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CONTROL OF ORAL CLOSURE AND RELEASE IN BILABIAL STOP CONSONANTS

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ABSTRACT - This paper examines the control of bilabial closure and release in stop consonants. Recordings of lip kinematics were made in five subjects using an electromagnetic transduction technique. Results suggest that the lips are moving at a high velocity at the instant of oral closure. During the closure, the lip tissues are compressed and the lower lip may push the upper lip upwards. The results are compatible with the hypothesis that one target in the production of labial stop consonants is a region of negative lip aperture.

INTRODUCTION

The production of labial stop consonants usually require a closure of the lips, controlled by the joint actions of the upper and lower lips, and the jaw. The purpose of this study is to make a detailed examination of lip kinematics in the production of bilabial stop consonants with particular emphasis on events before, during, and after the oral closure. While 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. One specific hypothesis to be addressed is that one target in the production of a labial stop consonant is a region of negative lip aperture and that the lips are moving at a high velocity at the instant of oral closure.

PROCEDURE

Three female (DB, LK, NSM) and two male subjects (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 (the author) is a native speaker of Swedish who is also fluent in English. The linguistic material consisted of aCV sequences, where the consonant (C) was one of /p, b/, and the second vowel (V) was one of /i, a, u/. The sequences were placed in the carrier phrase "Say ... again" with sentential stress occurring on the second vowel (V) of the sequence. 50 tokens were recorded for each sequence type.

The movements of the lips and the jaw were recorded using a three-transmitter magnetometer system (Perkell, Cohen, Svirsky, Matthies, Garabieta, & Jackson, 1992) . Receivers were placed on the upper and lower lips, and on the lower incisors (Only some of the lip data will be discussed here; a complete analysis of both the lips and the jaw is presented in Löfqvist & Gracco, submitted.). 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. The acoustic signal was pre-emphasized, low-pass filtered at 9.5 kHz, and sampled at 20 kHz.

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. In addition, the onset and release of the oral closure were identified in waveform and spectrogram displays of the acoustic signal. They were used for measurements of closure duration and of receiver positions and velocities at these two points in time. All signal processing and measurements were made using the Haskins Analysis Display and Experiment System (HADES) (Rubin & Löfqvist, in press) .

One purpose of the present study was to examine labial kinematics during the stop closure. To do so, it is necessary to have estimates of when the lip closure occurs, when it begins and when it ends. Its onset and offset cannot be identified from the kinematic signals, however. Therefore, in one subject (AL), the force of labial contact and the oral air pressure were recorded together with the movements.

An analysis of variance with stop consonant voicing and the quality of the second vowel in the sequence as the main factors was 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 ≤ 0.05 was adopted as significant.

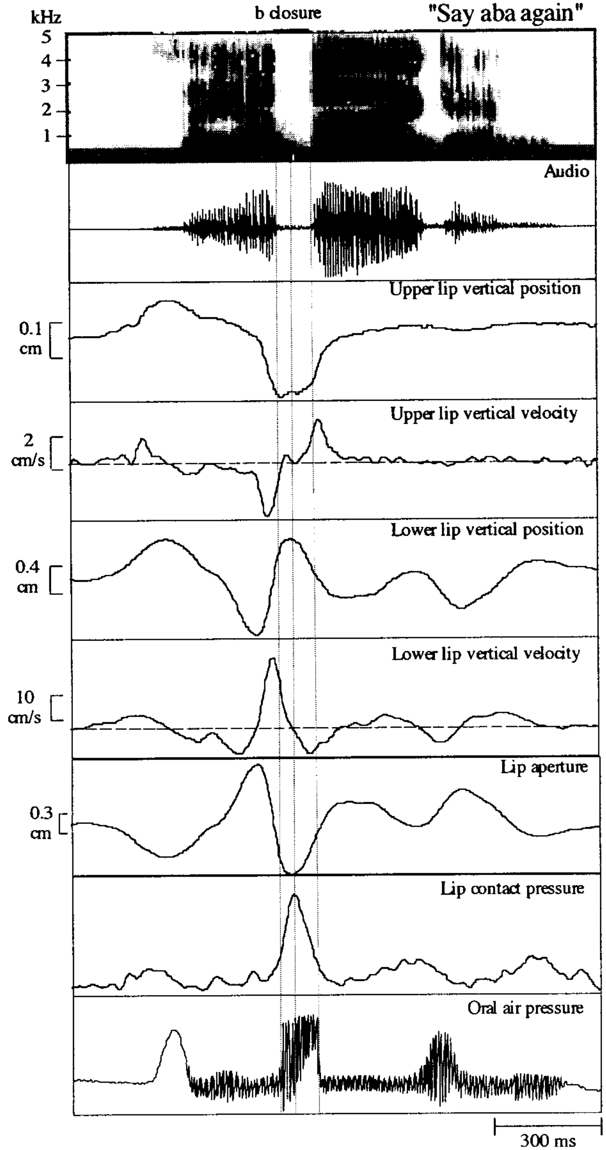

Figure 1. Kinematic, acoustic, and aerodynamic signals during the production of the utterance "Say aba again". The three vertical lines correspond to the following events from left to right: Onset of oral closure defined from the acoustic and pressure signals; peak force of labial contact; release of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

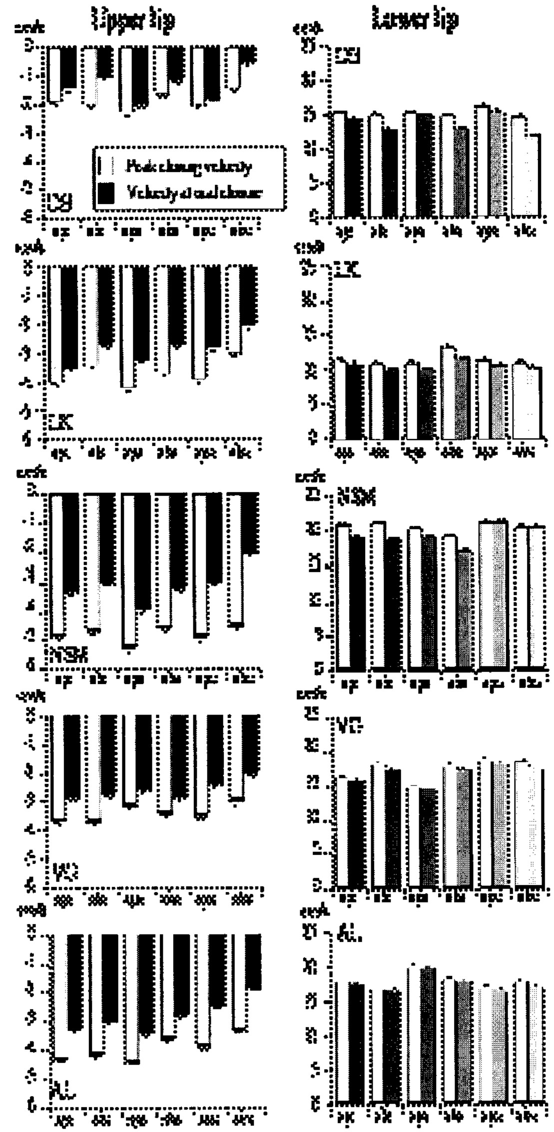

Figure 2. Peak closing vertical velocity and the vertical velocity at oral closure for the upper lip (left) and the lower lip (right). The mean and the standard error of the mean are plotted.

RESULTS

Before presenting the results, we should remind the reader that the kinematic signals represent the movements of receivers placed at the midline of the lips. 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.

To develop an understanding of the events during the oral closure, we will first qualitatively analyze one production for which the force of labial contact and the oral air pressure were recorded with the movement signals. Figure 1 presents one token of the utterance "Say aba again". This figure presents the acoustic signal, the vertical position and velocity of the upper and lower lips, the lip aperture, the labial contact pressure, and the oral air pressure. The three vertical lines in Figure 1 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 started to fall and the release burst was evident in the acoustic signal.

An inspection of 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 vertical 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 is upward movement until the point of peak force of labial contact (second vertical line). 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. This is evident from the zero crossing in the lower lip velocity signal. At the same point in time, the upper lip raising movement is interrupted and reversed. This can be seen in the upper lip velocity signal, where a zero crossing occurs at the point of peak force of labial contact and another one shortly afterwards. 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, while the peak velocity of the upper lip occurs after the release. In Figure 1, the lip aperture is changing during the oral closure. This is due to the fact that it represents the vertical distance between the upper and lower lip receivers. The receivers continue to move during the closure due to their placement and to compression of the lip tissues. The results presented in Figure 1 suggest that the lips may be meeting at a high velocity and also that there may be a mechanical interaction between the lips during the closure. Figure 2 plots the peak vertical velocity of the upper and lower lips during the closing movement and also the vertical velocity of the two lips at the acoustically defined onset of the oral closure. Several points are worth noting. The peak vertical velocity is much higher for the lower lip than for the upper lip, 10-20 cm/s compared to 1-5 cm/s. Also the relative velocity (re. peak velocity) is higher for the lower lip than for the upper lip at the instant of the acoustically defined oral closure. At this point, 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 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. At closure, the velocity of the upper lip was between 35% and 87% of the peak velocity of the closing movement. The peak vertical velocity of the lower lip closing movement was not systematically affected by either consonant voicing or the quality of the second vowel. In contrast, the peak closing velocity of the upper lip showed some influences of 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 the voicing effect to be significant ($F=18.68$, 58.76, 19.83, and 100.36 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.

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 during the closure. The correlations between these two positions, pooled across consonant voicing and the quality of the second vowel, were positive and reliable 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 Löfqvist & Gracco (submitted) show 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.

In the upper lip position and velocity signals showed in Figure 1, an upward movement is observed following the closure, when the lower lip is moving upward. In addition, the upward movement of the upper lip is briefly reversed when the lower lip starts to move down. Three different patterns of upper lip movement around the oral closure could be identified from the upper lip velocity signal. Pattern 1 showed a momentary decrease of the upper lip vertical velocity, so that there were two maxima in the velocity signal around the oral closure. Pattern 2 showed a reversal in the sign of the upper lip velocity, so that there were two maxima but also two extra zero crossings, as shown in Figure 1. Pattern 3 showed a single maximum in the upper lip vertical velocity. 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, while 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 voicing or vowel context.

In order to examine possible interactions 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 this subject, since she was the only one that had a reasonably large number of productions in each pattern category. The analysis was restricted to the closing movements of the lips, since they would appear most likely to be related to the pattern of upper lip movement. While 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) 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 trend as that of the peak velocity (F=10.57), while 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), 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, while 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 differed between the three upper lip movement patterns (F=23.03). 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.

Thus, for this subject upper lip movement pattern 3 showed a higher peak position of the lower lip and a longer closure duration than the other two patterns. This finding suggested that there might be relationship between the lower lip movement and the acoustic closure duration. Thus, a separate correlation between the peak lower lip position and the acoustic closure duration was made for all the productions of each subject. 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.

The material shown in Figure 1 suggests that the peak velocity of the lower lip lowering movement can occur before the acoustic release of the stop. A closer examination of this issue revealed, however,

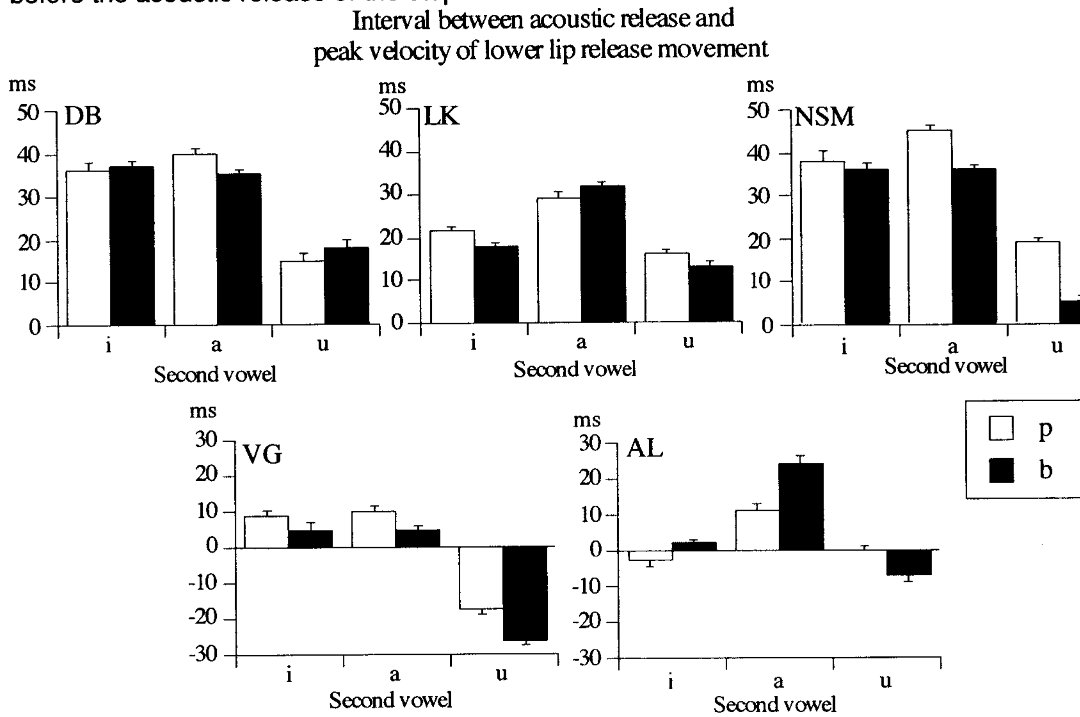

Figure 3. The interval between the acoustic release and the peak vertical velocity of the lower lip release movement. A negative value indicates that the peak velocity occurs before the acoustic release. The mean and the standard error of the mean are plotted.

that this pattern was not very frequent. Figure 3 summarizes the duration of the interval between the acoustic release and the peak velocity of the lower lip release movement. A negative value indicates that the peak velocity occurs before the release. It is evident from Figure 3 that the peak velocity only occurs before the acoustic release in some productions of speakers VG and AL. For these speakers, this pattern occurred in 44% and 29% of the productions, while for the other speakers this pattern was found in less than 5% of their productions.

For the release movements, the second vowel had a very robust and reliable effect for all subjects, as shown in Figure 4, plotting the peak velocity of the lip aperture for the release. 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, for subjects DB, LK, NSM, VG, and AL, respectively. The consonant effect was not significant for subject DB (F=1.57). One subject, LK, always showed a greater opening velocity for the voiced stops (F=73.46), while the results for the other speakers varied. In all cases, there was a significant interaction between the voicing and vowel effects. The velocity differences across vowel contexts are obviously related to the lip aperture for the second vowel which decreased in the order a>i>u.

DISCUSSION

The results of this experiment revealed a number of characteristic properties of lip movements in bilabial stop consonant production. One consistent finding was that the lips often were moving at close to their peak 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. The contact pressure between the lips reached its maximum when the lower lip reached its highest position. Such a mechanical interaction was suggested by the high-speed films presented by Fujimura (1961) . 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 than for the upper lip. 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 high velocity of the lips at closure and the resulting tissue compression would produce the air-tight closure for the stop. The lips meeting at high velocity also suggest that the virtual target for the lips in making the stop is a negative lip aperture. Since almost all speech articulations involve at least one

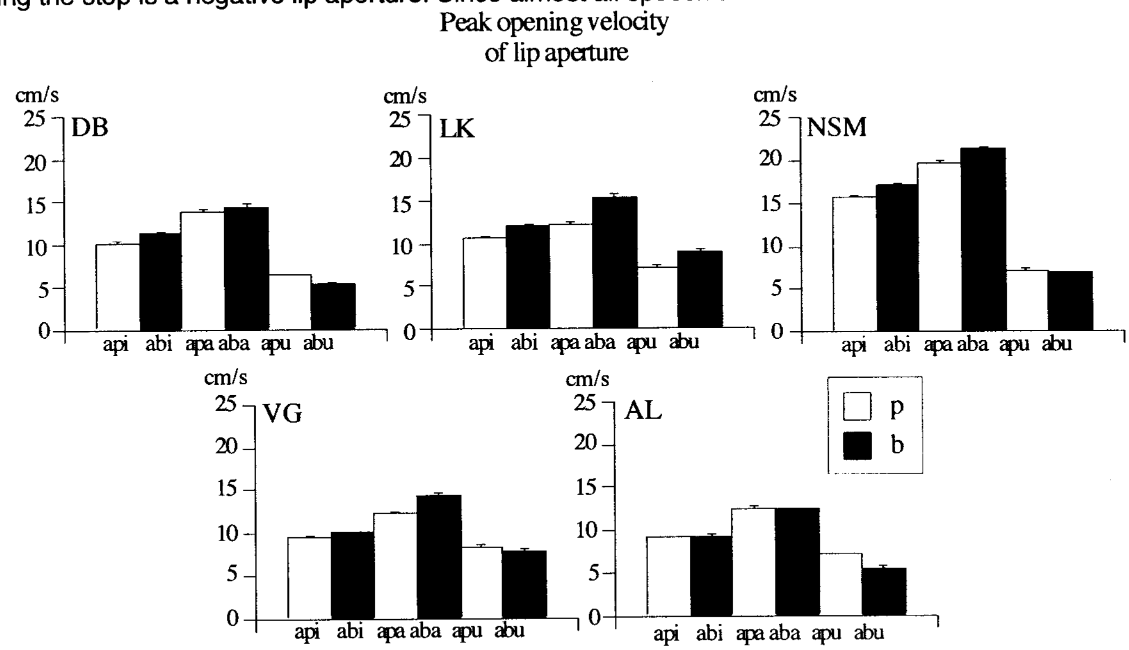

Figure 4. Peak velocity of lip aperture for the stop release.

articulator with soft and compressible tissues, e.g., the lips and the tongue, it is plausible that also stop consonants articulated with the tongue show a similar pattern of high velocity at the instant of oral closure, and there is some experimental evidence to supports this notion (Löfqvist & Gracco, 1994, 1995, unpublished observations).

The present results do not suggest that there are any stable differences in lip kinematics between voiced and voiceless stops across subjects. While three of the five subjects showed the peak velocity of the upper lip closing movement to be faster for voiceless than for voiced stops, there was no difference in the lower lip closing movements. Similarly, there were no reliable differences in the peak opening velocity between voiced and voiceless consonants, neither for the individual articulators nor for the lip aperture signal. It is also obvious from the present results that subjects show considerable variability as to coarticulatory influences. Thus, by only looking at 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 kinematics.

ACKNOWLEDGMENT

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