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Interarticulator phasing, locus equations, and degree of coarticulation

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A locus equation plots the frequency of the second formant at vowel onset against the target frequency of the same formant for the vowel in a consonant–vowel sequence, across different vowel contexts. It has generally been assumed that the slope of the locus equation reflects the degree of coarticulation between the consonant and the vowel, with a steeper slope showing more coarticulation. This study examined the articulatory basis for this assumption. Four subjects participated and produced VCV sequences of the consonants /b, d, g/ and the vowels /i, a, u/. The movements of the tongue and the lips were recorded using a magnetometer system. One articulatory measure was the temporal phasing between the onset of the lip closing movement for the bilabial consonant and the onset of the tongue movement from the first to the second vowel in a VCV sequence. A second measure was the magnitude of the tongue movement during the oral stop closure, averaged across four receivers on the tongue. A third measure was the magnitude of the tongue movement from the onset of the second vowel to the tongue position for that vowel. When compared with the corresponding locus equations, no measure showed any support for the assumption that the slope serves as an index of the degree of coarticulation between the consonant and the vowel. © *1999 Acoustical Society of America.* [S0001-4966(99)02009-3]

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INTRODUCTION

A locus equation is based on the onset frequency of the second formant and the steady-state value of the same formant during the vowel in a sequence of a consonant and a vowel. A linear regression is performed on these two values for productions of the same consonant in different vowel contexts (e.g., Lindblom, 1963; Sussman *et al.*, 1991). The consonants investigated using this paradigm have mostly been voiced stops or fricatives; it is hard to define the proper $F2$ onset frequency in a stop with a long voice onset time, where most of the transition occurs during the aspiration noise. Although there is an ongoing controversy about the proper interpretation of locus equations and their potential relevance for the perception of speech (e.g., Brancazio and Fowler, 1998; Sussman *et al.*, 1998), the present paper will not address these broader issues of locus equations. Its focus is rather on one property of the locus equation, i.e., its slope and the proper interpretation of slope differences.

Almost all the work on locus equations has been made using acoustic analysis. The first link between the slope of the locus equation and the degree of coarticulation between the consonant and the vowel in a CV sequence was made by Krull (1987, 1988). She noted that a locus equation slope of 1 would indicate maximum amount of coarticulation between a consonant and a vowel; in this case, the onset and target frequencies of the second formant would be identical. Conversely, a slope of 0 would indicate no coarticulation; here, the onset frequency of the second formant would remain the same when the consonant occurs in different vowel contexts (cf. Figure 10 in Sussman *et al.*, 1993). Although this interpretation was made in terms of acoustic results, the conceptual link between locus equation slope and articulatory kinematics was also made by Krull (1987), who wrote "Earlier results referred to above and the fact that the tongue is not involved in their production led us to expect more coarticulation with labial consonants, and such was also the case here" (Krull, 1987, pp. 50–51). More recent work on locus equations has also made such a link explicit. For example, Sussman *et al.* (1993) state "The relatively steep regression functions for both labials and velars indicate two stop places where the following vowel greatly influences articulation of the preceding stop closure" (Sussman *et al.*, 1993, p. 1267). In a study of locus equations for consonants preceding and following a vowel, the failure to find the normal relationship for a consonant following a vowel has also been rationalized in articulatory terms: "The 'vowel-dominant' view, if taken to a logical conclusion, would also claim that the V- to C_1 anticipatory interaction is more likely a planned articulatory sequence both demanding and realizing greater articulatory precision compared to a VC_2 articulation which is conceived more as a defaultlike, mechanical contextual effect" (Sussman *et al.*, 1997, p. 2834). Finally, the studies of Fowler (1994) and Brancazio and Fowler (1998) relate slope differences between consonants with different places of articulation to their coarticulatory resistance defined in articulatory terms.

In extending the acoustically based measure of coarticulation using locus equation slope, it has thus been assumed that this measure can reflect the articulatory coarticulation between the consonant and the vowel. The evidence in support of this extension is so far almost entirely indirect and

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based on inferred articulatory interpretations of slope differences. The notion of "degree of coarticulation" is interesting within the wider context of speech motor control, but there is little empirical evidence on which it can be based and evaluated. The present paper is an attempt to address this issue using records of articulatory kinematics and acoustic analyses.

The most common argument for a relationship between slope and degree of coarticulation is that labial stop consonants tend to have steeper slopes than alveolar and velar consonants (cf. Sussman *et al.*, 1991; Fowler, 1994; Brancazio and Fowler, 1998). The specific argument made is that in a sequence of a labial consonant and a vowel, the consonant does not require any specific tongue movements for its production, while the vowel does not require any lip movements for its production, unless it is produced with lip rounding. Since the analysis of locus equations is usually made using consonant–vowel syllables placed in a carrier sentence, it would appear, however, that any tongue movement during the labial consonant closure/constriction and/or during the vowel following the consonant would mostly reflect the influence of the vowel preceding the consonant rather than that of the consonant itself. This is so because the tongue movement from the first to the second vowel in a vowel-bilabial stop-vowel sequence will commonly start before the lip closure for the consonant has been made. Its exact timing varies, among other things, with the magnitude of the tongue movement from the first to the second vowel (Löfqvist and Gracco, 1999). The other evidence has been obtained in studies that have manipulated the linguistic material in ways that have been assumed to artificially affect the coarticulation, such as spontaneous versus read speech (Duez, 1992; Krull, 1989), stressed versus unstressed syllables (Bakran and Mildner, 1995; Duez, 1992; Krull, 1989), and by comparing sequences where the vowels preceding and following the consonant are identical or different (Brancazio and Fowler, 1998; Crowther, 1994). The expected slope differences have usually been found. One additional thing to keep in mind in this context is that for the velar stop consonant /g/, two locus equations have often been computed, one when it is paired with front vowels and another one when it is paired with back vowels. This has been done because a single regression across all vowel contexts usually results in a worse fit. It is, however, hard to see why the degree of coarticulation for the velar stop /g/ should differ as a function of vowel place. Both the tongue configuration and the point of tongue–palate contact for velar stops are heavily influenced by vowel context (e.g., Mooshammer *et al.*, 1995; Löfqvist and Gracco, 1994; Dembowski *et al.*, 1998). In fact, when a single regression is computed for /g/ across vowel contexts, the slope tends to be as steep for velars as for labials (Brancazio and Fowler, 1998). During the oral closure for a velar stop consonant, the tongue continues to move (Mooshammer *et al.*, 1995; Löfqvist and Gracco, submitted). For stop consonants produced with the tongue tip or the tongue blade, the location of the point of contact between the tongue tip and the palate, or alveolar ridge, is influenced by phonetic context (Kent and Moll, 1972; Butcher and Weiher, 1976). Also for these stops, the tongue continues to move during the oral closure. A comparison between the movement of the tongue body for a velar stop and the tongue tip for an alveolar stop during the oral closure has shown that the tongue tip movement is smaller than that of the tongue body (Löfqvist and Gracco, submitted).

Recently, Chennoukh *et al.* (1997) used an articulatory model to examine the relationship between speech articulation and locus equations. With the model, known as the Distinctive Region Model (cf. Mrayati *et al.*, 1988), they varied the amount of articulatory overlap between a stop consonant and a vowel in a vowel–stop-vowel sequence to see if the amount of overlap changed the slope of the locus equation. In one condition, the tongue movement from the first to the second vowel and the oral closing movement for the consonant started at the same time. In a second condition, the vowel-related tongue movement did not start until the closure for the consonant had occurred. In the third condition, the vowel movement started at the release of the consonant. The slope of the locus equation decreased from condition 1 to condition 3.[1]

One purpose of the present experiment was to examine the influence of consonant–vowel overlap on locus equation slope, following the paradigm suggested by Chennoukh *et al.* (1997). However, one limitation on real speech has to be acknowledged. In their modeling work, Chennoukh *et al.* (1997) could vary the overlap between the consonant and vowel gestures for three places of articulation for the consonant, labial, alveolar, and velar. Using real speech, it is not possible to perform a similar analysis, however. This is so because, in contrast to the model used by Chennoukh *et al.*, it is not possible to observe separate consonant and vowel gestures in a human vocal tract when the consonant is articulated with the tongue. The model does not have a tongue, and the movements are simulated by changing constriction size and location. In humans, the movements for the consonant and the surrounding vowels are blended when the consonant is alveolar or velar. Only in a sequence where the consonant is bilabial is it theoretically possible to examine the consonant and vowel gestures separately; in practice, such an analysis rests on a number of assumptions that will be discussed in more detail below. In a sequence of an unrounded vowel, a bilabial stop, and an unrounded vowel, the stop closure is made with the lips and the jaw, while the vowel gesture is made with the tongue and the jaw. Thus, in one part of the present study, articulatory movements in VCV sequences were analyzed only for the bilabial stop /b/ and in asymmetrical vowel contexts, i.e., the two vowels were not identical. In a sequence with the same vowel occurring before and after the consonant, the tongue movement is very small and it is impossible to reliably identify the onset and offset of the movement. The acoustic analysis also used symmetrical vowel contexts, however.

What is the proper quantification of "degree of coarticulation?" One possible index has already been discussed above, i.e., the phasing between articulatory movements. In the case of a bilabial stop consonant occurring between two vowels, one can thus view the temporal phasing between the tongue movement from the first to the second vowel and the lip closing movement as providing a metric. When the tongue movement starts well before the consonant movement, there is, in a sense, more overlap than if it starts late. Such temporal relationships have been the focus of several studies of anticipatory coarticulation (e.g., Perkell and Matthies, 1992; Abry and Lallouache, 1995). These studies have mostly focused on how far in advance one articulatory movement for a segment starts before the ''segment itself.'' A typical case is lip rounding for a vowel, where the lip movements have been shown to start well before the acoustic onset of the vowel itself. Note that this definition of a segment presupposes that it is possible to define a point in time where a segment properly ''begins'' in the acoustic and/or articulatory record. This is far from a trivial task, however, since the movements for successive segments blend seamlessly with each other. Thus, drawing boundaries between segments in acoustic or articulatory records requires that these boundaries be properly justified. In some cases, drawing such boundaries may, in fact, be impossible. Although they have provided a wealth of evidence on the temporal aspects of speech production, these studies of coarticulation do not provide much information about the shape of the vocal tract during speech production and how it is influenced by phonetic context. A proper metric of coarticulation would need to supply, or be based on, such information.

This study examined the relationship between locus equation slope and measures of articulatory overlap, or coarticulation. Three different measurements of coarticulation were used. The following specific hypotheses were examined.

The first measure of articulatory overlap was essentially the one used by Chennoukh *et al.* (1997). That is, it consisted of the temporal interval between the onset of the lip closing movement for a bilabial stop and the onset of the tongue movement from the first to the second vowel in a VCV sequence. The predicted outcome here would be that as the overlap between the tongue and lip movements increased, the slope of the locus equation should become steeper. An increased articulatory overlap would be indexed by an earlier onset of the tongue movement relative to the onset of the lip movement. The second metric chosen for degree of coarticulation was the magnitude of the tongue movement during the oral closure for a stop consonant. The prediction would be that a large tongue movement during the closure would signify a high degree of coarticulation between the stop consonant and the following vowel, and hence be associated with a steeper slope, because the consonant would allow rather than resist such coarticulatory influences. A third metric chosen was the magnitude of the tongue movement during the vowel following the consonant. A small tongue movement between the consonant release and the vowel target would imply a large degree of articulatory overlap, and thus a steeper slope, since most of the tongue movement would have occurred during the consonant. Since the movement of the whole tongue will affect the vocal tract shape, for both these measures the movement magnitude was taken as the average across four receivers placed on the tongue. As a first approximation, a large change in vocal tract shape would lead to a large acoustic difference, while a smaller articulatory change would lead to a smaller acoustic change. Here, we immediately have to acknowledge a limiting factor for making direct comparisons between articulation and acoustics. There is a lawful relation between articulation (vocal tract shape) and the acoustic signal, but it is not linear. A further limitation in the present context is that we are tracking only receivers at the midline of the tongue and not the whole vocal tract. Nevertheless, it appears to be fruitful to explore the possibility of such a link between articulation and acoustics within the framework of locus equations.

I. 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 Mid-West, 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. Subject AL is the author.

B. Linguistic material

The linguistic material consisted of V_1CV_2 sequences, where the first and second vowels (V_1 and V_2) were always one of /i, a, u/, and the consonant (C) was one of /b, d, g/. 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 lips, the jaw, and the tongue were recorded using a three-transmitter magnetometer system (Perkell *et al.*, 1992). Receivers were placed on the upper and lower lips, on the lower incisors, and on four positions on the tongue. The tongue receivers will be referred to as tongue tip, tongue blade, tongue body, and tongue rear. 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. For the tongue, the first receiver was placed as far back as the subject could tolerate, and the next one close to the tongue tip; next, an attempt was made to space the other two receivers evenly between the first and the second. Two additional receivers placed on the nose and the upper incisors were used for the correction of head movements. The receivers on the lips, the incisors, and the nose were attached using Iso-Dent (Ellman International). For the tongue receivers, Ketac-Bond (ESPE) was used. 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 three-point central difference algorithm. The velocity signals were smoothed using the same triangular window. A measure of lip opening was obtained by subtracting the vertical position of the lower lip receiver from that of the upper lip receiver. Only the vertical distance was used, since the lip movements for a bilabial stop closure primarily occur in the vertical dimension (Löfqvist and Gracco, 1997). All the signal processing was made using the Haskins Analysis Display and Experiment System (HADES) (Rubin and Löfqvist, 1996). The acoustic signal was preemphasized, low-pass filtered at 9.5 kHz, and sampled at 20 kHz.

The definition of the onset of the closing movement of the lips for the bilabial stop presented some problems. Usually, movement onsets are defined at zero crossings in velocity signals. Here, the second derivative of the derived lip opening signal was used. Using a zero crossing in the first derivative of the lip opening signal was difficult when the first vowel was /u/ that included lip rounding. In this case, the rounding gesture made the lip opening change continuously and a zero crossing would not appear in the first derivative at a point in time close to the oral closure. Thus, the onset of the lip closure for the stop consonant was defined as the minimum in the second derivative of the lip opening signal prior to the oral closure, cf. Fig. 1. This point was defined algorithmically. In a strict sense, this point is not the "onset" of the lip closing movement, but it is related to it.^{2} Figure 1 presents the acoustic, lip opening, and tongue body signals for one production of the sequence "abu" by subject VG. Since the interpretation of a second derivative is not always straightforward, the lip opening signal and its first derivative are also included in Fig. 1. We should add that the actual lip opening is at zero throughout the oral closure. The change in the lip opening signal during the closure is due to the fact that it represents the vertical distance between the receivers on the upper and lower lips, and these receivers move during the closure (cf. Löfqvist and Gracco, 1997; Westbury and Hashi, 1997). The tongue body receiver was used for defining measurement points for the tongue movements. Its speed $[v=\sqrt{(\dot{x}^2+\dot{y}^2)}]$ was calculated. Tongue movement onsets and offsets were identified algorithmically from the speed signal as minima during the first and second vowels. Their identification is also shown in Fig. 1. The onset is shown by the vertical line labeled "First vowel" in Fig. 1, while the offset of the movement is shown by the vertical line labeled "Second vowel" in Fig. 1. We should note that at these points in time, the horizontal and vertical velocity of the tongue is not necessarily zero. However, at these points in time the tongue movement is minimal.

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 its burst. The onset of regular glottal vibrations for the second vowel was also marked. The second formant frequency were measured from both DFT and LPC spectra with 28 coefficients, using a Hamming window, a 51-ms window size, and a window separation of 6 ms. Measurements were made at the onset and at the midpoint of the vowel following the criteria described by Sussman *et al.* (1991). All labeling and acoustic measurements were made by the author.

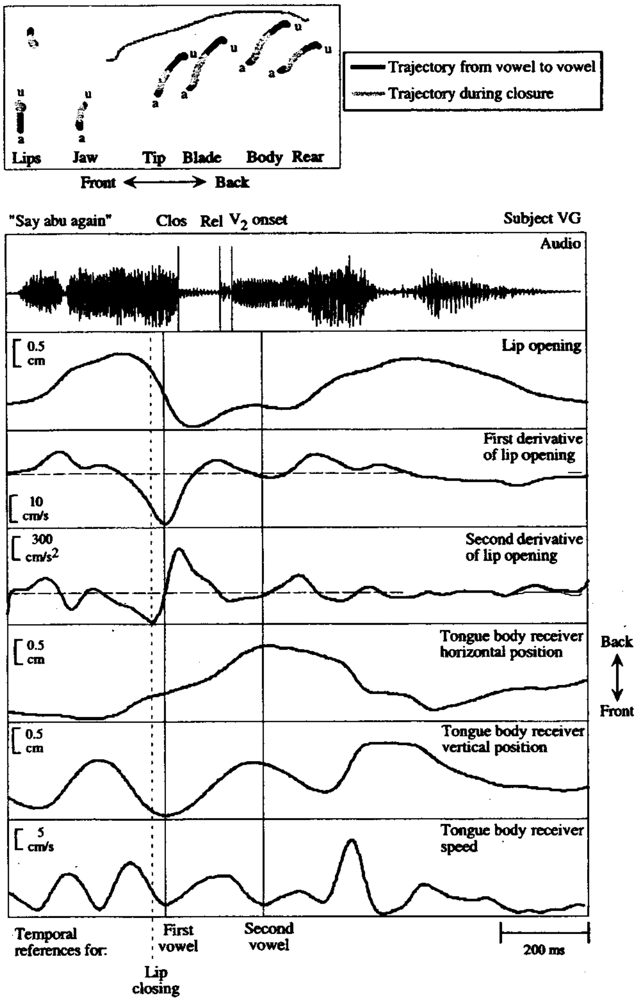

FIG. 1. Acoustic and movement signals during the production of the utterance "Say abu again" by subject VG. In addition to the derived lip opening signal, its first and second derivatives are shown. The labels in the audio signal correspond to the onset and release of the oral closure for the /b/, and the onset of the second vowel in /abu/. The label in the second derivative of the lip opening signal was used to mark the "onset" of the lip closing movement for the consonant. The labels in the speed signal of the tongue body identify the onset and offset of the tongue movement from the first to the second vowel in /abu/. The top 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 movement.

As a measure of the temporal overlap between the bilabial stop consonant and the vowel, the interval between the onset of the tongue movement from the first to the second vowel and the onset of the lip closing movement was used.

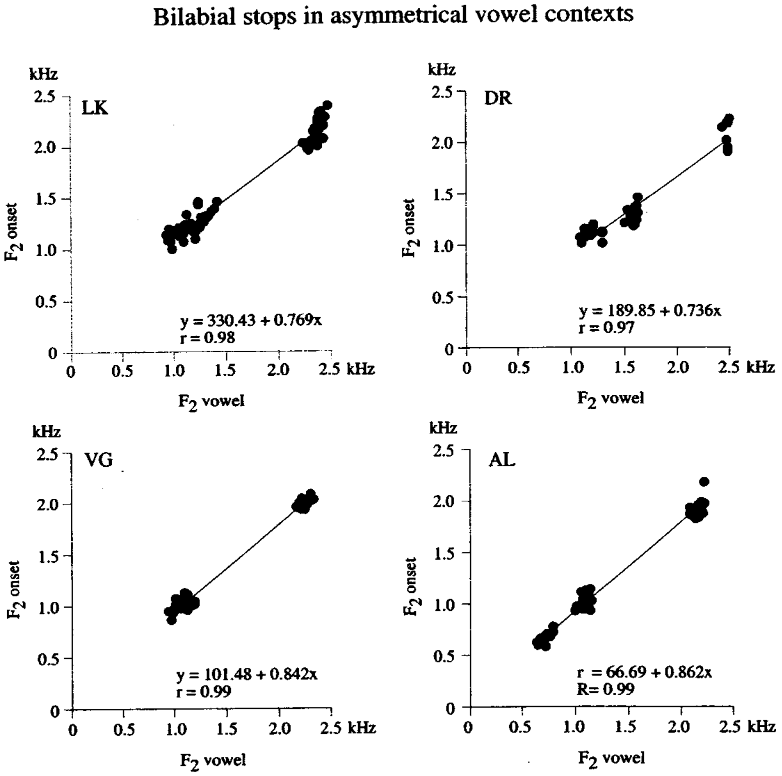

FIG. 2. Scatter plots, locus equations, and correlation coefficients for the consonant /b/ produced in asymmetrical vowel contexts.

The magnitude of the tongue movement trajectory during the oral closure was obtained by summing the Euclidean distances between successive samples between the acoustically defined onset and offset of the closure for each receiver. A measure of overall tongue movement was then obtained as the average of the four receiver movements during the oral closure. The same procedure was used to measure the average tongue movement from the acoustically defined onset of the second vowel to the end of the tongue movement from the first to the second vowel.

The kinematic signals represent the movements of receivers placed at the midline of the lips, the jaw, and the tongue. When presenting the results, we will use the terms "tongue body receiver" and "tongue body" 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 lips, or the tongue. The tongue and lower lip signals contain the contribution of the jaw. These are the appropriate movements to examine when the focus of the analysis is on the lower lip and the tongue as end effectors. It is reasonable to assume that a speaker has joint control of different articulators during speech production to produce the desired results.

II. RESULTS

Figure 2 shows plots of the second formant at vowel onset and vowel steady state together with the locus equations for the sequences with a voiced bilabial stop /b/ and asymmetrical vowel contexts. The derived locus equations show a high degree of linearity and the slope values are similar to the ones reported previously in the literature. To see if there was a difference in the slope of the locus equations between symmetrical and asymmetrical vowel contexts, separate regressions were calculated for the symmetrical contexts. The slopes for the symmetrical vowel contexts were 0.889, 0.712, 0.878, and 0.948 for subjects LK, DR, VG, and AL, with all *r* values 0.99. Thus, with the exception of subject DR, the slopes were higher in the symmetrical vowel context.

The analysis of locus equation slopes and the measure of articulatory overlap between a labial stop consonant and the following vowel will focus on differences between speakers. Chennoukh *et al.* (1997) interpreted their results in terms of differences between speakers. In addition, within-speaker comparisons are difficult, since the calculation of the locus equation requires that several different vowel contexts be used. Figure 3 plots the slope of the locus equation for each

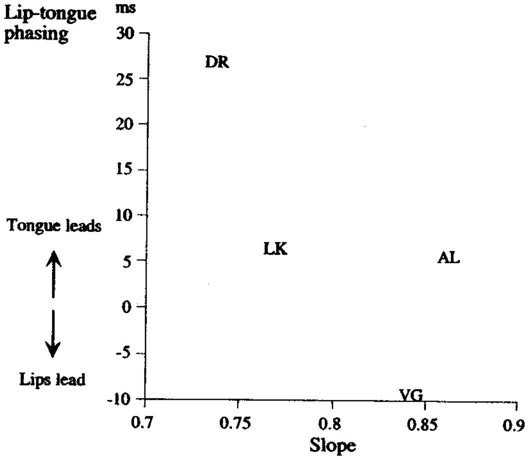

FIG. 3. The slope of the locus equation for each subject plotted against the interval between onset of tongue movement from the first to the second vowel and the onset of the lip closing movement for the consonant. The letters refer to the four subjects.

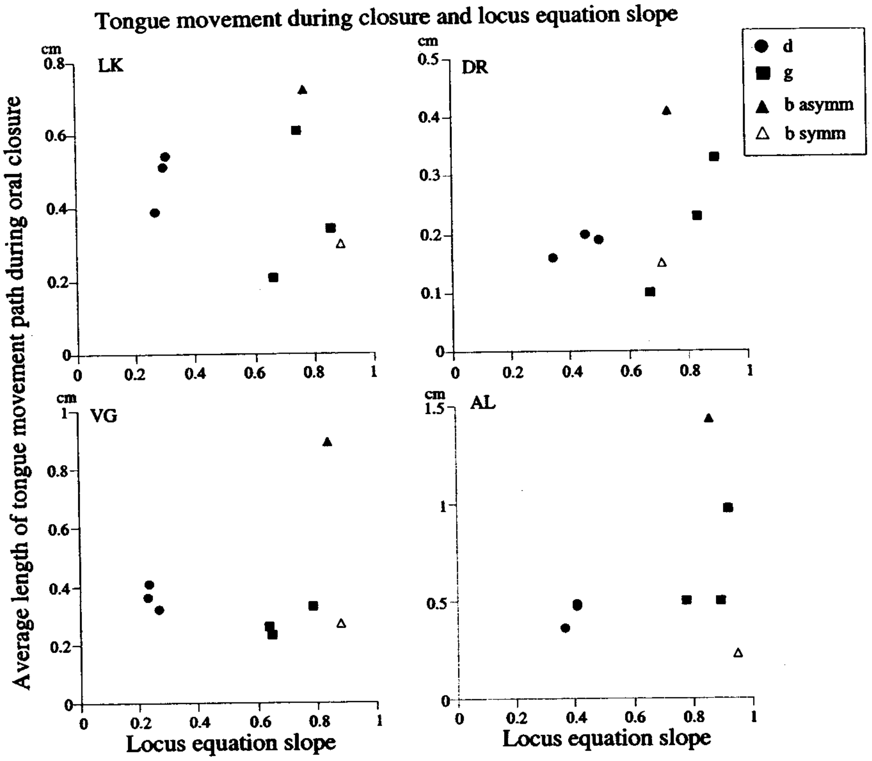

FIG. 4. Plot of the slope of the locus equation and the magnitude of the tongue movement during the stop closure.

subject against the interval between the onset of the tongue movement from the first to the second vowel and the onset of the lip closing movement for the consonant. The slope of the locus equation is that for the asymmetrical vowel contexts. The measure of lip-tongue phasing has been averaged across all sequences with a voiced bilabial stop /b/ and asymmetrical vowel contexts. The subjects are represented by their initials. According to the hypothesis that a higher slope is related to a greater degree of articulatory overlap, we would expect the following relationship between the two variables. In those instances where the tongue movement starts well before the lip movement, thus signifying a large degree of articulatory overlap, the slope of the locus equation should be high. That is, as the tongue movement leads the lip movement, the slope of the locus equation should increase. However, that is not what is shown in Fig. 3. The results show rather the opposite. We should note here that even though the lip movement may lead the tongue movement, the tongue movement does not necessarily start after the oral closure. The reason is that the onset of the lip movement, as defined here, always precedes the oral closure, cf. Fig. 1.

Figure 4 plots the slope of the locus equation against the magnitude of the tongue movement during the oral closure for the stop consonant. The results for the velar and alveolar consonants are shown separately for the three different first vowel contexts. In addition, the results for the bilabial stops in symmetrical and asymmetrical vowel contexts are shown. The plots show that for all four subjects, the slope for the velar stop is higher than that for the alveolar consonant. The working assumption here is that a large tongue movement during the closure is associated with more coarticulation, and hence a higher slope. The relationship between the two variables is not very strong and quite different between subjects, however. Note that the labial stop in the asymmetric vowel environment is associated with the largest tongue movements during the closure for all subjects. It does not necessarily have the highest slope, however. In comparison, the tongue movement is much smaller for the bilabial stop in a symmetric vowel environment, but the slope difference between the labial stops in these two vowel environments is rather small. Although the slope is always higher for the velar than for the alveolar stop, the magnitude of the tongue movement during the oral closure tends to be larger for the alveolar stop for subjects LK and VG, and about the same for subjects DR and AL. In some instances, there is almost a linear relationship between the two variables, e.g., the alveolar stops for subjects LK and AL, and the velar stops and the (symmetrical) labial stops for subject DR. Here, the relationship between tongue movement and locus equation slope is, in fact, the expected one.

Figure 5 plots the slope of the locus equation for each subject against the magnitude of the tongue movement during the vowel following the consonant. According to the hypothesis, one might expect that when there is a small amount of tongue movement during the second vowel, the slope of the locus equation should be high. This is so because most of the tongue movement would have been anticipated and occurred during the consonant, since it would allow it. A smaller movement during the second vowel would correspond to greater articulatory overlap and thus a steeper slope. One thing to note in Fig. 5 is that the bilabial stop in the asymmetric vowel context has the least amount of tongue movement during the second vowel. The locus equation slope is not necessarily the highest for this consonant, however. Only subject AL shows an overall negative relationship between the two variables plotted in Fig. 5, which is the predicted result. For the other three subjects, there is no clear overall relationship. In two instances, the velar stops for sub-

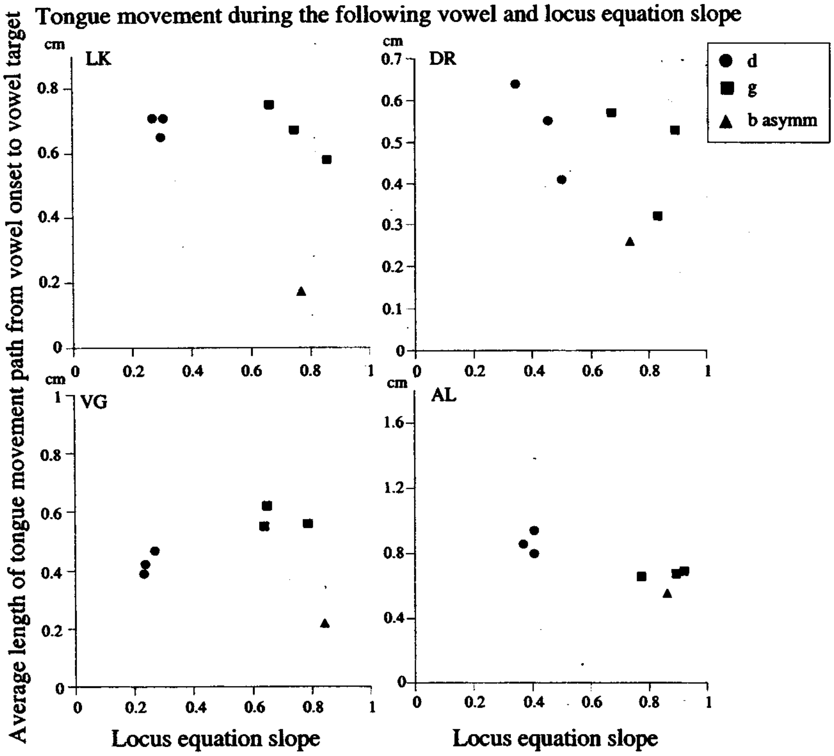

FIG. 5. Plot of the slope of the locus equation and the magnitude of the tongue movement during the vowel following the stop consonant.

ject LK and the alveolar stops for subject DR, there is an almost linear negative relationship as predicted.

III. DISCUSSION

The locus equations obtained in the present study are in good agreement with those presented in other studies. Alveolar consonants have a less steep slope than labial and velar consonants. When the velar consonants are analyzed across front and back vowel contexts, their slope is as high as that for the labial consonants. Before discussing the present results, it is important to note that the articulatory analyses presented here are, by necessity, coarse grained. This is so because the nature of locus equations requires that they be obtained across a variety of vowel contexts. A single consonant production does not have a locus equation slope, so comparisons cannot be made at a finer grain of analysis. Another limitation is that only four receivers placed on the midline of the tongue have been recorded. This restriction on receiver placement along the midline is an inherent limitation on the recording technique used. The movements of the rearmost part of the tongue have not been recorded and analyzed due to the difficulty of placing receivers in this area, and also because grooving of the tongue may make the recordings unreliable due to receiver tilt. In spite of these limitations, the present results form a first examination of locus equation slope and articulatory overlap, or coarticulation.

The present results do not show any real support for the idea that the slope of the locus equations is related to the degree of coarticulation between the consonant and the vowel. At least, this is not the case for the three measures of coarticulatory overlap used here. The first one is essentially adapted from Chennoukh *et al.* (1997), who found the expected relationship in their simulations. One reason for these conflicting results appears to be that their simulations included some degrees of overlap that are not found in human productions. In particular, the tongue movement hardly ever starts after the oral closure for the consonant and never at the release of the consonant (cf. Löfqvist and Gracco, 1999). The latter was one condition used in the simulations, however. Another reason is most likely that human subjects vary the amplitude, velocity, and duration of their tongue movements in different ways. Again, this is in contrast to the simulations, where these parameters were held constant.

The second measure of coarticulation showed a substantial difference in the amount of tongue movement during the oral closure for the bilabial stops in symmetrical and asymmetrical vowel contexts, but a very small difference in locus equation slope. Similarly, there was a consistent difference in locus equation slope between alveolar and velar stops for all subjects, with the slope being higher for the velar consonants. However, the amount of tongue movement during the closure did not show any consistent related difference with a larger movement for the velar stops.

Although it may be generally true that a labial stop consonant will allow quite substantial movements of the tongue during the oral closure [more than 50% of the vowel-to-vowel trajectory in a VCV sequence (Löfqvist and Gracco, 1999)], this assumes that the context in fact requires movements of the tongue. That is not the case in a VCV sequence where the two vowels are identical. Hence, Fig. 5 shows a substantial difference in the amount of tongue movement for a bilabial stop in symmetrical and asymmetrical vowel contexts, but a very small difference in locus equation slope. Possibly, the slope is so high in these two cases that the slope measure is unable to capture the difference in tongue movement. It is more troublesome for the hypothesized relationship between locus equation slope and coarticulation that the articulatory difference between alveolar and velar stops are not really related to the great difference in slope.

The third measure was based on the assumption that a large degree of articulatory overlap between a consonant and a following vowel would result in a small movement during the vowel, since most of the movement has already been made during the consonant. Again, this measure did not show the overall expected relationship to the slope of the locus equation. One reason for concern here is that the relationship between articulation and acoustics is lawful but not linear.

It thus appears that the hypothesis about a link between locus equation slope and degree of articulatory overlap (coarticulation) as operationally defined here should be questioned. The hypothesis is not supported because of the finding that labial stops in different vowel contexts have similar slopes but differ in degree of coarticulation, and also by the finding that alveolar and velar stops differ in slope but show the same degree of coarticulation. Although there were a few cases for some subjects where the expected relationship between slope and coarticulation was found, the overall results suggest otherwise. Hence, it appears that caution is necessary in making claims that locus equation slope can be used to assess differences in coarticulation and applied to studies of developmental issues (e.g., Sussman *et al.*, 1996), or deviant speech production, as suggested by Sussman *et al.* (1998).

The technique for recording articulatory movement used here only provides information on receivers placed at the midline of the articulators under investigation. Hence, the overall vocal tract shape cannot be captured. This is a limitation of the technique that can only be alleviated by trying to get estimates of the tongue shape by curve fitting procedures. Another way to address the relationship between degree of coarticulation and locus equation slope would be to use an analysis-by-synthesis approach with articulatory models that allow selective manipulations of articulators (cf. Lindblom, 1998). One simulation briefly reported by Lindblom (1998) does, in fact, show some support for a relationship between slope and coarticulation. In this simulation, a /dV/ syllable was modeled using two conditions. In one of them, the tongue body had the shape for the vowel during the oral closure for the stop. In the other condition, the tongue shape was more neutral. The derived locus equation slope was 0.94 in the first condition and 0.07 in the second. Further simulation work using realistic variations in tongue shape would obviously be useful for understanding coarticulatory overlap and acoustics.

The arguments for a relationship between the slope of the locus equation and the degree of coarticulation between the consonant and the vowel in a CV sequence have been based on inferences about articulatory organization based on phonological and/or phonetic descriptions of consonants and vowels. It appears from the present results, however, that making predictions about the detailed characteristics of articulatory movements in connected speech on such a basis is at best difficult and at worst impossible, as has also been suggested by Mooshammer *et al.* (1995) and by Dembowski *et al.* (1998).

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[1] Although these simulations do provide support for a relationship between degree of articulatory overlap and locus equation slope, there are a few things that should be considered before these results are accepted. All the movements used in the simulations were of constant duration, amplitude, and velocity. Perhaps more importantly, the variation in the amount of overlap between the three conditions is quite extreme compared to human articulatory data. In fact, a recent study by Löfqvist and Gracco (1999) indicated that the onset of the tongue movement from the first to the second vowel in a sequence of a vowel, a bilabial stop, and a vowel almost always occur before the oral closure for the consonant has occurred. Although there is variability in the temporal phasing of the lip closing movement and the tongue movement, both the lip and the tongue movements start before the oral closure for the consonant.

[2] The temporal interval between movement onset and peak velocity does not appear to change very much across variations in movement amplitude for some speech movements (e.g., Löfqvist and Yoshioka, 1981; Munhall and Ostry, 1985) and also for arm movements (Freund and Büdingen, 1978). Hence, the same might well be true for acceleration.

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