



# Lip and Jaw Kinematics in Bilabial Stop Consonant Production

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This paper reports two experiments, each designed to clarify different aspects of bilabial stop consonant production. The first one examined events during the labial closure using kinematic recordings in combination with records of oral air pressure and force of labial contact. The results of this experiment suggested that the lips were moving at a high velocity when the oral closure occurred. They also indicated mechanical interactions between the lips during the closure, including tissue compression and the lower lip moving the upper lip upward. The second experiment studied patterns of upper and lower lip interactions, movement variability within and across speakers, and the effects on lip and jaw kinematics of stop consonant voicing and vowel context. Again, the results showed that the lips were moving at a high velocity at the onset of the oral closure. No consistent influences of stop consonant voicing were observed on lip and jaw kinematics in five subjects, nor on a derived measure of lip aperture. The overall results are compatible with the hypothesis that one target for the lips in bilabial stop production is a region of negative lip aperture. A negative lip aperture implies that to reach their virtual target, the lips would have to move beyond each other. Such a control strategy would ensure that the lips will form an air tight seal irrespective of any contextual variability in the onset positions of their closing movements.

**KEY WORDS:** speech motor control, lip kinematics, jaw kinematics

The purpose of this study is to make a detailed examination of lip and jaw kinematics in the production of bilabial stop consonants, with particular emphasis on events before, during, and after the oral closure. A large number of productions were recorded in several subjects to examine inter- and intrasubject variability. The influences of stop consonant voicing and vowel environment on movement kinematics are evaluated. Although lip and jaw kinematics have been quite extensively studied for this class of sounds, earlier studies have often been limited to one or two articulators, and the recordings have not been made in a well-defined coordinate system standardized across subjects.

The influence of stop consonant voicing on acoustic properties and articulatory movements has been under study for many years. At the acoustic level, some differences between voiced and voiceless consonants have been reported (e.g., Slis & Cohen, 1969a,b). For example, the closure or constriction duration for stops and fricatives is often longer for the voiceless cognates, although the magnitude of the difference varies with stress and may be reduced, or not present, in connected speech (Crystal & House, 1988a,b). The acoustic duration of a vowel tends to be longer when it is followed by a voiced stop or fricative (e.g., Chen, 1970; Crystal & House, 1988b). The fundamental frequency at the onset of a vowel following a voiceless stop or fricative is usually higher than when

the preceding consonant is voiced (e.g., Löfqvist, Baer, McGarr, & Story, 1989). Although some of these acoustic differences between voiced and voiceless consonants tend to be quite robust, studies of oral articulatory kinematics for these consonants have not shown the same clear results.

Articulatory velocities of the closing movements for bilabial stops have often been reported to be higher for voiceless than for voiced stops (Caldognetto, Vagges, Ferrigno, & Zmarich, 1993; Chen, 1970; Fujimura & Miller, 1979; Gracco, 1994; Summers, 1987; Sussman, MacNeilage, & Hanson, 1973). Chen (1970) also showed that the duration of the lower lip closing movement towards consonantal closure for a bilabial stop was longer for a voiced than for a voiceless stop. However, these kinematic differences are not as robust as they might appear. For example, Sussman et al. (1973) found higher closing velocity of the jaw only for the voiceless consonant, whereas the lower lip closing velocity was higher for the voiced cognate. Only by combining the lower lip and the jaw velocities did Sussman et al. (1973) find higher closing velocity for the voiceless consonant, but they apparently did the combination in the counter-intuitive way of adding the jaw signal to the lower lip signal already containing the contribution from the jaw. At the same time, Sussman et al. found the closing velocity of the upper lip to be higher for /p/ than for /b/. The results presented by Summers (1987) showed that bilabial stop consonant voicing influenced both the jaw lowering and the jaw raising movements during a preceding vowel. Jaw lowering velocity and amplitude were higher when the following stop was voiceless. Similarly, jaw raising velocity was higher for voiceless stops, whereas the duration of the raising gesture was longer for voiced stops. Gracco (1994) reported no consistent differences in jaw, lower lip, and upper lip opening movement amplitudes for vowels preceding voiced and voiceless bilabial stop consonants. Lip and jaw closing movements for bilabial stops were not consistently affected by stop consonant voicing. Movement kinematics at the bilabial stop release have also been studied. Sussman et al. (1973) found no consistent differences between voiced and voiceless bilabial stops for either lip or jaw movements, whereas Gracco (1994) reported lower peak velocity for the lips at the release of voiceless stops.

The results of these studies suggest that kinematic differences between voiced and voiceless labial consonants are inconsistent, whereas movement durations appear to be longer for voiced consonants. Differences in movement velocity between voiced and voiceless consonants do not appear in all the articulators, jaw, upper and lower lip, that are involved in the formation of the bilabial closure. For example, Smith and McLean-Muse (1987) found that the net lower lip closing velocity (i.e., without the jaw component) was higher for /p/ than for

/b/ in speakers of different age. However, Smith and McLean-Muse (1986) reported the opposite for the lower lip closing velocity with the jaw component left in. These findings would seem to cast doubt on functional interpretations of such velocity differences, usually expressed with reference to the higher oral air pressure commonly observed for voiceless consonants (e.g., Arkebauer, Hixon, & Hardy, 1967). Finally, there is a potentially confounding factor that has to be taken into account. Peak velocity of movement has been found to scale with movement amplitude for both speech and nonspeech movements. Thus, the relationship between stop consonant voicing and movement velocity may be related to variations in movement amplitude rather than to consonant voicing per se. Studies of tongue movements in stop consonant production (Kent & Moll, 1969; Löfqvist & Gracco, 1994, 1995; Ostry, Keller, & Parush, 1983; Parush, Ostry, & Munhall, 1983) have shown that the velocity of the closing movement may be higher for the voiced cognate. The results presented by Löfqvist and Gracco (1994, 1995) indicated that in these instances there was also a difference in movement amplitude.

Jaw movements are influenced by vowel characteristics. Jaw position is usually higher for the high vowels /i, u/ than for the low vowel /a/ (e.g., Edwards, 1985; Gay, 1977; Macchi, 1985; Oshima & Gracco, 1992; Perkell, 1969; Schulman, 1989; Sussman et al., 1973). In a  $V_1pV_2$  sequence where the first vowel is /a/ and the second vowel one of /i/ or /u/, the jaw position at the bilabial closure for the medial consonant can be lower preceding the /a/ than the /i/ (cf. Gay, 1974; Macchi, 1988). If the jaw position at the closure for a bilabial stop differs as a function of vowel context, it is possible that the lower lip and/or the upper lip show concomitant variations to offset the changes in the jaw position. The results presented by Sussman et al. (1973) and by Macchi (1988) suggest that this can be the case.

This paper reports two experiments, each designed to clarify different aspects of bilabial stop consonant production. The first one examined events during the labial closure using kinematic recordings in combination with records of oral air pressure and force of labial contact. The results of this experiment allowed an understanding of lip kinematics and lip interactions during the closure that was applied in the analysis of the second experiment, which studied patterns of lip movements and the effects on lip and jaw kinematics of stop consonant voicing and vowel context.

## Methods

### General Procedures

The movement and acoustic recordings in the two experiments were carried out using the same techniques.

The movements of the lips and the jaw were recorded using a three-transmitter magnetometer system (Perkell et al., 1992). Receivers were placed on the upper and lower lips and on the lower incisors. The lip receivers were placed below and above the vermilion border of the upper and lower lip, respectively, with a vertical separation of approximately 1 cm when the lips were in a closed position. Two additional receivers placed on the nose and the upper incisors were used for the correction of head movements. All receivers were attached using Iso-Dent (Ellman International). 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. To obtain instantaneous velocity, the first derivative of the position signals was calculated using a 3-point central difference algorithm. The velocity signals were smoothed using the same triangular window. A measure of lip aperture was obtained by subtracting the vertical position of the lower lip receiver from that of the upper lip receiver. All the signal processing was made using the Haskins Analysis Display and Experiment System (HADES; Rubin & Löfqvist, in press). The acoustic signal was pre-emphasized, low-pass filtered at 9.5 kHz, and sampled at 20 kHz.

The kinematic signals represent the movements of receivers placed at the midline of the lips and the jaw. When presenting the results, we will use the terms "lower lip receiver" and "lower lip" 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 parts of the lips during closure and release.

## Subjects

Three women (DB, LK, NSM) and two men (VG, AL) participated. All subjects had normal speech and hearing and no history of speech or hearing disorders. Four of the subjects (DB, LK, NSM, VG) are native speakers of American English. Speaker AL is a native speaker of Swedish and is also fluent in English. Subjects VG and AL are the two authors.

## Experiment 1: Kinematic Events During the Stop Closure

The purpose of this experiment was to examine labial kinematics during the stop closure in order to develop an understanding of possible interactions between the upper and lower lips; such an understanding is necessary for the analysis of the movement patterns in Experiment 2. To understand any interactions between the lips, it is necessary to know when the lip closure occurs, when it begins, and when it ends. Its onset and offset cannot be reliably identified from the kinematic signals alone. Therefore, part of this experiment was conducted on one subject with simultaneous recordings of articulator movement, labial contact force, and oral air pressure.<sup>1</sup> In another part of this experiment, two receivers were placed on the upper and lower lips in order to examine how different parts of the lips move during the closure.

## Procedure

Lip and jaw movements and an acoustic recording were obtained as described above. In addition, a small (1 mm thick, 8 mm diameter) miniature pressure transducer (Precision Measurement Co., model 105), with a frequency response of DC-3 kHz and temperature compensation, was attached to the lower lip with dental adhesive. Oral air pressure was recorded using a catheter tip transducer (Millar SPC-350) with a frequency response of DC-2 kHz. It was introduced through the nose, with the tip in the pharyngeal cavity. The contact pressure and the air pressure signals were sampled at 625 Hz after low-pass filtering at 300 Hz. The contact signal was further low-pass filtered using a 25-point triangular window with a 3-dB cutoff at 17 Hz.

Only subject AL participated in this recording. The linguistic material consisted of  $V_1CV_2$  sequences, where the first vowel ( $V_1$ ) was always /a/, the consonant (C) one of /p, b/, 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. Twelve repetitions of each sequence were obtained.

To further examine the movement patterns of different parts of the lips, a separate recording was made

<sup>1</sup>We acknowledge that the exact instance of oral closure cannot be identified in the oral pressure signal. One reason is that the pressure begins to rise before the closure has occurred (cf. Müller & Brown, 1980). A second reason is that in voiceless stops, the initial increase in oral pressure can be caused by the glottal opening starting before the closure has occurred (cf. Löfqvist & McGowan, 1992; Koenig, Löfqvist, Gracco, & McGowan, 1995). In Experiment 2, only the acoustic signal was used to estimate oral closure and release, because the experimental procedure was simplified by excluding the pressure recording.

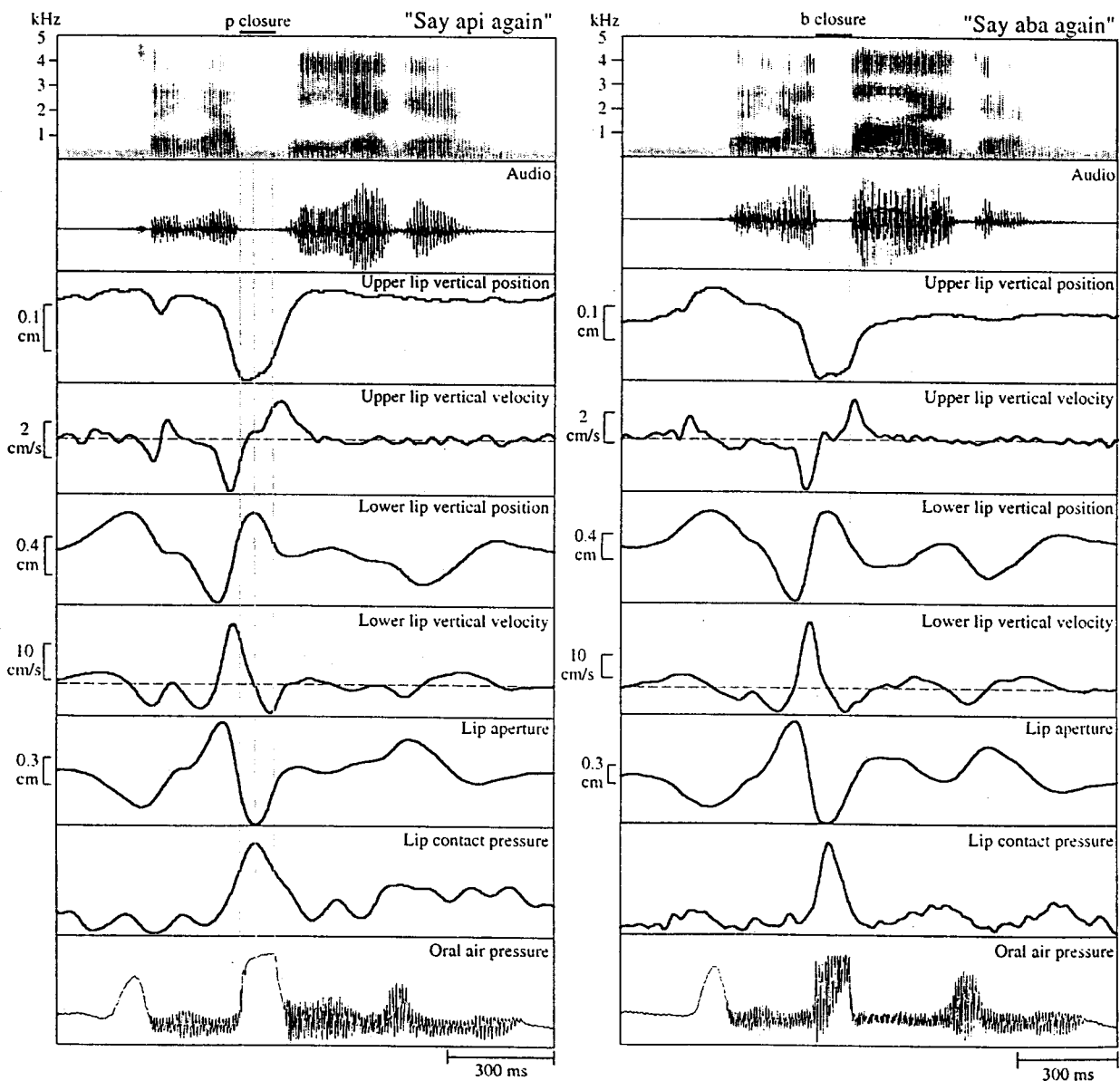
of one subject (VG) with two receivers placed on the upper and lower lips. Receivers were placed above and below the vermillion border of the lips.

## Results

We will examine selected productions for which the force of labial contact and the oral air pressure were recorded with the movement signals. The left panel of Figure 1 presents the acoustic signal, the vertical position

and velocity of the upper and lower lips, the lip aperture signal, the labial contact pressure, and the oral air pressure for one token of the utterance "Say api again." The three vertical lines in the panel correspond to the following events (from left to right): onset of oral air pressure rise for the labial stop /p/; peak labial contact pressure; release of the oral closure for the stop. The first event was identified as the point in time when the oral air pressure started to rise and the amplitude of the acoustic signal decreased. The third event was identified as the point in time when the oral pressure

**Figure 1.** Kinematic, acoustic, and aerodynamic signals during the production of the utterance "Say api again" (left) and "Say aba again" (right). The three vertical lines correspond to the following events from left to right: Onset of oral closure defined from the acoustic and pressure signals. Peak force of labial contact. Release of the oral closure defined from the acoustic and pressure signals.



started to fall and the release burst was evident in the acoustic signal.

An inspection of the left panel in Figure 1 reveals the following sequence of events between the onset and the offset of the acoustically and aerodynamically defined closure for the labial stop /p/. When the oral air pressure first rises from the baseline (the first vertical line), the upper lip is moving down, while the lower lip is moving up. This is evident from the velocity signals. In fact, at the instant of oral pressure rise, the velocity of the lower lip is close to its peak velocity. The lower lip continues its upward movement until the point of peak force of labial contact (second vertical line); at this point, the derived lip aperture signal is at its minimum value. (We should add that the actual lip aperture is at zero throughout the oral closure. The lip aperture signal changes during the closure because it represents the vertical distance between the receivers on the upper and lower lips, and these receivers move during the closure.) During the interval between oral closure and peak force of labial contact, the upper lip reaches its lowest position and begins to move upward (zero crossing in upper lip velocity signal). At the instant of peak force of labial contact, the lower lip reaches its highest position and starts to move down (zero crossing in lower lip velocity signal). At the same point, there is an inflection in the upper lip velocity signal, suggesting a momentary slowing down of the upper lip raising movement. At the instant of the release of the oral pressure (third vertical line), both lips have moved a considerable distance. Note that the peak velocity of the downward movement of the lower lip occurs before the oral release, whereas the peak velocity of the upper lip occurs after the release.

The right panel in Figure 1 shows the same signals recorded during a sequence with a voiced bilabial stop "aba." The sequence of events is similar to the one shown for the sequence "api." Note, however, that in "aba" the upper lip raising movement is interrupted at the time of peak labial contact and reversed. This can be seen in the upper lip velocity signal, where a zero crossing occurs at the point of peak labial contact and another one shortly afterwards.

We turn next to the recordings made with two receivers on the upper and lower lips. The left panel in Figure 2 shows the vertical and horizontal trajectories of two receivers on the upper and lower lips during the sequence /æpæ/. The movements of the two receivers that are closest together show a similar trajectory during the last part of the upward and forward movement and during the first part of the downward and rearward movement. This pattern suggests that the lower lip may be pushing the upper lip upwards during part of the closure. Because there is no temporal information shown in the left panel of Figure 2, the movements of the four

receivers on the lips are also plotted in the right panel of Figure 2, together with the audio signal and the tangential velocity [ $v = \sqrt{(\dot{x}^2 + \dot{y}^2)}$ ] of the receivers placed on the inferior surface of the upper lip and the superior surface of the lower lip. The vertical line in the right panel indicates the lowest vertical position of the upper lip receiver. At this point, the lower lip is moving upward at a maximum of tangential velocity. Note, in particular, that the upper lip changes its direction of movement at this point and begins to move upward.

The right panel of Figure 2 also shows the vertical position of all four lip receivers. The amplitude of the raising movement of the upper lip during the first part of the oral closure for the stop consonant differs between the two receivers placed on the upper lip. It is larger for the one placed on the inferior surface of the upper lip.

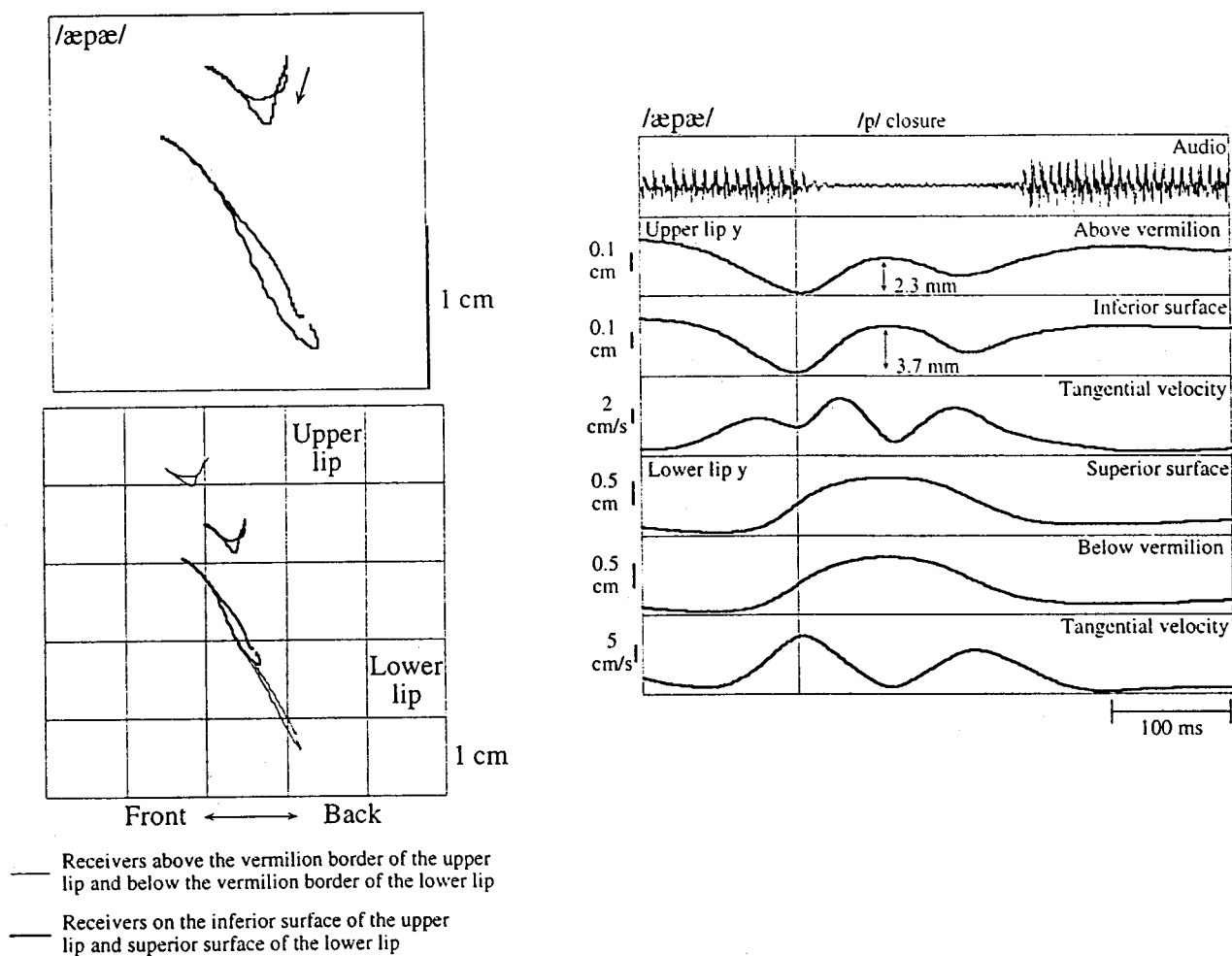
## Discussion

The patterns of the force of labial contact shown in Figure 1 are similar to the ones presented by Lubker and Parris (1970), Hinton (1996), and by Hinton and Luschi (1992). In particular, the force of labial contact is changing continuously during the stop closure. These data also suggest that the lips have a high velocity at the time of oral closure. Because the receiver on the lower lip continues its upward movement after the instant of oral closure, it is possible that the lip tissues compress up to the point of peak force of labial contact, as suggested by the high-speed film data presented by Fujimura (1961). Compression could explain why the receiver placed on the lower lip is moving upward after the closure has occurred and also the difference in the amplitude of the movements of the two receivers placed on different positions on the upper lip. Moreover, the present results also suggest that the lower lip may be pushing the upper lip upward after the onset of closure. Although one might argue that the presence of the force transducer and the receivers on the inferior and superior surface of the upper and lower lip could induce an unnatural mechanical effect on the lip movements, the results presented in Experiment 2 show that similar movement patterns occur under more normal speaking conditions—that is, without the force transducer and with only a single receiver on each lip.

## Experiment 2: Labial and Mandibular Kinematics in Stop Production

Experiment 2 quantitatively evaluated lip and jaw kinematics as a function of stop consonant voicing and vowel context. Another purpose was to examine in more

**Figure 2.** The left panels show the trajectories of two receivers placed on the upper lip and two receivers placed on the lower lip during the sequence /æpæ/. The top panel shows in more detail the trajectories of the receivers on the inferior surface of the upper lip and the superior surface of the lower lip; the arrow points in the direction of the upper lip trajectory. The right panel shows the audio signal and the vertical position of two receivers placed on different locations on the upper lip, the tangential velocity of a receiver placed on the inferior surface of the upper lip, the vertical position of two receivers placed on different locations on the lower lip, and the tangential velocity of a receiver placed on the superior surface of the lower lip.



detail the nature of lip interactions during the closure and movement variability within and across speakers by recording a large number of productions.

## Procedure

The movement and acoustic recordings were made as described above. All five subjects participated. The linguistic material consisted of  $V_1CV_2$  sequences, where the first vowel ( $V_1$ ) was always /a/, the consonant (C) one of /p, b/, 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. Fifty repetitions of each sequence were recorded.

The vertical movements into and out of the oral closure were measured. Movement onsets and offsets were identified algorithmically from zero crossings in the velocity signals of the lips and the jaw. Receiver positions were measured at movement onset and offset. Movement amplitude and duration were calculated between the onsets and the offsets. The peak velocity of the movement was also identified algorithmically and measured. Signal averages were obtained using the acoustic onset of lip closure, identified from spectrogram and waveform displays, as the line-up point.

The identification of zero crossings in the upper lip velocity signal presented some problems. As discussed above and shown in Figure 1 (right), the upper lip velocity signal sometimes showed two "extra" zero crossings during the interval of oral closure. An examination

of the upper lip signals for all tokens revealed that they could be classified into three different categories, on the basis of the pattern of velocity changes around the interval of oral closure. Examples of these patterns from the productions of the sequence /aba/ by subject LK are shown in Figure 3. The top panel shows a momentary decrease of the upper lip vertical velocity, so that there are two maxima in the signal around the oral closure. The middle panel shows a reversal in the sign of the upper lip vertical velocity, so that there are, again, two maxima in the signal around the closure but also two zero crossings. Finally, the bottom panel of Figure 3 shows a case where there is a single maximum in the upper lip vertical velocity. Based on the results of Experiment 1 and to maintain consistency in the measurements, the zero crossing and the velocity peak labeled by Z and P, respectively, were used for measurements. The zero crossing (Z) was used to determine the vertical position of the upper lip at the offset of the lowering movement. The label at the velocity peak (P) was used for measuring the peak velocity of the upper lip raising movement, even though the first velocity peak in the movements of categories 1 and 2 was sometimes higher.

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. Measurements of closure duration and of receiver positions and velocities at these two points in time were made. All measurements were made by the first author. An analysis of variance with stop consonant voicing and the identity of the second vowel in the sequence as the main factors were used for statistical analysis. The degrees of freedom for the analysis of variance are 1,294 for voicing and 2,294 for vowel and interaction. Protected *t* tests (Bonferroni procedure) were applied to examine differences. A *p* value of  $\leq 0.05$  was adopted as significant. Given the large number of degrees of freedom,  $\eta^2$  values showing the variation accounted for are also reported (cf. Young, 1993).

## Results

Plots of the average vertical and horizontal positions of the lip and the jaw receivers are shown in Figure 4 for all five subjects and utterances with a voiceless stop. For all subjects except AL, the vertical component of the lip and jaw movements is much larger than the horizontal one. The jaw movements for all subjects follow straight-line trajectories. Subjects LK, NSM, VG, and AL showed a clear difference in the horizontal movement of the upper and lower lips between the rounded vowel /u/ and the two other vowels /i, a/. Subject DB

showed almost no lip protrusion for the rounded vowel, however—possibly as a result of her California dialect (cf. Labov, 1991; Youmans, 1993). Because of space limitations, the presentation of the results will focus on some salient features. A more comprehensive presentation of the results can be obtained from the authors.

## Acoustic Measurements

One subject (DB) showed a reliably longer closure duration for the voiceless than for the voiced stop ( $F = 52.67$ ,  $\eta^2 = 0.15$ ) and also a significant vowel effect with no interaction [ $F = 3.04$  ( $\eta^2 = 0.02$ ) and 0.6]. Subjects LK, NSM, and VG showed a reliable effect of voicing with a longer closure duration for the voiced stop ( $F = 46.05$ , 45.05, and 8.65 for LK, NSM, and VG, respectively;  $\eta^2 = 0.11$ , 0.13, 0.02). Subjects LK and VG showed a reliable effect of vowel quality ( $F = 44.09$  and 55.75,  $\eta^2 = 0.21$ , 0.27), with no interaction ( $F = 1.27$  and 0.79). For subject NSM, the vowel effect was not significant ( $F = 0.68$ ) with an interaction ( $F = 8.97$ ,  $\eta^2 = 0.05$ ). Subject AL showed no effect of voicing ( $F = 0.01$ ), a significant effect of vowel ( $F = 26.10$ ,  $\eta^2 = 0.14$ ), with an interaction ( $F = 13.77$ ,  $\eta^2 = 0.08$ ). For those subjects who showed an effect of vowel quality, it was always the case that the closure duration was shorter when the second vowel was /a/. However, the differences associated with consonant voicing and the quality of the second vowel were small and generally less than 10 ms; the  $\eta^2$  values are also small.

## Jaw Movements

Signal averages of vertical jaw position and velocity are presented in Figure 5. Of note is that the organization of jaw movements differs across subjects according to the second vowel. Although all subjects show a raising and lowering pattern for the sequence with /a/ as the second vowel, the movements for the sequences with the high vowels /i, u/ are organized differently. Three of the subjects, DB, NSM, and AL, show a distinct lowering movement for the release of the consonant and/or the second vowel. This can be most clearly seen in the velocity signals for DB, NSM, and AL in Figure 5, where there is a zero crossing approximately 60–75 ms following the peak velocity of the raising movement. For the other two subjects, LK and VG, the jaw shows a continuous raising movement from the first vowel, during the consonant closure, and to the second vowel when this is /i/ or /u/; this pattern is also found in subject NSM's productions of /abu/.

A closer examination of the jaw movements of all the productions revealed some within-subject variability. Subject DB produced 4% of all bilabial stop consonants followed by the vowel /u/ with a continuous movement,

**Figure 3.** Records of three productions of the utterance "Say aba again" by subject LK, showing three patterns of upper lip movements during the oral closure.

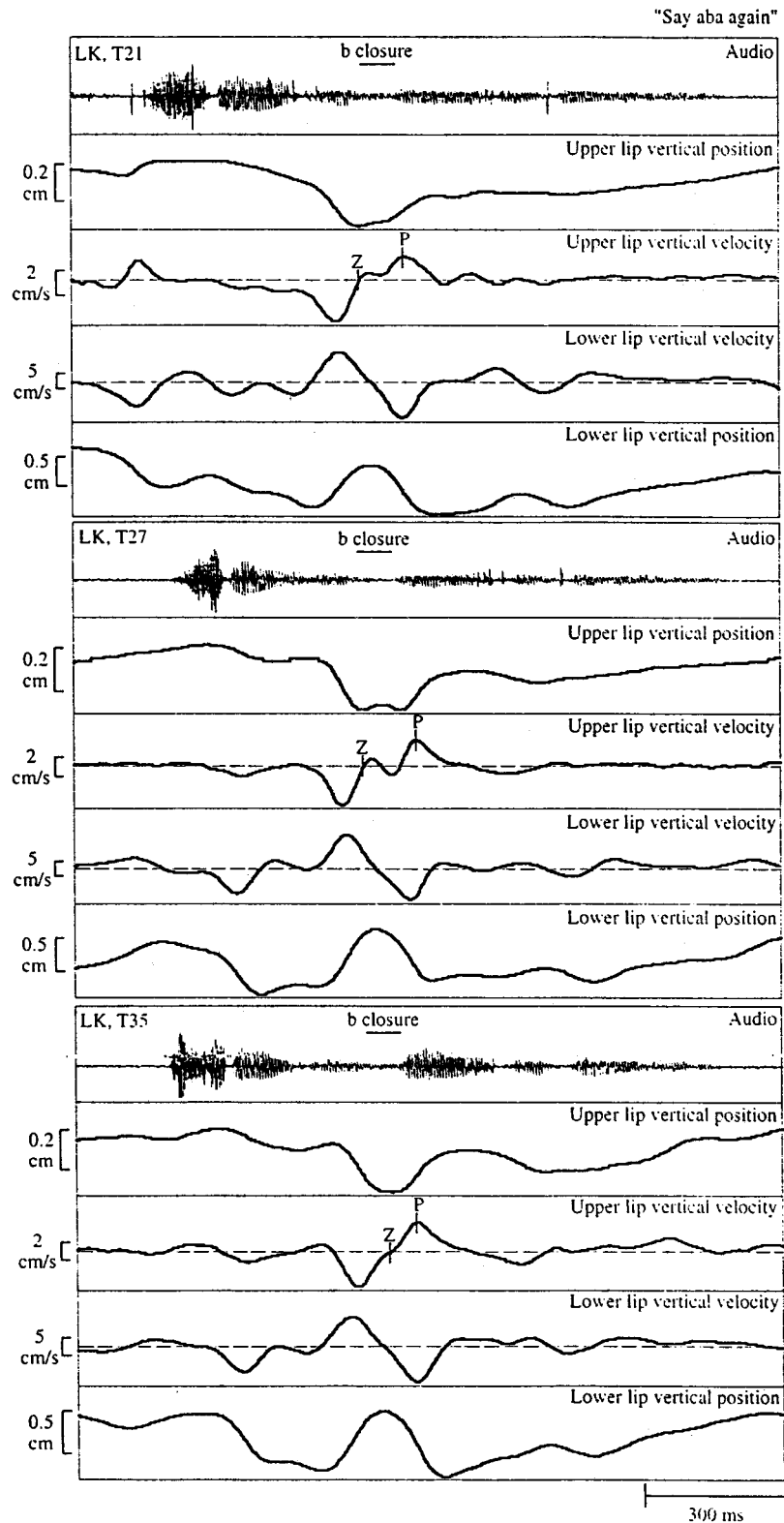
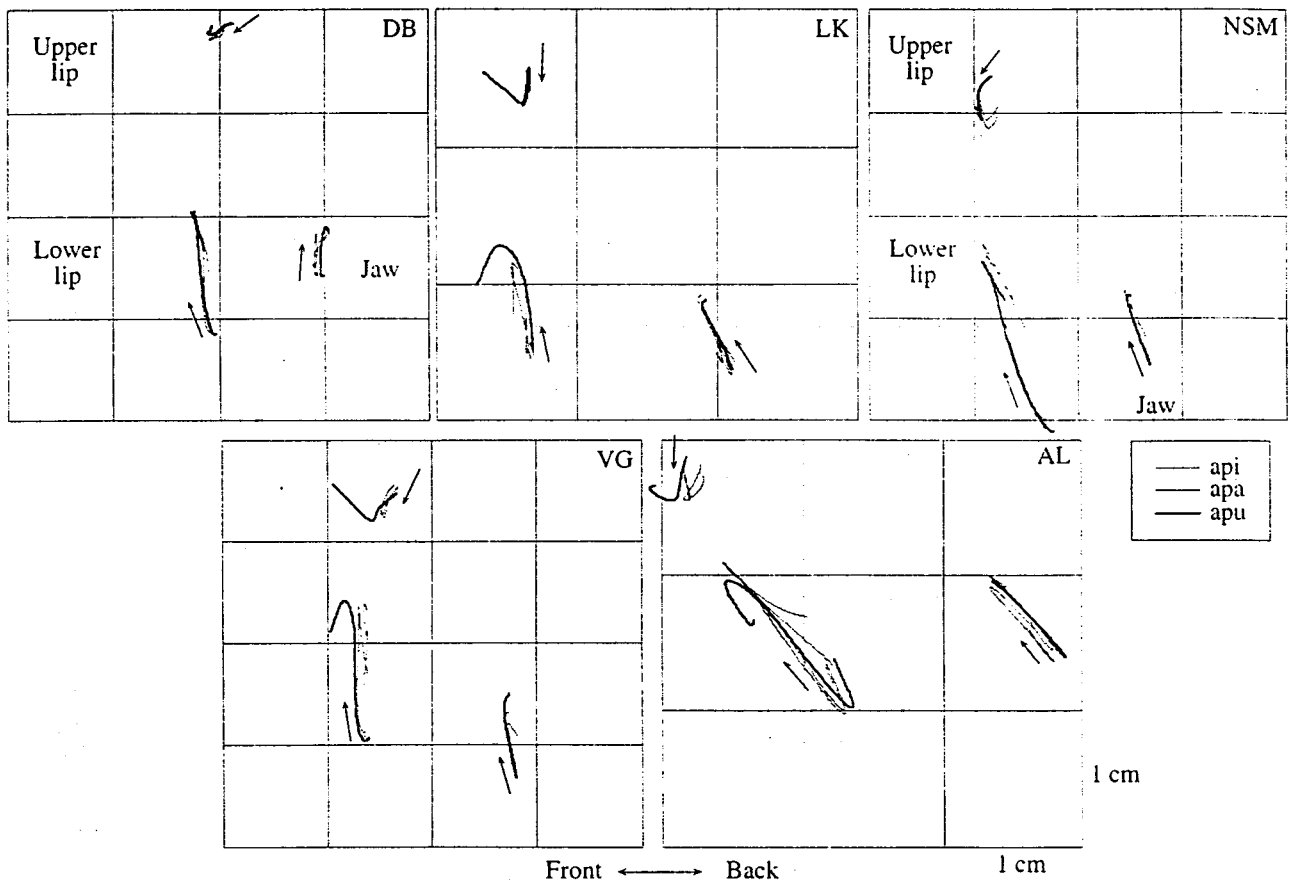




Figure 4. Average lip and jaw signals for all subjects and utterances with a voiceless stop. The arrow indicates the direction of the trajectory.



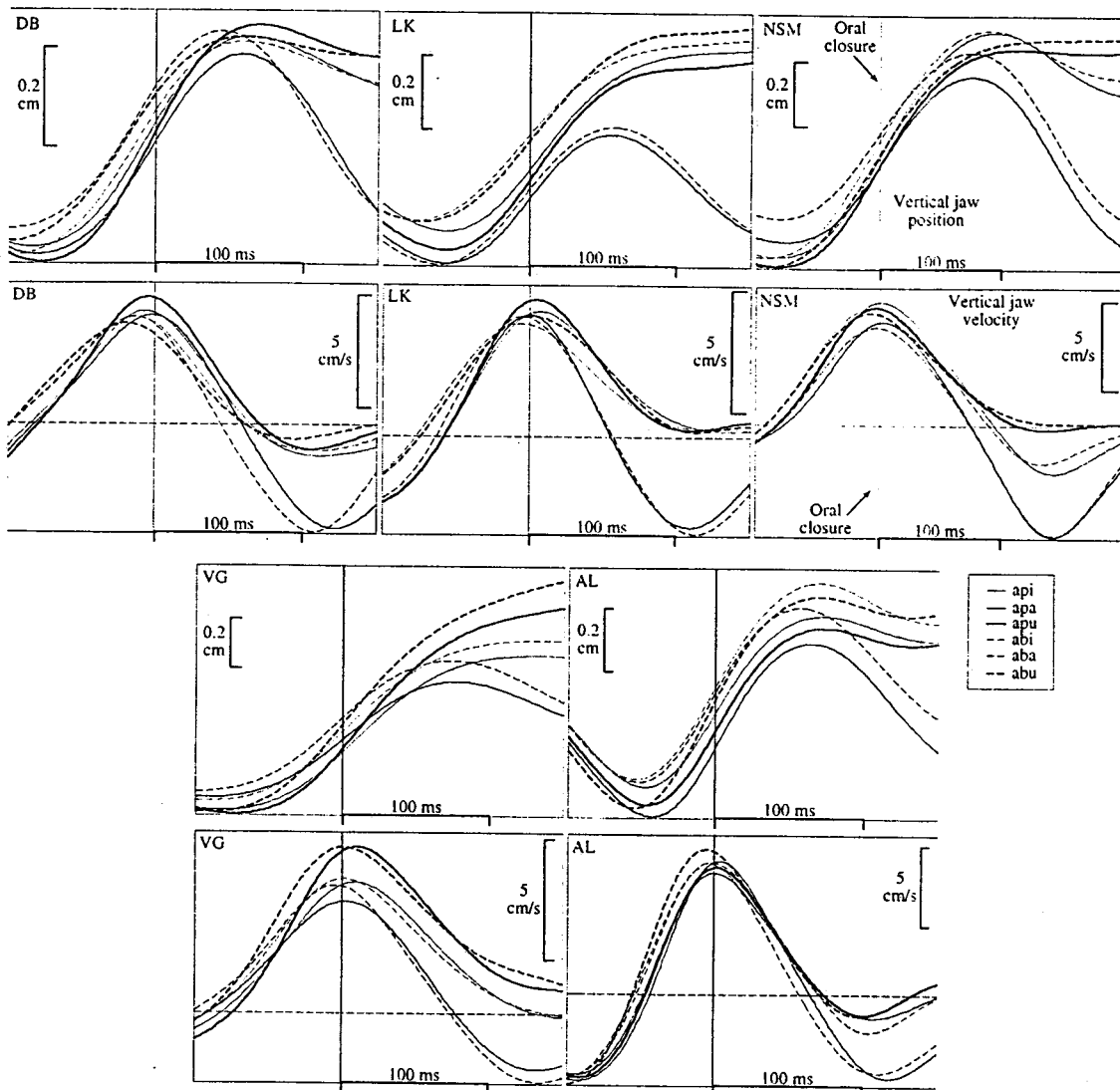
whereas the corresponding number for subject AL was 2%. Subject VG showed a continuous movement in 76% of his bilabial stops followed by the vowel /i/. For subject LK, a continuous movement occurred in 35% of the stops followed by /i/ and in 40% when followed by /u/.

The present results did not show any consistent influence of the second vowel, or of consonant voicing, on the jaw position at the onset of the raising movement for the consonant. It appears, however, that there is a difference in the timing of the raising movement of the jaw between voiced and voiceless consonants.<sup>2</sup> This is most clearly seen in the velocity signals of Figure 5. For all subjects, the zero crossing for the raising movement occurs earlier (15–20 ms) when the consonant is voiced (the dashed lines). One consequence of this difference in timing is that the jaw position is consistently 0.5 to 1 mm higher at the oral closure when the consonant is voiced. Voicing had a reliable influence on the jaw position at oral closure, with  $F$  values of 42.49 (DB), 30.14 (LK), 28.69 (NSM), 73.34 (VG), and 101.73 (AL); the corresponding  $\eta^2$  values were 0.12, 0.08, 0.09, 0.19, and 0.24.

The analysis of the closing and opening movements of the jaw was restricted to the three subjects (DB, NSM, and AL) who showed a closing-opening movement for the consonant. The peak velocity of the jaw closing movement did not show any systematic effect of the second vowel or consonant voicing. The highest position of the

<sup>2</sup>The nature of this timing difference is not clear at present. It could simply be a result of an inconsistency in the identification of the closure onset from the acoustic signal between voiced and voiceless stops. The identification of the closure onset was made from waveforms and spectrogram displays. The criterion used was the decrease in the amplitude of the waveform and the disappearance of the energy at higher frequencies. Because the glottis begins to open before the oral closure in a voiceless stop, the voice source changes into a breathy mode of phonation towards the end of a preceding vowel (cf. Löfqvist, Koenig, & McGowan, 1995). Such a mode of vibration is associated with a reduction in the energy of the source at higher frequencies. Thus, the onset of the closure might be marked earlier in a voiceless stop. We have checked the markings of the closure onset, and they appear to be consistent across voicing contexts. One other argument against the possibility of labeling error is that the magnitude of the timing difference in the jaw is in the order of 15–20 ms. This would cover 2–3 glottal periods for the men's voices and 3–4 glottal periods for the women's voices. Such a large inconsistency should be readily detected. In addition, a constant misidentification of the stop closure would most likely show a consistent effect of voicing on the velocity at oral closure, but none was found.

Figure 5. Average vertical jaw position and velocity for all subjects and utterances.



jaw during the closure for the consonant showed a reliable effect of the second vowel for subjects NSM and AL ( $F = 70.22$  and  $10.37$ ,  $\eta^2 = 0.3, 0.06$ ), with a lower jaw position when the upcoming vowel was /a/.

From the signal averages shown in Figure 5, it is evident that the vowel /a/ has a completely different influence on the jaw lowering movement than the vowels /i/ and /u/. The peak velocity and the displacement of the jaw lowering movement are consistently higher and larger for the vowel /a/. In addition, the jaw position during the /a/ vowel is lower than for the other two vowels. The analysis of variance showed the vowel effect to be reliable for the peak velocity with  $F$  values of 821.66,

1721.44, and 244.39 ( $\eta^2 = 0.84, 0.92, 0.61$ ) for subjects DB, NSM, and AL. In all cases, the peak velocity is higher for /a/ than for /i/ and /u/. The corresponding  $F$  values for the displacement were 179.17, 716.37, and 589.90 ( $\eta^2 = 0.55, 0.83, 0.8$ ), with all displacements larger for /a/. The position of the jaw for the second vowel was reliably lower for /a/ ( $F = 204.58, 880.47, \text{ and } 759.42$ ;  $\eta^2 = 0.57, 0.84, 0.8$ ). Stop consonant voicing had no consistent effect on the peak-lowering velocity nor on the lowering displacement. Although some studies have shown that the jaw position during the bilabial closure may be lower when a following vowel is low than when it is high, in the present study only two subjects (NSM, AL) showed

a significantly lower jaw position during the closure when the second vowel was /a/.

### Lower Lip Movements

The lower lip receiver movements contain the jaw component of the movement as well as the lower lip component. This is the appropriate movement to examine when the focus of the analysis is on the lower lip as the end effector and on how its movements are related to those of the upper lip. Average upper and lower lip vertical positions for all utterances and all subjects are shown in Figure 6, whereas Figure 7 shows the average vertical velocity signals. Because the lower lip signals contain the contribution of the jaw, there are some obvi-

ous similarities between the signals for the jaw and the lower lip. There is, however, one clear difference between the lip and jaw signals. All subjects showed a distinct closing and opening movement of the lower lip across vowel contexts, whereas such a pattern was found for three of the five subjects for the jaw (cf. Figure 5). Thus, the lower lip and the jaw can move in opposite directions at and after the oral release. It is also clear from Figures 6 and 7 that the lower lip continues to move upward after the oral closure has occurred. This is the pattern observed in Experiment 1, and it thus appears to be a regular feature of bilabial stop consonant production. Finally, Figure 7 shows that the lower lip is moving at close to peak velocity at the acoustically defined instant of oral closure.

Figure 6. Average vertical upper and lower lip position for all subjects and utterances.

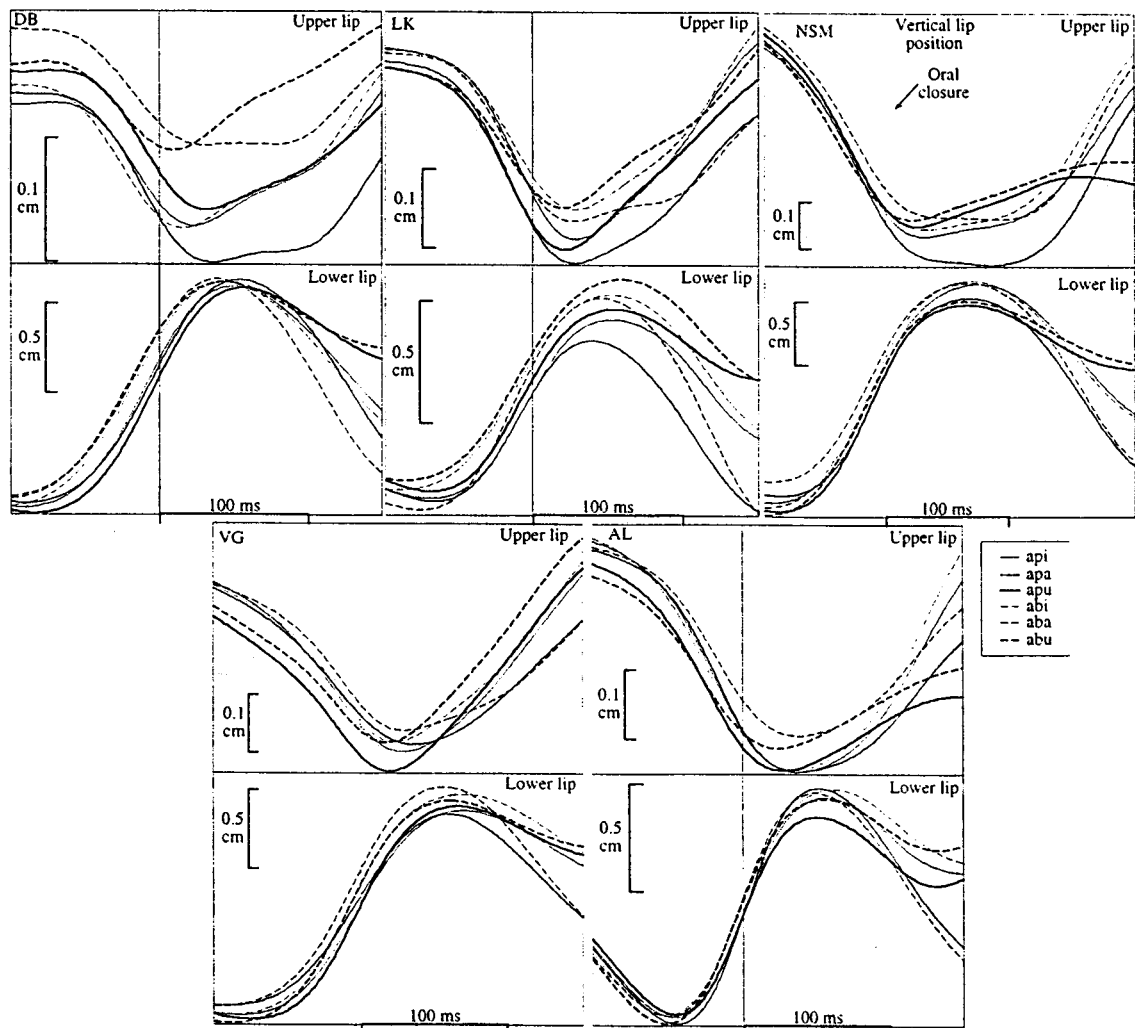
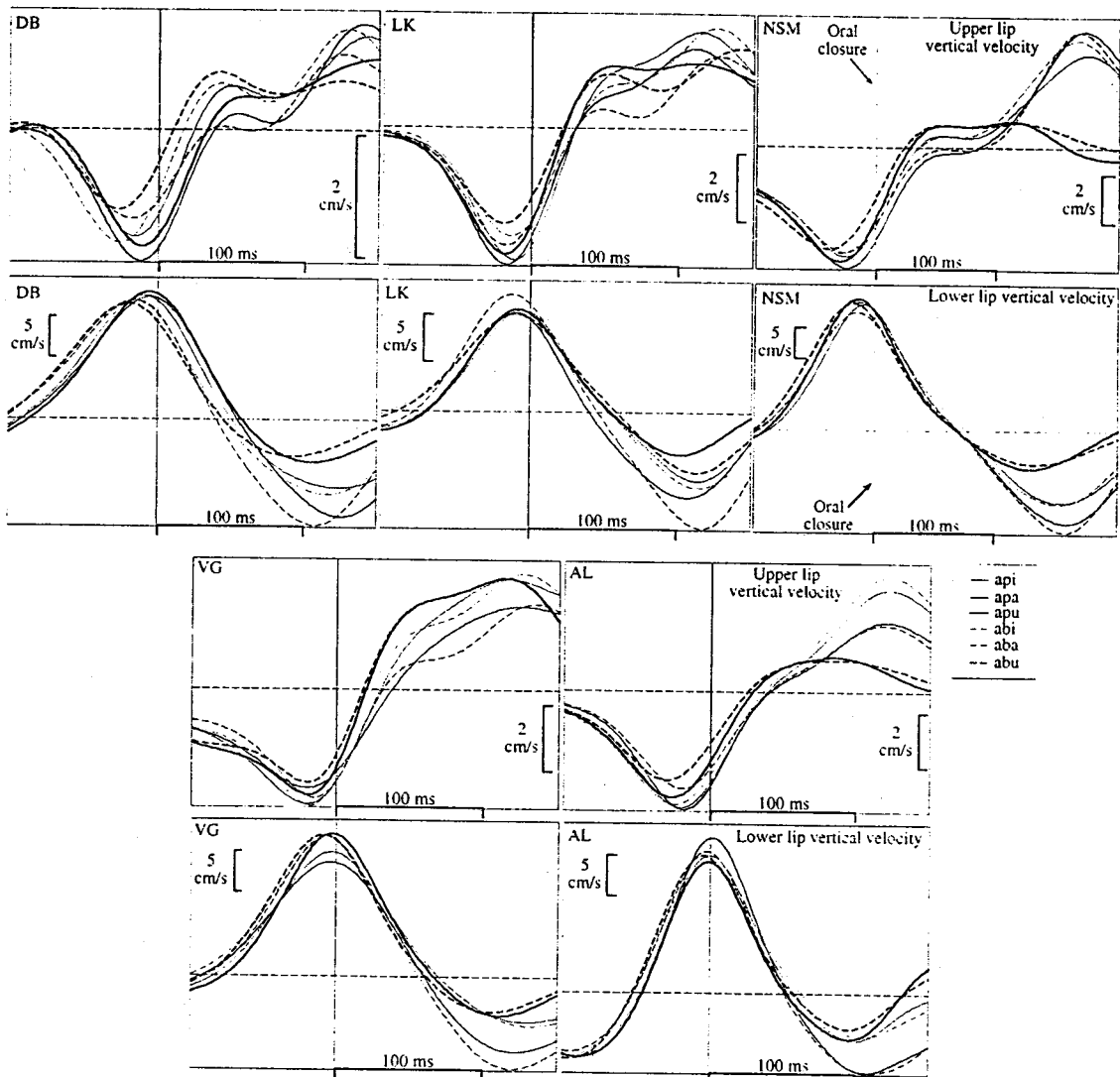


Figure 7. Average vertical upper and lower lip velocity for all subjects and utterances.



At the instant of oral closure, the velocity of the lower lip was between 81% and 98% of the peak velocity. There was no consistent pattern for voiced and voiceless stops. For example, in the data for subject DB, the lower lip velocity was in the range of 80% to 85% of peak velocity for the voiced stops and in the range of 93% to 97% for the voiceless stops. For subject AL, on the other hand, the velocity at closure was 97% of peak velocity irrespective of the voicing of the consonant.

As was the case for jaw movements, there were no consistent effects of the second vowel identity or consonant voicing on the lower lip position at the onset of the closing movement. Figures 6 and 7 show a timing difference for the lower lip movement, similar to the jaw, between voiced and voiceless stops. Consequently, the

position of the lower lip at oral closure is about 1 mm lower when the consonant is voiceless. This voicing effect was reliable for (all) subjects DB, LK, NSM, VG, and AL, respectively:  $F = 223.1, 93.97, 38.73, 73.66,$  and  $14.67$ ;  $\eta^2 = 0.41, 0.23, 0.11, 0.19,$  and  $0.04$ .

The lower lip closing displacement, the peak velocity of the closing movement, and the peak position of the lower lip during the closure were not systematically affected by either consonant voicing or the identity of the second vowel. As might be expected from the jaw data, the lower lip opening movement was reliably influenced by the second vowel, with displacement and peak velocity decreasing in the order  $a > i > u$ . The lower lip position at the offset of the lowering movement was successively lower in the same order. The

material presented in Figure 1 suggested that the peak velocity of the lower lip release movement can occur before the oral release. An examination of all the productions by each speaker showed, however, that this pattern was not common. It occurred in less than 5% of all productions of DB, LK, and NSM, and in 44% and 20% of all productions of VG and AL.

### Upper Lip Movements

Signal averages of the upper lip vertical position for all subjects and utterances are shown in Figure 6. The corresponding velocity signals are presented in Figure 7. From the signal averages, it is apparent that the upper lip is moving downwards at the acoustically defined instant of oral closure. Across subjects and consonant/vowel contexts, the velocity of the upper lip was between 35% and 87% of the peak velocity of the closing movement at the onset of closure. In contrast to the jaw and the lower lip, there was no difference in the timing of the upper lip closing movement between the voiced and voiceless stops.

The onset of the closing movement of the upper lip showed considerable variability. The peak velocity of the lowering movement always occurred just before the closure, and its magnitude showed some influence of consonant voicing. That is, with the exception of subject VG, who showed no reliable effect of stop consonant voicing ( $F = 0.35$ ), the other subjects showed voicing to be a significant factor ( $F = 18.68, 58.76, 19.83, \text{ and } 100.36$ ;  $\eta^2 = 0.05, 0.16, 0.06, \text{ and } 0.18$  for subjects DB, LK, NSM, and AL, respectively). For these four subjects, the peak velocity was generally higher for the voiceless stop, except for subject DB where the opposite was true for the /i/ context. The differences were reliable across vowel contexts for subject LK, in the context of the vowels /a/ and /u/ for subjects DB and AL, but only in the context of /a/ for subject NSM.

### Interactions Between the Upper and Lower Lips

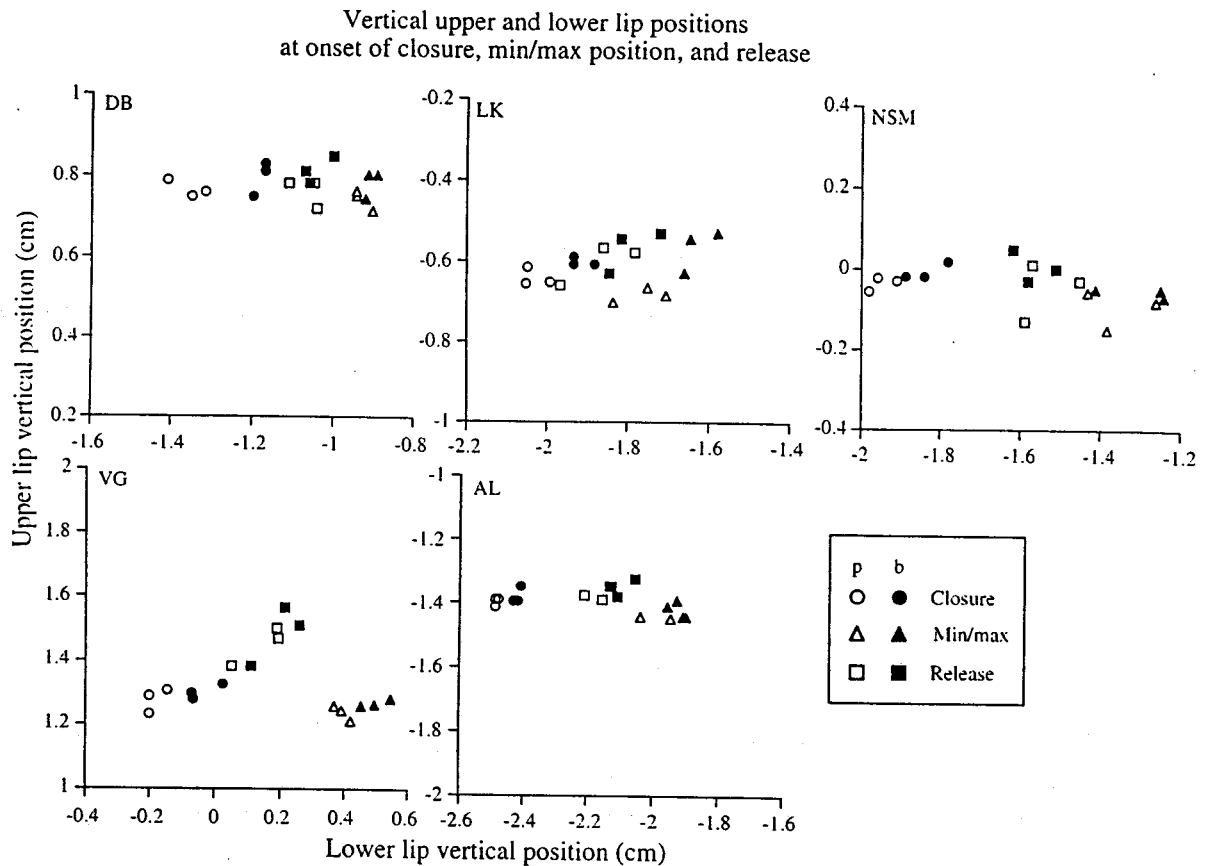
An overview of the lip movements between oral closure and release are presented in Figure 8. This figure plots the average vertical positions of the lower and upper lips at three points in time: the onset of the oral closure as defined in the acoustic signal, the maximum/minimum position identified in the kinematic signals, and the release of the oral closure defined in the acoustic signal. The lower lip position is plotted on the x-axis and that of the upper lip on the y-axis. We should note that the max/min positions of the lower and upper lip do not occur at the same point in time, because they have been identified from the respective velocity signals (cf. Figure 3). The most consistent result in Figure 8 is

the movement pattern of the lower lip. From the position at oral closure, the lower lip moves up (right in the figure) to its peak position, and then down to the position at the oral release. For subjects DB, NSM, VG, and AL, there is almost no overlap between the lower lip positions at these three points in time. The lower lip moves approximately 3–6 mm between the onset of closure and its peak position. The duration of the lower lip movements during the closure was examined by measuring the intervals between closure and release and the peak position of the lower lip during the closure. The interval between closure and peak position was longer (50–70 ms compared to 40–50 ms), but there was no consistent influence of consonant voicing or vowel context on any of the two intervals.

To examine more closely the relationship between the upper and lower lip positions during the closure, measurements were made of the vertical position of the lips at the point in time when the lower lip reached its highest position. The correlations between these two positions, pooled across consonant voicing and vowel contexts ( $n = 300$ ), were positive for all subjects, with  $r$  values of .23, .63, .39, .59, and .24 for subjects DB, LK, NSM, VG, and AL, respectively. These results thus suggest a covariation between the vertical positions of the lips. That is, they both have a higher or a lower vertical position at the same point in time during the oral closure. The overall strength of these correlations might seem low if there is a mechanical interaction between the lips. The material presented in Figure 2 suggested that the magnitude of the upper lip movement during the oral closure is influenced by the position of the receiver on the upper lip. However, the pattern of upper lip movement also differs between productions within a subject when the position of the receiver on the upper lip is constant. This indicates that there is variability in the amount of upper and lower lip interaction within a subject. The next analysis will focus on this variability.

Three different patterns of upper lip movement during the closure were identified above (cf. Figure 3). Pattern 1 had two maxima in the velocity signal. Pattern 2 showed two maxima in the velocity signal but also two zero crossings. Pattern 3 showed a single maximum in the velocity signal. These three different patterns of upper lip movement differed in their frequency of occurrence between the subjects. Subject DB showed the most even distribution of the three patterns of all subjects: 54% for number 1, 24% for number 2, and 23% for number 3, whereas for subject AL pattern number 3 was the dominant one and occurred in 95% of the productions, with number 1 accounting for the remaining 5%. The percentages for the remaining three subjects were 41, 9, 50 (LK), 47, 15, and 38 (NSM), and 15, 1, and 84 (VG). The frequency of these patterns had no apparent relationship to either consonant voicing or vowel context.

Figure 8. Plot of the average vertical positions of the lower (x-axis) and upper (y-axis) lips at three different points in time during the stop closure.



In order to examine possible relationships between movement kinematics and the pattern of upper lip movement, a separate analysis of variance was carried out for subject DB with the pattern of upper lip movement as the independent variable and the tokens pooled across stop consonant voicing and vowel context. The analysis was restricted to the closing movements of the lips, because they would appear most likely to be related to the pattern of upper lip movement. Although the statistical analysis showed that the three patterns of upper lip movement were associated with reliable differences in some articulatory parameters, these differences were generally very small, because the upper lip movements of this subject tended to be small and often less than 1 mm. The peak velocity of the upper lip closing movement was reliably different for the three patterns ( $F_{2,297} = 12.60$ ,  $\eta^2 = 0.08$ ), with the peak velocity decreasing in the order of pattern 3 (-2.13 cm/s), pattern 1 (-1.87 cm/s), and pattern 2 (-1.54 cm/s). A protected  $t$  test showed all these differences to be reliable. The peak velocity of the lower lip closing movement showed the same trend, but it was not significant ( $F = 2.44$ ). The velocity of the

upper lip at the instant of oral closure showed the same differences as that of the peak velocity ( $F = 10.57$ ,  $\eta^2 = 0.07$ ), whereas that of the lower lip was not significant ( $F = 2.68$ ). The peak position of the lower lip differed for the three patterns ( $F = 6.91$ ,  $\eta^2 = 0.04$ ), increasing in the order of pattern 3 (-.93 cm), pattern 1 (-.92 cm), and pattern 2 (-.89 cm). A post hoc analysis showed the differences between patterns 1 and 2, and between patterns 2 and 3, to be reliable. Thus, although different patterns of upper lip movement do occur, the only reliable differences were in the peak closing velocity of the upper lip and the peak position of the lower lip.

One further difference was found to be associated with the different patterns of upper lip movement for subject DB. A separate analysis of variance showed that the acoustic duration of the oral closure was reliably influenced by the upper lip movement pattern ( $F = 23.03$ ,  $\eta^2 = 0.13$ ). Specifically, movement pattern 2 was associated with a longer closure duration (90 ms) than either pattern 1 (82 ms) or pattern 3 (73 ms). A post hoc analysis revealed that all three closure durations differed from each other.

This finding suggested that there might be a relationship between the lower lip movement and the acoustic closure duration. Thus, a separate correlation between these two variables was made for all the productions of each subject ( $n = 300$ ). Overall, there was no strong correlation between them, however. All the correlation coefficients were positive, with  $r$  values of .30, .49, .15, .07, and .16 for subjects DB, LK, NSM, VG, and AL.

### Lip Aperture

The aperture during the oral closing showed no consistent influences of stop consonant voicing or the nature of the second vowel. A timing difference was found for the jaw and the lower lip closing movement between voiced and voiceless stops and is reflected in the lip aperture signal. Lip aperture at the oral closure was thus reliably smaller for voiced than for voiceless stops for (all) subjects DB, LK, NSM, VG, and AL ( $F = 142.78, 52.88, 40.63, 62.56, \text{ and } 6.45$ ;  $\eta^2 = 0.3, 0.14, 0.12, 0.17, \text{ and } 0.02$ ) respectively. For the release, the second vowel had a very robust and reliable effect for all subjects. The peak velocity decreased in the order  $a > i > u$ . The  $F$  values for the vowel effect were 672.84, 194.58, 1938.80, 333.8, and 706.87 ( $\eta^2 = 0.81, 0.51, 0.92, 0.65, \text{ and } 0.81$ ) for subjects DB, LK, NSM, VG, and AL, respectively. The consonant effect was not consistent across speakers. In all cases, there was a significant interaction between the voicing and vowel effects.

### Discussion

The results of Experiment 2 revealed a number of characteristic properties of jaw and lip movements in bilabial stop consonant production. One consistent finding was that the lips were moving at high velocities at the instant of oral closure. As a consequence, the lower lip was continuing its upward movement after the closure had occurred. During this time, the upper lip often showed an upward movement that appeared to result from a mechanical interaction between the two lips. This pattern of lip movement during the oral closure was identical to the one observed in Experiment 1, where it was shown that the contact pressure between the lips reached its maximum when the lower lip reached its highest position. One factor responsible for the pattern of lip interactions would appear to be the peak velocity of the closing movement, which is considerably higher for the lower (10–20 cm/s) than for the upper lip (1–5 cm/s). Also, the relative velocity of the upper lip (re. its peak velocity) is lower than that of the lower lip at the instant of oral closure. In addition, the stiffness of the upper lip has been reported to be lower than that of the

lower lip (Ho, Azar, Weinstein, & Bowley, 1982). The same study also showed the lips of females to be less stiff than those of males. This might explain why the incidence of pattern 2 was very low for the male speakers in the present study, although differences in the placement of the receiver on the upper lip between subjects also play a role. Because the lip tissues would appear to be compressed during the oral closure, it is possible that the first part of the opening movement is influenced by the recoil forces that are due to tissue compression (cf., Abbs, 1973). The placement of the receivers and the resolution of the measurement system make it difficult to examine this issue in more detail, however.

The lips meeting at high velocity suggests that the virtual target for the lips in making the stop is a region of negative lip aperture—that is, to reach the virtual target the lips would move beyond each other. The resulting tissue compression produces the air-tight seal for the stop to allow the build-up of oral air pressure. Because almost all speech articulations involve at least one articulator with soft and compressible tissues (e.g., the lips and the tongue) it is plausible that stop consonants articulated with the tongue show a similar pattern of high velocity at the instant of oral closure. There is some experimental evidence to support this notion (Löfqvist & Gracco, 1994, 1995, unpublished observations). In addition, the time course of the contact pressure between the tongue and the alveolar ridge appears to be similar to the one observed here for the contact pressure between the lips (McGlone, Profitt, & Christiansen, 1967). Finally, the temporal evolution of tongue-palate contact patterns is also similar (e.g., Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989; Marchal, 1988). Such a control strategy would ensure that the lips form an air-tight seal irrespective of any contextual variability in the onset positions of their closing movements. It would also seem to require less of a trading relationship between the lips and the jaw in normal speech production. Although such a relationship has been postulated on the basis of different jaw positions during the stop closure as a function of vowel context, the present results do not provide any unequivocal evidence for such differences in jaw position across subjects.

Interestingly, also for labiodental fricative consonants, which are produced with a constriction rather than a complete closure, the velocity of the lower lip is close to its peak velocity at the instant of lip-teeth contact (Löfqvist & Gracco, unpublished observations). At the same time, the peak velocity of the closing movement tends to be lower for fricatives than for stops even when the displacement is of equal magnitude (Gracco & Löfqvist, 1994).

The present results do not suggest that there are any stable differences in lip or jaw kinematics between

voiced and voiceless stops across subjects. As might be expected, the nature of the second vowel had a consistent influence on the opening movements for the jaw, the lower lip, and the lip aperture. Finally, it is obvious from the present results that subjects show considerable variability as to coarticulatory influences. Thus, by looking at only a subset of the present subjects, different conclusions can be drawn. Moreover, by analyzing a subset of the vowel contexts, different conclusions can be drawn about the influence of stop consonant voicing on lip and jaw kinematics.

The present results are in basic agreement with those summarized in the introduction on oral kinematic differences between voiced and voiceless stops. Specifically, such differences are not consistently found across subjects, and the direction of the differences is inconsistent. Although some of the effects of consonant voicing proved to be significant, the  $\eta^2$  values were generally very low, indicating that the effect accounted for a small proportion of the variance. The commonly stated view that voiceless stops are produced with faster and shorter oral articulatory movements is thus not necessarily true. One reason for this appears to be that 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 or follow from general principles of biomechanics and motor control. This does not appear to be the case for the influence of voicing on articulatory movements, and variability between speakers is thus to be expected. Although the present study did not find any consistent differences in the oral articulatory movements between voiced and voiceless stops, there are differences in laryngeal activity. The voiceless stops are produced with a laryngeal opening movement that prevents glottal vibrations and creates a period of aspiration noise following the stop release (e.g., Löfqvist, 1995).

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