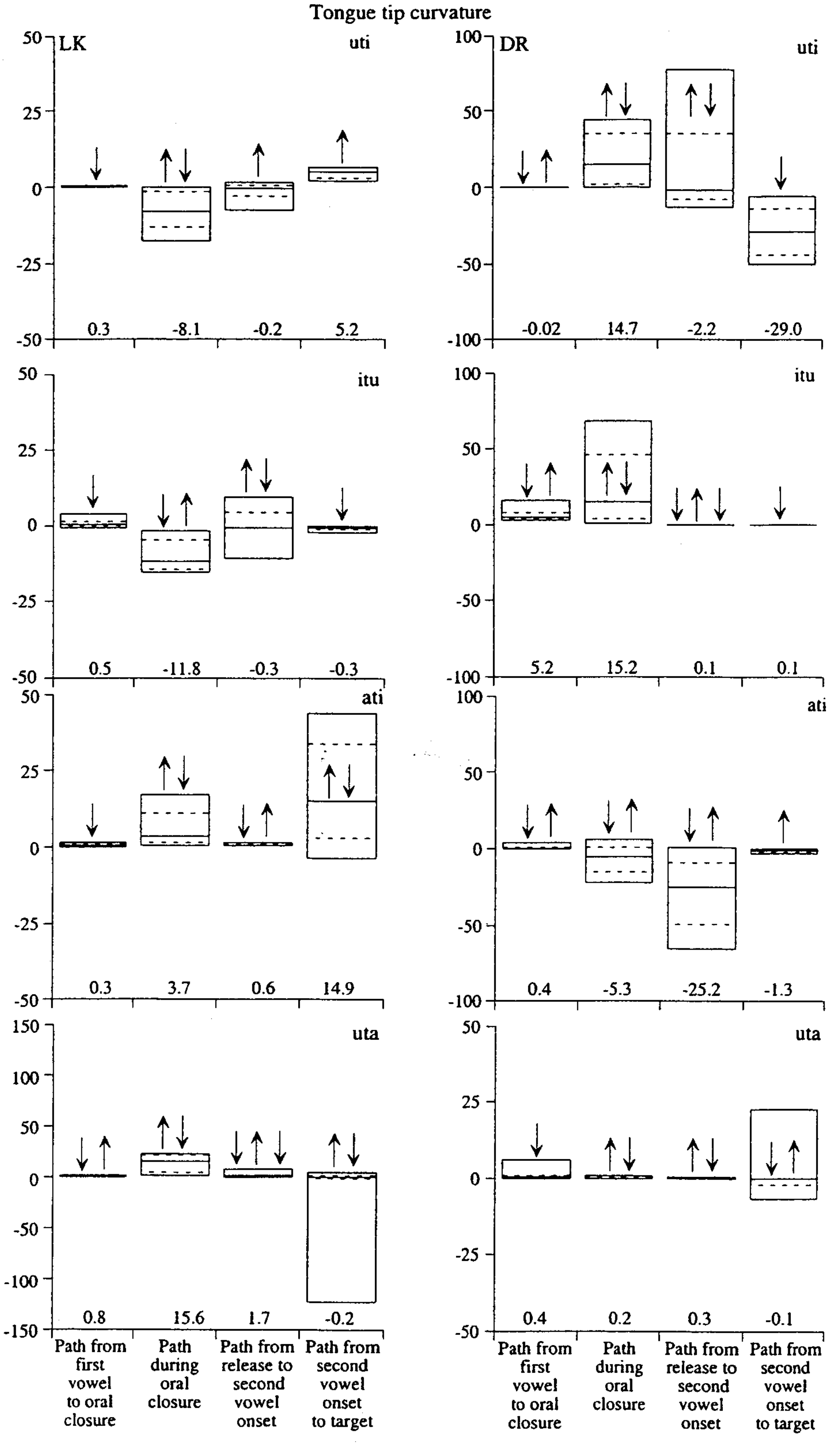

FIG. 5. Percentile plots of tongue tip curvature for the productions with an alveolar stop consonant shown in Fig. 3. The box encloses 90% of the data with the bottom representing 5% and the top 95% of the data. The solid line inside the box is the median value, while the lower and upper two dashed lines in the box represent 25% and 75% of the data, respectively. The numbers below each box show the median curvature for the interval. The arrows above or in each box show the change in curvature for the interval. Two or more arrows indicate several changes occurring in the order from the left to the right arrows.

and the top 95% of the data. The solid line inside the box is the median value, while the lower and upper two dashed lines in the box represent 25% and 75% of the data. Recall that a positive value of curvature indicates a clockwise forward–backward-going movement. The numbers below each box show the median curvature for the interval. The arrows above or in each box show the change in curvature for the interval. Two or more arrows indicate several changes occurring in the order from the left to the right arrows.

The median values for the curvature were always positive, with a few exceptions. These occurred in subject LK's productions of /iku/ and /uka/, and in subject DR's productions of /iku/, /aki/, and /uka/. Thus, the movement direction of the tongue body was going forward–backward. In many

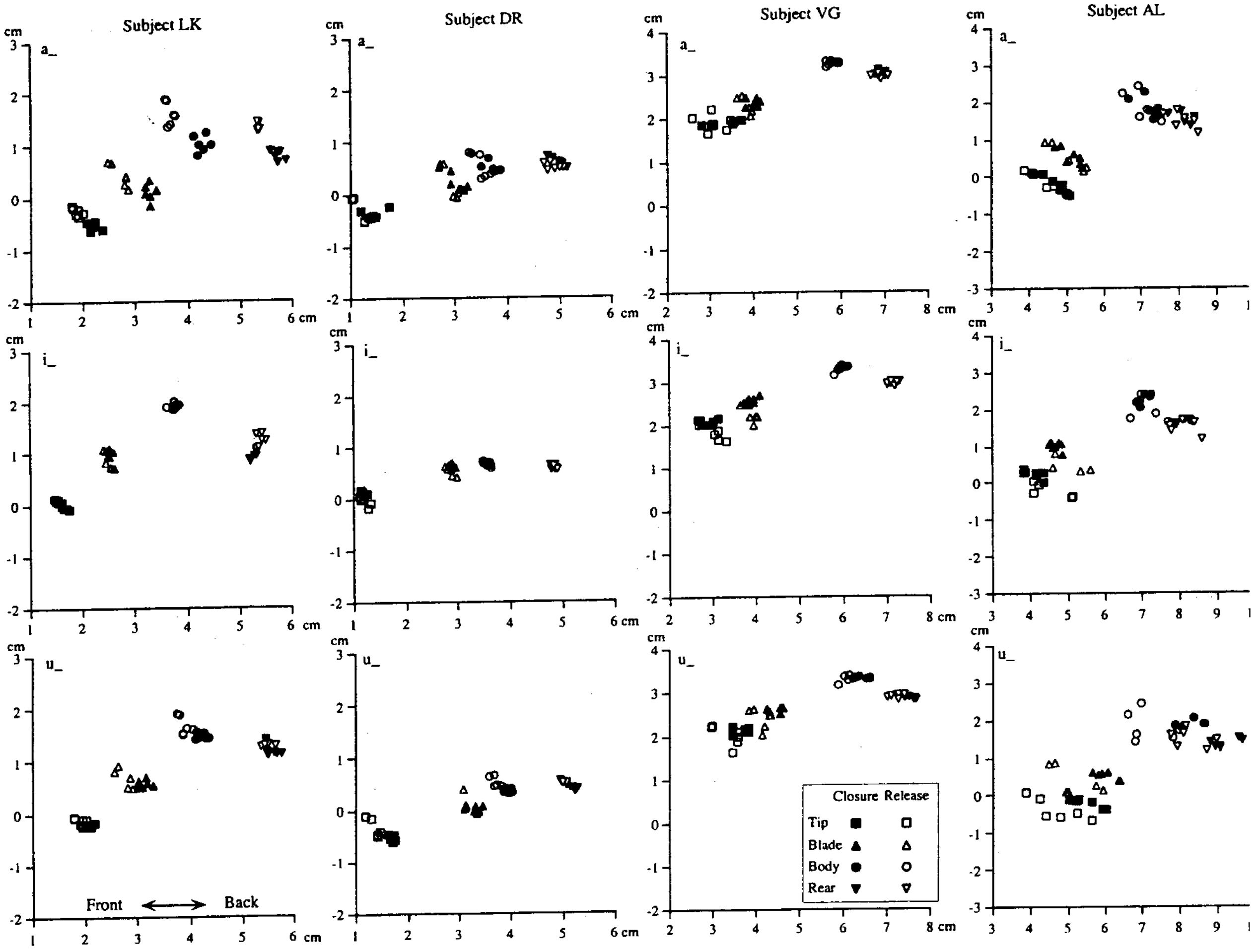

FIG. 6. Receiver positions at onset and release of oral closure for velar stops.

productions, the curvature of the tongue body was positive during all articulatory intervals. However, it is also apparent in Fig. 4 that the tongue body often changed its movement direction during the VCV sequence and sometimes even during an interval, e.g., during the movement during the closure in the sequence /uki/ for both subjects LK and DR.

During the closing movement, different tongue receivers sometimes moved in different directions. For example, in the sequence /aki/ of subject LK in Fig. 2, the tongue tip and tongue blade always moved clockwise while the tongue body and the tongue rear moved counterclockwise. On the other hand, in the closing movement of the sequence /iku/ of subject DR, the tongue tip and tongue blade always moved counterclockwise while the tongue body and tongue rear moved clockwise.

For the sequences with an alveolar stop consonant shown in Fig. 3, the most notable aspect is the difference in the tongue body and tongue rear receiver movements between the two subjects in the sequences /uti, itu/. In particular, during the oral closure the tongue body and tongue rear receivers of subject LK show an extensive lowering movement that is not found in the same sequences for subject DR. For subject LK, the vertical displacement of the tongue body during the closure is 0.7 and 0.8 cm for /uti/ and /itu/, respectively, while the same numbers for subject DR are 0.1 and 0.3 cm. For subject LK, the tongue tip vertical movement during the closure is 0.2 cm in both sequences. In the case of subject LK, this lowering of the tongue body during the oral closure in the sequences with the vowels /i, u/ is also followed by an upward movement after the release of the closure to the position for the second vowel. The path of the tongue body movement from the first to the second vowel is thus much longer for subject LK than for subject DR in the sequence /uti/, 2.0 and 0.7 cm respectively, and 2.2 and 0.9 cm for the sequence /itu/.

Figure 5 shows percentile plots of the curvature of the tongue tip for the productions shown in Fig. 3. Like the tongue body, the median tongue tip curvature was positive with the exception of five intervals for subject LK (/uti/, /itu/, /uta/) and five intervals for subject DR (/uti/, /ati/, /uta/). In general, the absolute curvature values were smaller for the tongue tip than the tongue body. It was also less common for the tongue tip to change its direction of movement during the individual articulatory intervals shown in Fig. 5.

The tongue receivers can move in both straight-line and curved paths. The ratio of the tongue movement measured as the Euclidean distance and as the length of the path provides a metric for how much the path deviates from a straight line.

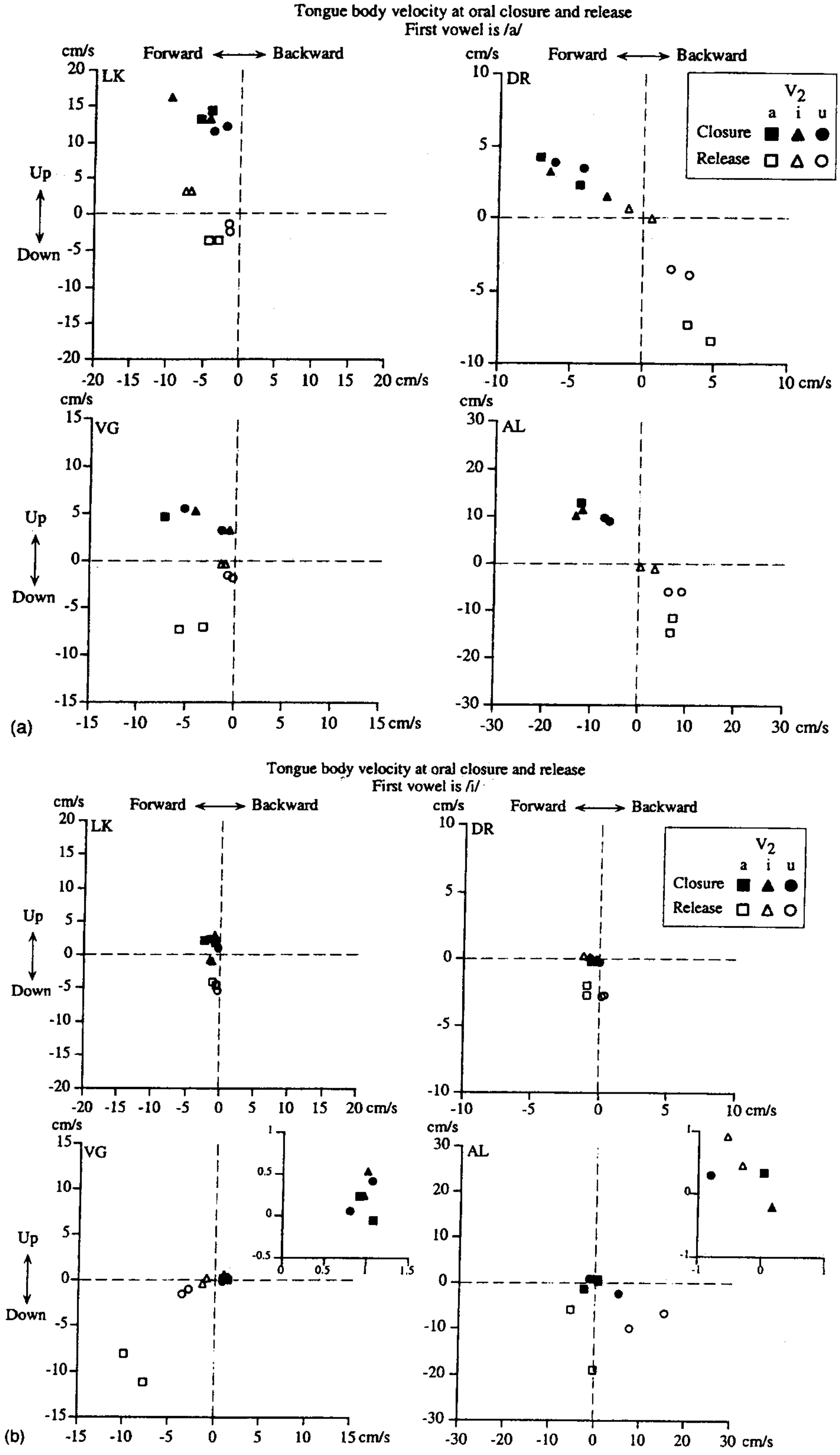

FIG. 7. Average tongue body velocity at the onset and offset of the oral closure in sequences where the first vowel is (a) /a/; (b) /i/; and (c) /u/.

Examination of such ratios for the tongue tip and tongue body movement during the stop closure for the utterances shown in Figs. 2 and 3 showed ratios higher than 2 for the tongue tip in /uti/ of subject LK and in /itu/ and /uta/ of subject DR. In these cases, the tongue tip was moving up and down during the closure, so that its position at the beginning and end of the closure was very similar. It is obvious from a qualitative analysis of the trajectories shown in Figs. 2 and 3 that in many cases the different parts of the tongue move in different paths during parts of the trajectory from the first to the second vowel.

The trajectory for a pair of VCV sequences with the same vowels but in different positions, such as /uki/ and /iku/ or /uti/ and /itu/, do not show paths that are mirror images of each other. This is due, in part, to the fact that the context for the first and second vowels differ due to the carrier phrase

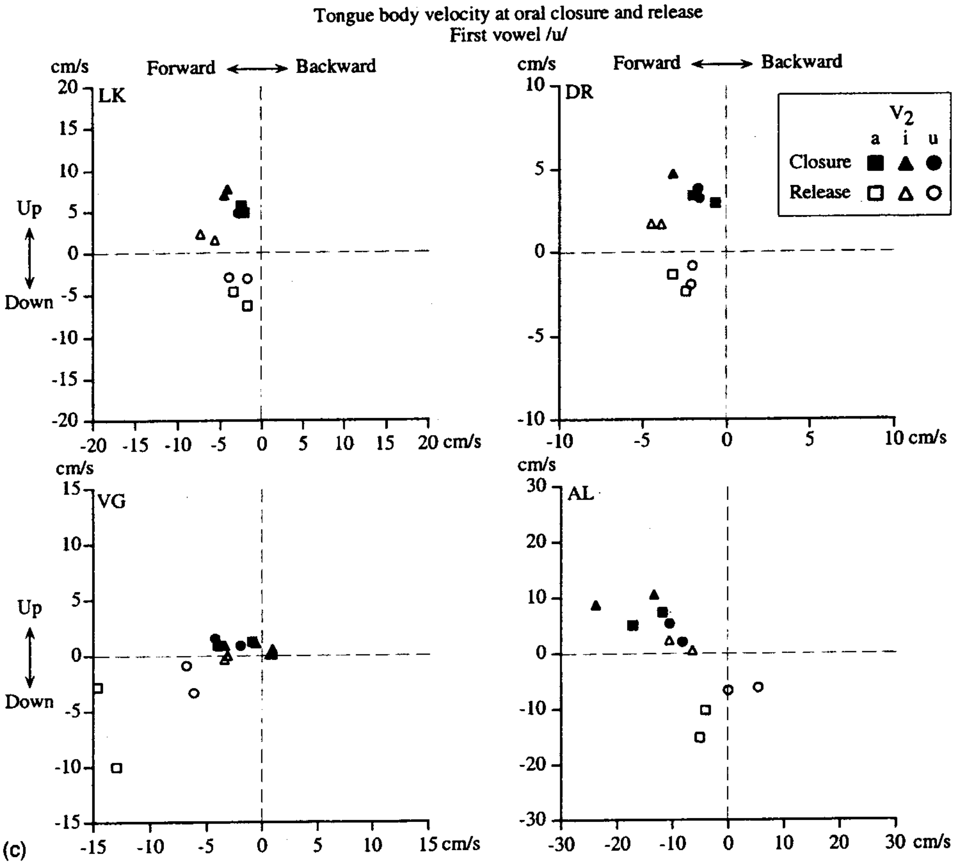

FIG. 7. (*Continued.*)

used, and also to the stress pattern (see Löfqvist and Gracco, 1999, for a detailed analysis of this issue).

A. Tongue body movements at stop closure

The first set of analyses focused on the tongue body and tongue tip before, during, and after the oral closure for the velar and alveolar stop consonants, respectively. An overview of all average receiver positions at onset and release of the oral closure for velar stops is shown in Fig. 6. In almost all cases, the positions of the open- and filled-circles representing the tongue body receiver differ, thus indicating tongue body movement during the closure. Generally, the tongue body is at a higher and more forward position at the release of the closure.

The average horizontal and vertical velocity of the tongue body receiver at the onset and offset of the oral closure for the velar stops are shown in Fig. 7 for all subjects. In this figure, there are two identical symbols for each subject, e.g., the filled triangles. They refer to the voiced and voiceless velar stops. As will be discussed in more detail below, the effect of stop consonant voicing was inconsistent. A first thing to note in this figure is that the tongue body is generally moving up and forward at the onset of the closure: The filled symbols cluster in the upper left quadrant of each panel. The only exceptions to this pattern are found when the first vowel is /i/ for subjects DR, VG, and AL [Fig. 7(b)], where the tongue body may be moving backward and down at closure. A second thing to note is that the velocity at closure is heavily influenced by the first vowel in the VCV sequence: The filled symbols in Figs. 7(a), (b), (c) tend to cluster in nonoverlapping regions of the plots. Conversely, within Figs. 7(a), (b), and (c), the filled squares, triangles, and circles, coding the quality of the second vowel, overlap. The filled symbols in Fig. 7(b) cluster around zero along both axes, indicating that the velocity at closure is very low when the first vowel is /i/. For the other two vowels /a, u/, the pattern shows some differences between speakers for the horizontal and vertical velocity. The results of the analysis of variance are summarized in Table I. (In this and the following section, the degrees of freedom in the analysis of variance were 1,162 for consonant voicing and 2,162 for vowels.)

The analysis of variance showed that the horizontal ve-

TABLE I. F and η^2 values for tongue body movements at the stop closure. Boldface indicates significant effect at $p<0.0001$.

Measure	LK	DR	VG	AL
Horizontal velocity at closure				
V1	**84.73**, 0.15	**501.01**, 0.36	**184.20**, 0.36	**449.79**, 0.28
V2	**20.91**, 0.04	1.98	**12.04**, 0.02	**85.92**, 0.05
Vertical velocity at closure				
V1	**1163.66**, 0.3	**556.61**, 0.32	**346.61**, 0.41	**832.37**, 0.38
V2	**29.85**, 0.02	4.83	1.51	**40.30**, 0.02
Horizontal velocity at release				
V1	**74.19**, 0.13	**434.92**, 0.62	**155.99**, 0.13	**123.21**, 0.26
V2	**71.89**, 0.13	**82.36**, 0.12	**561.71**, 0.22	**154.3**, 0.33
Vertical velocity at release				
V1	**22.44**, 0.07	**120.12**, 0.14	5.04	3.64
V2	**126.99**, 0.38	**264.79**, 0.32	**441.25**, 0.41	**757.47**, 0.36
Movement path during closure				
V1	**815.89**, 0.23	**391.03**, 0.21	**108.44**, 0.11	**551.33**, 0.16
V2	**45.47**, 0.01	**12.2**, 0.001	**98.32**, 0.1	**86.19**, 0.03

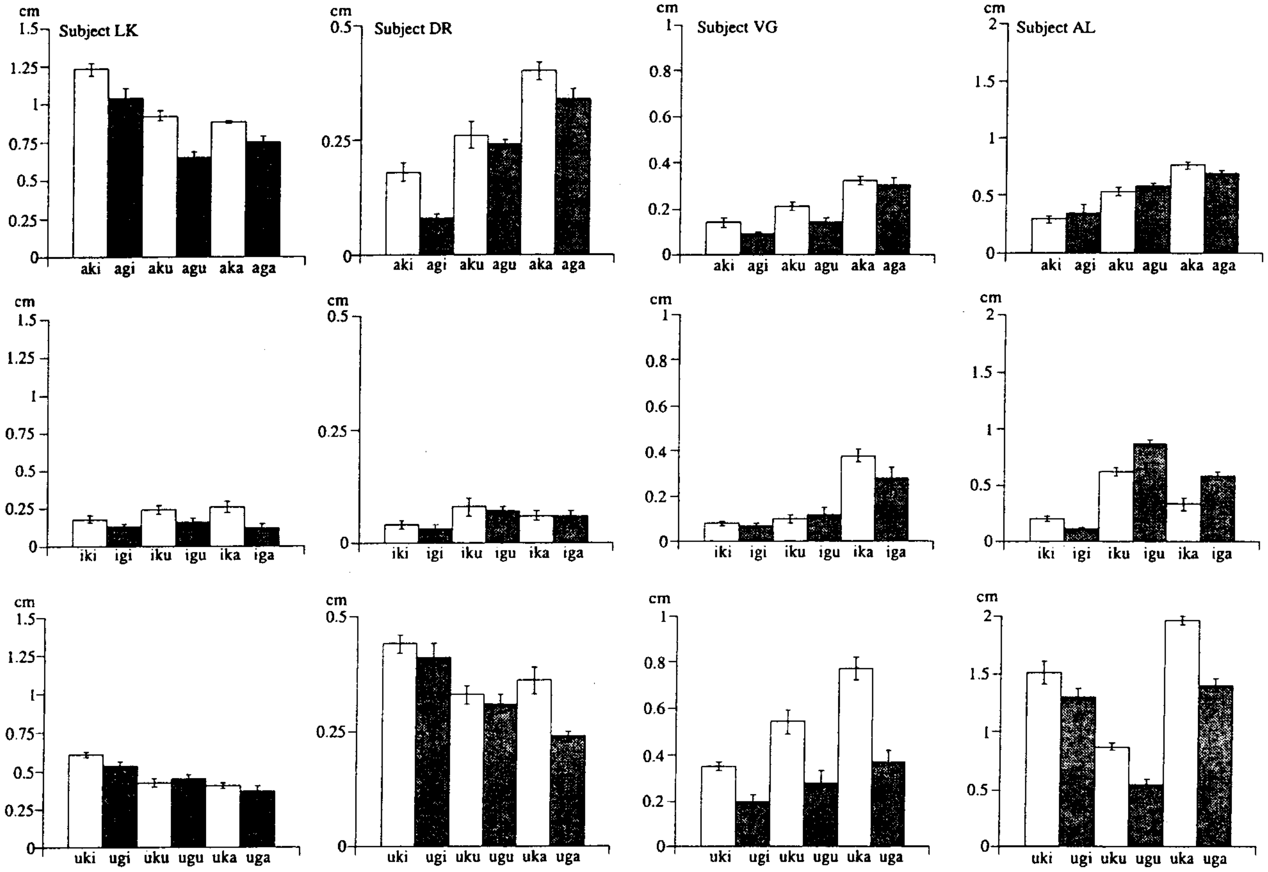

FIG. 8. Average movement path of the tongue body receiver during the period of oral closure; the error bars show the standard deviation.

locity at oral closure was reliably influenced by the quality of the first vowel. The same was true for the vertical velocity at closure. The effect of the second vowel on the horizontal velocity at closure was significant for subjects LK, VG, and AL, but not for subject DR. For the vertical velocity at closure, the second vowel effect was significant for subjects LK and AL. The η^2 values for the effect of the second vowel are very low compared to those of the first vowel. Stop consonant voicing did not show any consistent influences on the tongue body movement at oral closure across subjects.

At the release of the oral closure for the velar stops, the results presented in Fig. 7 show more variability between the subjects. In the majority of cases, the tongue body is moving downward at the release, but exceptions to this pattern are found for all subjects when the second vowel is /i/, the unfilled triangles. The vertical velocity at the release tends to be smaller when the second vowel is /i/ (unfilled triangles) than when it is /a/ or /u/ (unfilled squares and circles. For two subjects, LK and VG, the tongue body is always moving forward at the release, whereas for the other two subjects, DR and AL, a backward movement occurs in the vowel contexts /a_a/ [Fig. 7(a)], /a_u/ [Fig. 7(a)], and /i_u/ [Fig. 7(b)]. It is reasonable to assume that at the release of the velar closure, the tongue body movement is mostly influenced by the second vowel in the VCV sequence. Thus, the unfilled symbols should cluster by shape. This is generally the case for all subjects.

The horizontal velocity of the tongue body at the release was reliably influenced by the first vowel for all subjects. However, the first vowel only had a reliable influence on the vertical velocity at the release for subjects LK and DR. Also, the influence of the second vowel on the horizontal and vertical velocity at the release was reliable. Thus, to judge from the η^2 values, the horizontal velocity of the tongue body at the release of the velar closure is still influenced by the first vowel, whereas the vertical velocity is mostly influenced by the second vowel. Again, the influence of consonant voicing was inconsistent.

The tongue body receiver usually continued to move during the oral closure for the velar stops; the path of the movement was generally less than 1, as summarized in Fig. 8. The effect of the first vowel on the movement path was reliable for all subjects; see Table I. The second vowel also reliably influenced the movement path during the closure, although the η^2 values were lower. Consonant voicing had a reliable effect on tongue body movement during the closure for subjects LK, DR, and VG. As is evident in Fig. 8, the path was longer for the voiceless stops.

B. Tongue tip movements at stop closure

An overview of all average receiver positions at onset and release of the oral closure for alveolar stops is shown in Fig. 9. In almost all cases, the positions of open- and filled-

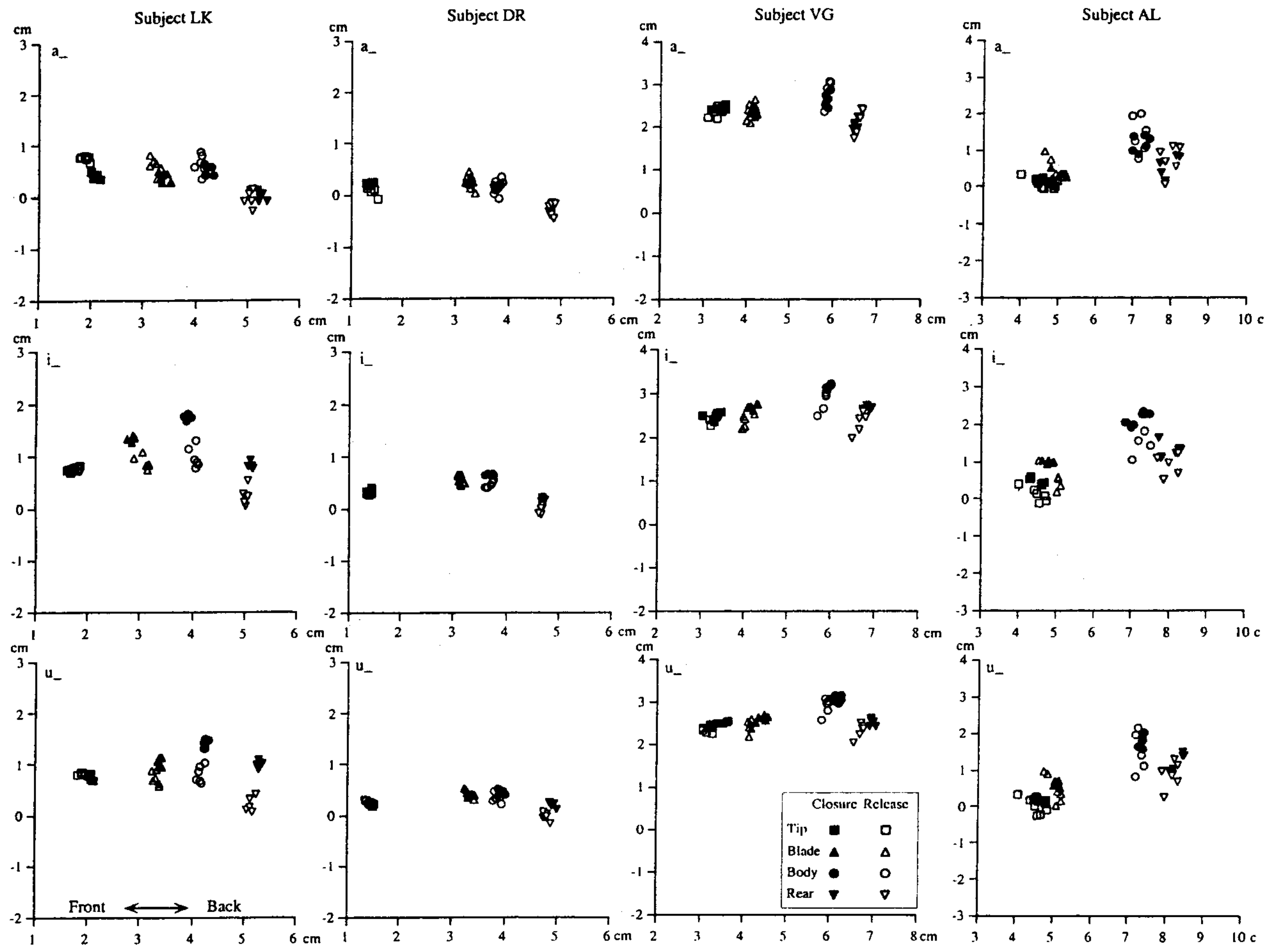

FIG. 9. Receiver positions at onset and release of oral closure for alveolar stops.

squares representing the tongue tip receiver differ, thus indicating tongue tip movement during the closure. Generally, the pattern of tongue tip movement during the closure is more variable across subjects that that of the tongue body shown in Fig. 6.

The average horizontal and vertical velocity of the tongue tip receiver at the onset and offset of the oral closure for the alveolar stops are shown in Fig. 10. In this figure, there are two identical symbols for each subject, e.g., the filled triangles. They refer to the voiced and voiceless alveolar stops. At the onset of the oral closure, the tongue tip is generally moving upward. A few exceptions to this pattern occur for subject AL. The pattern of horizontal movement differs between subjects. Subject DR always shows a forward movement, while subjects LK, and AL have a forward movement when the first vowel is /a/ and /u/ [Figs. 10(a) and (c)], but a backward movement when the first vowel is /i/ [Fig. 10(b)]. For subject VG, the movement is forward when the first vowel is /u/ and backward when the first vowel is /i/. Interestingly, when the first vowel is /a/, the movement is forward for the voiced stops but backward for the voiceless ones. The strong influence on the movement velocity at oral closure from the first vowel is evident from the fact that the filled symbols tend to cluster in nonoverlapping regions in Figs. 10(a)–(c). Note, however, that the filled symbols are higher in Fig. 10(a) for subjects LK, VG, and AL than in Figs. 10(b) and (c), whereas the filled symbols are higher for subject DR in Fig. 10(c) than in Figs. 10(a) and (b). This shows that the tongue tip is moving upwards at a faster speed when the preceding vowel is /a/ for subjects LK, VG, and AL, but when it is /u/ for subject DR.

The strong influence on the first vowel on the tongue tip velocity at the closure for the alveolar stops was also shown by the statistical analysis, summarized in Table II. For the horizontal velocity at closure, the effect of the first vowel was reliable. The influence of the second vowel was only significant for subjects DR and AL and accounted for a smaller proportion. Also, for the vertical velocity at closure there was a reliable influence of the first vowel. The effect of the second vowel was only significant for subject LK.

At the release of the oral closure, Fig. 10 shows that the tongue tip is moving downward; there are only two exceptions, one for subject DR, /a_i/ [Fig. 10(a)], where the velocity is very small, and one for subject AL, /u_i/ [Fig. 10(c)]. The horizontal movement at the release is mostly forward for subject VG, mostly backward for subjects DR and AL, and variable for subject LK. For subject AL, the tongue tip is moving forward at the release when the second vowel is /i/ [the open triangles in Figs. 10(a)–(c)]. At the release of the alveolar closure, the velocity of the tongue tip is mostly governed by the second vowel. This is shown by the fact that the unfilled symbols cluster by shape.

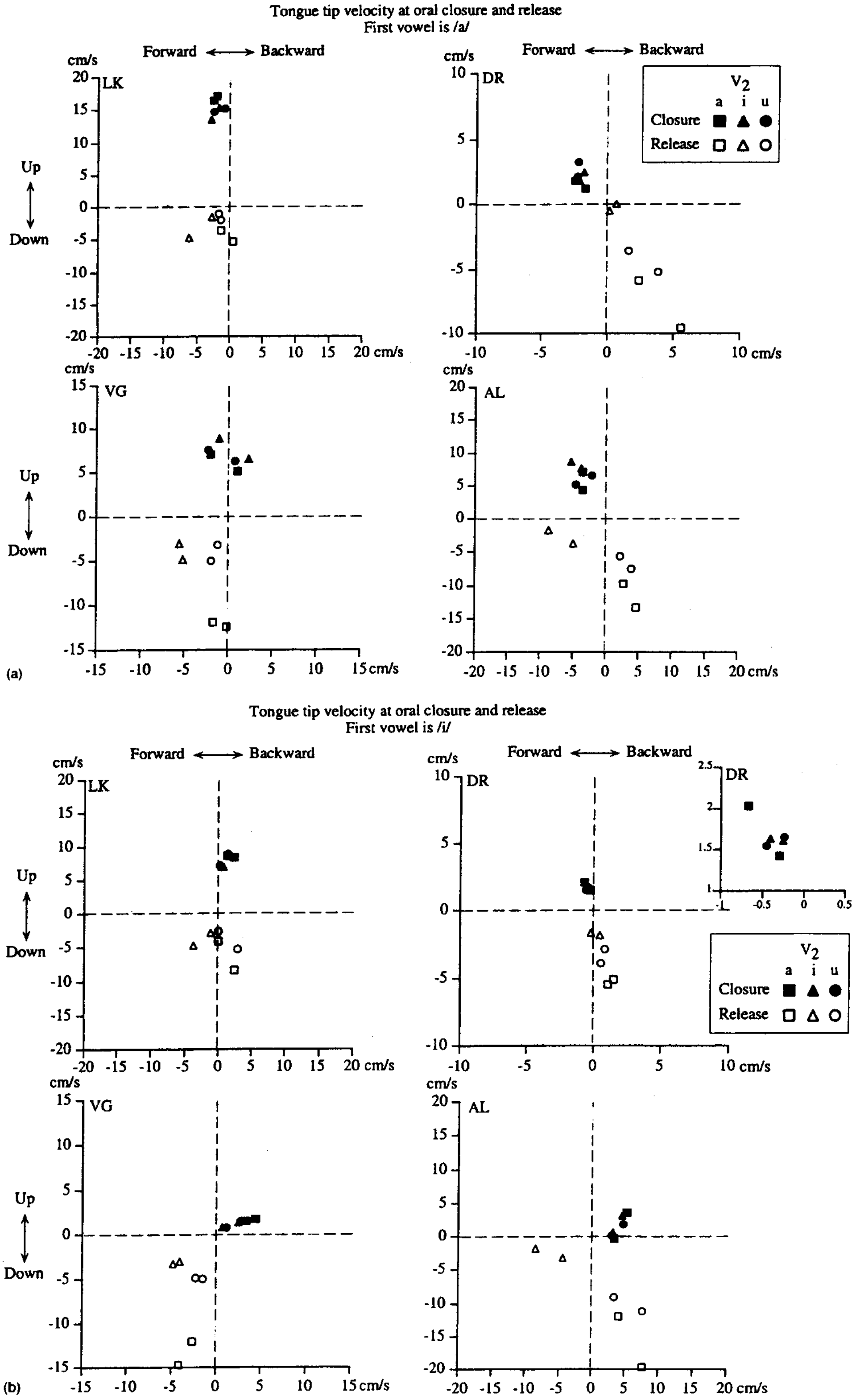

FIG. 10. Average tongue tip velocity at the onset and offset of the oral closure in sequences where the first vowel is (a) /a/; (b) /i/; and (c) /u/.

The effect of the first vowel on the horizontal velocity at the release was reliable for all subjects. The same was true for the second vowel. As for the vertical velocity, the first vowel had a significant effect for subjects LK, DR, and AL. The second vowel had a significant effect for all subjects.

Similar to the tongue body, the tongue tip moved during the closure for the alveolar stops but the length of its path was small and generally less than 0.5 cm; see Fig. 11. The effect of the first vowel on the tongue tip path during the closure was reliable for all subjects. The second vowel had a reliable effect for subjects DR, VG, and AL. Note, however that the η^2 values shown in Table II are quite small. Consonant voicing only had an effect of the tongue tip path during the closure for subject DR, who had a tendency for longer paths in the voiced stops.

The final analysis examined of the relative movement

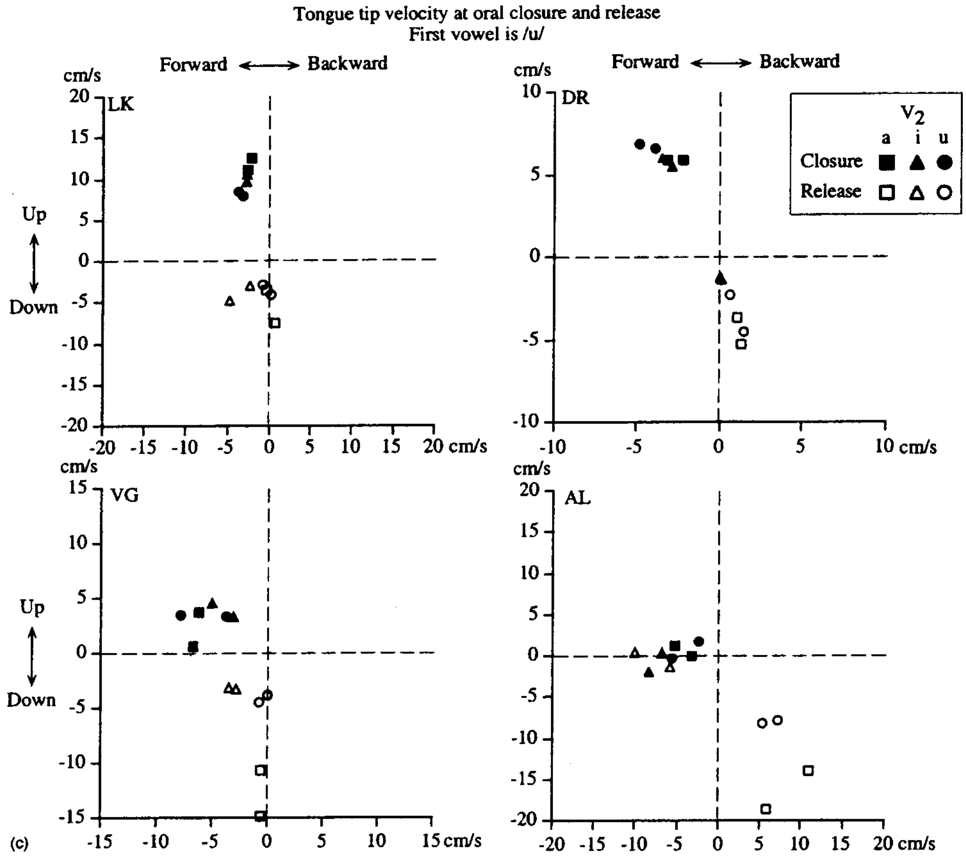

FIG. 10. (*Continued.*)

trajectories during the tongue movement from the first to the second vowel. The results are shown in Table III for the individual subjects and the sequences where the movement during a given interval exceed 50% of the whole trajectory. The first thing to note that during the oral closure, more than 50% of the whole trajectory only occurred for only five sequences (subjects LK and AL) and these sequences all had velar stops. The interval from the first vowel to the stop closure took more than 50% of the whole trajectory in a number of sequences for subjects DR, VG, and AL. In 82% of these sequences, the first vowel was /a/, while the first vowel was /u/ in the remaining sequences. In addition, 70% of these sequences had an alveolar stop. The interval between the stop release and the onset of the second vowel accounted for more than 50% of the whole trajectory in a few sequences for subjects LK, DR, and VG. In 86% of these sequences, the first vowel was /i/, and 86% of them had a velar stop. Finally, the movement during the second vowel took more than 50% of the whole trajectory in some sequences for all subjects. In 63% of them, the second vowel was /a/, while in the remaining 37% the second vowel was /u/ 58% of these sequences had a velar stop, while 42% had an alveolar stop.

TABLE II. F and η^2 values for tongue tip movements at the stop closure. Boldface indicates significant effect at $p<0.0001$.

Measure	LK	DR	VG	AL
Horizontal velocity at closure				
V1	**208.14**, 0.52	**299.46**, 0.25	**204.79**, 0.59	**696.81**, 0.72
V2	4.08	**13.45**, 0.01	2.73	**22.17**, 0.02
Vertical velocity at closure				
V1	**266.23**, 0.07	**457.62**, 0.25	**311.95**, 0.24	**319.12**, 0.4
V2	**20.6**, 0.01	8.16	7.23	1.89
Horizontal velocity at release				
V1	**65.61**, 0.13	**112.75**, 0.16	**12.51**, 0.04	**31.91**, 0.02
V2	**203.96**, 0.39	**123.29**, 0.16	**41.68**, 0.15	**1182.73**, 0.79
Vertical velocity at release				
V1	**37.04**, 0.02	**21.88**, 0.01	1.73	**43.02**, 0.01
V2	**50.59**, 0.03	**450.83**, 0.2	**597.80**, 0.25	**1091.13**, 0.26
Movement path during closure				
V1	**81.69**, 0.03	**70.33**, 0.05	**10.62**, 0.01	**76.88**, 0.02
V2	3.27	**47.71**, 0.03	**35.29**, 0.001	**97.15**, 0.03

IV. DISCUSSION

The present results are compatible with the idea of a virtual target for the tongue in making a stop closure. Similar to the lips for a bilabial stop (Löfqvist and Gracco, 1997), the tongue can move at a high velocity at the onset of the oral closure for the stop. The resulting tissue compression thus makes the airtight seal during the closure. Such a control strategy would also ensure that the tongue will form an airtight seal irrespective of any contextual variability in the onset positions of its closing movements. Together with the results presented by Mooshammer *et al.* (1995) and Fuchs *et al.* (2001), the present findings thus suggest a virtual target for the tongue that would make it move into the nasal cavity. The velocity of both the tongue tip and tongue body at oral closure was closely related to the quality of the preceding vowel. In particular, it was very low when the preceding vowel was /i/, compared to /a/ and /u/. This variation is related to the fact that movement velocity scales with movement amplitude. Hence, the tongue has a longer distance to

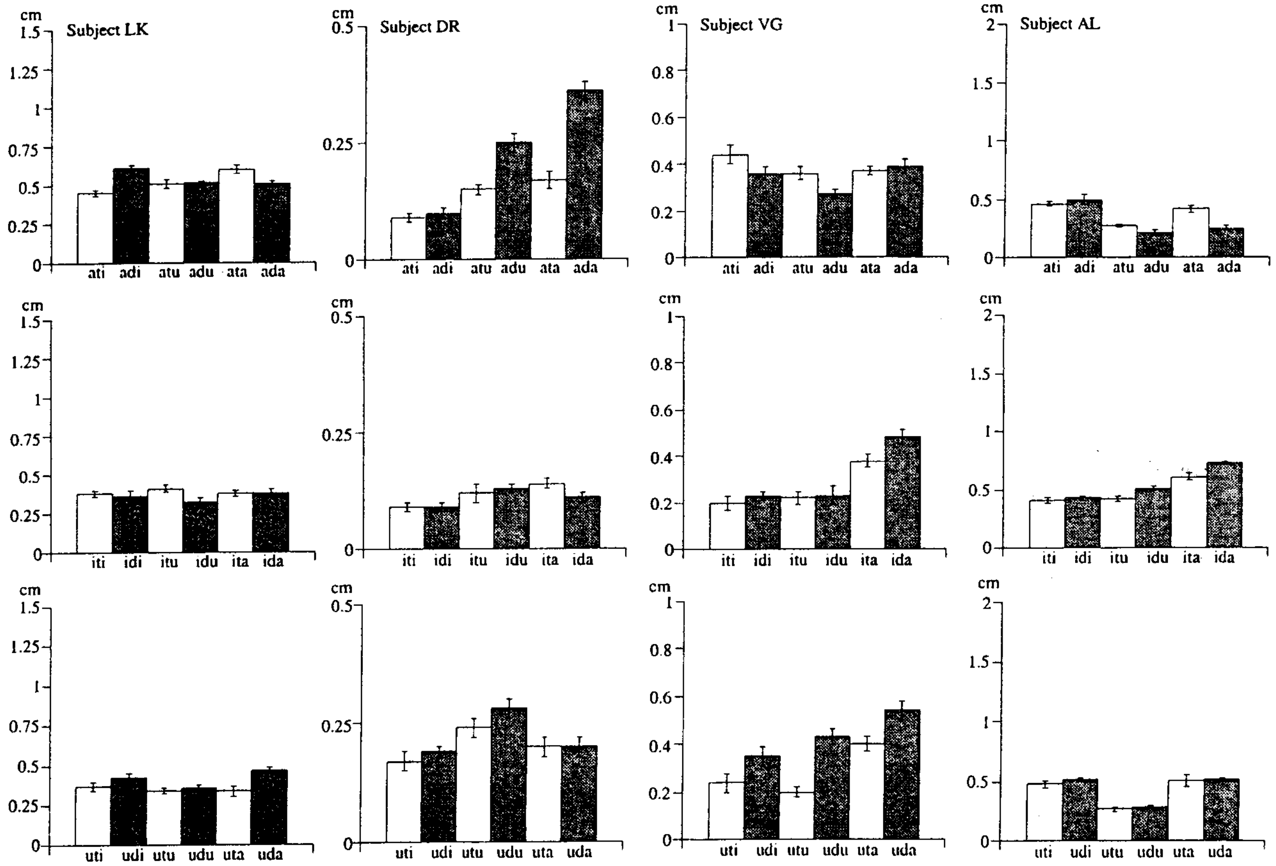

FIG. 11. Average movement path of the tongue tip receiver during the period of oral closure; the error bars show the standard deviation.

travel when the preceding vowel is /a/ or /u/. For the vowel /i/, the tongue is already raised in the oral cavity, however.

The tongue movement trajectories for subjects LK and DR shown in Fig. 3 illustrate a substantial individual difference in the trajectories for the alveolar stop occurring between the high vowels /i/ and /u/. Here, subject LK lowers the rear portion of the tongue for the production of the stop. No similar pattern was observed for the other subjects. In these productions of subject LK, the tongue seems to be pivoting around an imaginary axis located behind the tongue tip receiver. Similar pivoting patterns have been described by Stone (1990), who showed them to occur both in the longitudinal and transverse dimensions of the tongue. The nature of such individual differences is poorly understood at present. As we have argued before (Löfqvist and Gracco, 1997), if an articulatory pattern is to be maintained and transmitted across generations of speakers, the pattern would have to either be recoverable by auditory or audiovisual means, and/or follow from general principles of biomechanics and motor control. Since most differences in tongue movements between subjects LK and DR in Fig. 3 occur during the oral closure, the movements may not produce audible effects and hence the variability may be random.

In producing a stop consonant, one task of the speaker is to make a momentary closure in the vocal tract. This closure

TABLE III. VCV sequences and articulatory intervals where the tongue movement path occupied more than 50% of the whole path from the first to the second vowel. For sequences with the velar stop /g/, the movement is that of the tongue body receiver, while for the sequences with an alveolar stop /d/, the movement is that of the tongue tip receiver.

Interval	LK	DR	VG	AL
From first vowel to closure		aki, agi, ati, atu, uti, adi ada, udi	aki, agi, agu, ati, atu, adi adu	aki, agi, ati, uti, adi, ada, adu, udi
Oral closure	aki, agi			uki, uka, ugi
Release to onset of second vowel	ika, uka	iki, iku, itu	iki, iku	
During second vowel	iga, igu, aga, uga, ida, ada, uda	ika, iga, igu, uga, ugu, ita, ida, idu, uda	iga, igu	idu

allows for a build-up of oral air pressure that drives the transient noise source at the release of the oral closure. In the present study, all the stops were produced with an oral closure, based on acoustic analyses, which may not be the case in normal running speech (cf. Crystal and House, 1988). The present results are compatible with the assumption that as long as the closure is maintained, the articulators can move. In the bilabial stops studied by Löfqvist and Gracco (1997), the lower lip was moving vertically during the closure. The present results show that movements during the closure also occur for an articulator that is directly involved in making the oral closure such as the tongue tip and the tongue body. As long as the closure is maintained, the tongue can slide along the palate. The amount of tongue movement during the closure was heavily influenced by vowel context, in particular for the velar stops, cf. Figs. 8 and 11. The path of the tongue tip was generally shorter than that of the tongue body during the consonant closure. The velocity of the tongue tip and tongue body at the onset of the oral closure did not show any consistent pattern across or within subjects. Thus, it was not the case that the velocity of one of them was always greater than that of the other.

As expected, more than 50% of the whole tongue movement trajectory from the first to the second vowel only occurred during the closure in a few sequences with a velar stop, as shown in Table III. This is contrast to what happens in a VCV sequence with a bilabial stops where commonly more than 50% of the trajectory from vowel to vowel occurs during the bilabial closure (Löfqvist and Gracco, 1999).

The tongue movement observed during the stop closure suggests that it is appropriate to view the "target" in lingual stop production as making a vocal tract closure. Given the magnitude of the tongue movement during the closure, it would appear to be actively controlled and not only due to biomechanical and/or aerodynamic factors. The best way of describing the patterns of tongue movements observed in this and other studies is that of a curved trajectory between the two vowels. This is the case for both the tongue body and the tongue tip. The direction of this movement is predominantly forward–backward, with its speed and amplitude modulated by the vowel context. The results of the statistical analyses revealed strong influences from both the preceding and following vowels. We should add that the present data on tongue movements include the contribution of the jaw. It is unlikely, however, that representing the tongue movements in a mandible-based coordinate system would significantly alter the trajectories, as shown by the different coordinate systems used in the study by Munhall *et al.* (1991).

The present results show that at the instant of the acoustically defined oral closure for a velar stop the tongue body is moving forward in the majority of cases. Also for the alveolar stop, the tongue tip is moving forward at the oral closure. Such a forward tongue body movement for a velar stop consonant can also occur when the vowel preceding the stop is the front vowel /i/ and the vowel following the stop is a back vowel /a, u/, although this only consistently occurred for subject LK. One implication of this is that the tongue is not necessarily moving along a path that might be considered to be the most direct one. This is most likely related to the fact that the tongue movement for a sequence of a vowel, a velar stop consonant, and a vowel does not follow a straight path, but a curved one. That is, even in the case when the vowels before and after the consonant are identical, such as the back vowel /a/, the tongue does not stop during the closure and then return to the low back position for the second vowel. Such a looping pattern appears to be the most common one, but a generally accepted explanation for it has not been put forward. Mooshammer *et al.* (1995) present an extensive discussion of some of the proposed explanations. One of these suggests that the forward movement is made to help sustain voicing in voiced stops by expanding the cavity behind the closure. The problem with this suggestion is that the same movement pattern is also found for voiceless stops. Another explanation proposes that the build-up of air pressure behind the closure is a contributing factor. Hoole *et al.* (1998) specifically examined the role of aerodynamic factors in explaining tongue movement trajectories. They thus had speakers produce speech with the normal egressive air flow and also with an ingressive air flow. Their results showed that the magnitude of the tongue movement during the closure was reduced when speakers spoke on inhalation. However, there was no reversal in the commonly observed forward movement during the stop closure in the egressive condition. Hence, aerodynamic factors alone do not explain the movement patterns. In addition, a recent simulation experiment by Perrier *et al.* (2000) suggested that the influence of air pressure and flow on tongue movements is limited and may only play a role in a sequence like /ika/, where the tongue body is raised towards the palate for the vowel, cf. Fig. 6. Based on simulations using a tongue model, Perrier *et al.* (1998) argue that the movement pattern of the tongue is due, at least in part, to biomechanical factors. One problem with this suggestion is that in another very basic tongue function, i.e., swallowing, the movement pattern of the tongue is the opposite of the one observed in speech. In the oral part of swallowing, the tongue is moving backward in contact with the palate to move the bolus into the pharynx (e.g., Logeman, 1995). In addition, tongue movements during speech can go in the direction opposite to the one observed here for the VCV sequences with lingual consonants. That is, the case in VCV sequences with a labial consonant, where the tongue movement is made from the first to the second vowel in the sequence (e.g., Löfqvist and Gracco, 1999). It is thus not clear that the biomechanics of the tongue muscles can explain the commonly observed forward–backward curved path of the tongue in speech.

Since none of these explanations is entirely satisfactory in itself, we should perhaps view the movement pattern observed for the tongue in stop production as an example of a more general principle of motor control. Such principle could be based on a cost minimization, often expressed as a minimum jerk criterion (Flash, 1987; Flash and Hogan, 1985) or as a smoothness constraint (Uno *et al.*, 1989). The development of this principle has been based on studies of reaching movements of the hand. In a reaching task where the hand has to move through a sequence of target positions, the hand moves in a curved path between the targets. The observed hand trajectory could be accurately modeled based on such a cost minimization function. In the case of tongue movements, a similar principle may thus explain why in a sequence such as /aka/ the tongue moves in a loop and not in a straight line from the first vowel to the consonant closure and then returns along a similar straight-line path. Such a movement pattern would involve successive accelerations and decelerations of the tongue that might involve a higher effort. In the production of /iku/ with a very high curvature value of subject DR, the velocity of the tongue body is very small, as shown in Fig. 7(b). This idea is also compatible with a continuous tongue movement during the stop closure, since the tongue maintains contact with the palate during its movement. In this view, the whole trajectory from the first to the second vowel is planned and there is no point target for the tongue during the stop. Biomechanical models of the tongue (e.g. Sanguineti *et al.*, 1998) could be used to explore this idea. The present results are also useful in constraining the movement trajectories that such models will have to generate. In addition, the development of speech motor control might provide further insights, since the subjects examined in this and other studies of speech movement kinematics have all been beyond childhood, and their speech movement patterns are thus well established.

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