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**Recording Speech Movements Using Magnetometry:
One Laboratory's Experience**

ANDERS LÖFQVIST, VINCENT L. GRACCO, and PATRICK W. NYE

Address: Haskins Laboratories, 270 Crown Street, New Haven, CT 06511-6695, USA

Phone: (203) 865-6163 Fax: (203) 865-8963

E-mail: LOFQUIST@YALEHASK (Bitnet),

LOFQUIST%YALEHASK@VENUS.YCC.YALE.EDU (Internet)

1 Introduction

For studies of speech production, safe and reliable methods for transducing articulatory movements are necessary. Over the years, several different methods have become available and been applied to speech articulation, such as x-ray, x-ray microbeam, ultrasound, strain gages, optoelectronic techniques, and Magnetic Resonance Imaging. While x-ray provides an image of the whole vocal tract, its inherent safety problems (arising from subject exposure to ionizing radiation) impose limitations on the amount of data that can be recorded. The x-ray microbeam reduces the radiation exposure, but at present no system is available for general use. Strain gauges and optoelectronic procedures offer excellent resolution and can provide three-dimensional records but only of lip and jaw movements. Ultrasound is limited in the number of articulators that can be tracked simultaneously. Magnetic Resonance Imaging provides excellent images of the whole vocal tract but, at present, image acquisition times are too long to permit movement tracking; this may well change in the near future, however. The development of electromagnetic transduction as an alternate measurement technique (Schönle, 1988; Perkell, Cohen, Svirsky, Matthies, Garabieta, and Jackson, 1992) offers a number of advantages compared to other methods, provided that proper care is taken during data collection - many receivers can be tracked simultaneously, the spatial and temporal resolution is good, the absolute positions of receivers can be measured, and all the necessary signal processing can be automated and simplified. The present paper presents a number of our experiences at Haskins Laboratories in using an electromagnetic articulometer. Some of our current thinking about, and approaches, to processing magnetometer signals will be illustrated with data on articulatory movements in VCV sequences, with particular emphasis on tongue movements. Since several of our approaches are still exploratory, they are likely to change in the future. Other practical and theoretical problems that we have encountered are discussed by Gracco and Nye (1993).

Processing two-dimensional movement signals like those obtained from a magnetometer system often requires the handling and storing of a large amount of data. In a typical experiment, x and y position signals are obtained from which velocity and acceleration may be derived. In some systems, a correction index is also recorded for each receiver coil, providing information on the operation of the tilt correction algorithm. If data from nine receivers have been recorded together with the audio signal during the production of many utterances with several repetitions of each, the number of data files tends to grow very quickly. Software is required for opening and displaying multiple signal files, marking events such as the peaks, valleys and zero crossings in signals, and making measurements of the labeled signals. In addition to displaying position or velocity over time, it is also very useful to display x-y position plots of signals so that articulatory movement trajectories can be observed. Furthermore, it is helpful to have routines for filtering, differentiating, and averaging of signals and to derive new representations of the data using functions of the position information. Since many of the processing routines will be used repetitively on tokens and utterances, it saves time to automate these routines as much as possible. At Haskins, we have developed a software package, Haskins Analysis Display and Experiment System (HADES), that incorporates most of these features (see Rubin and Löfqvist, in preparation, for a more detailed description). All of the signal plots in this paper have been created using HADES.

2 Experimental procedures

The movement data to be discussed here were recorded using a three-coil transmitter system known by its acronym EMMA and described by Perkell, Cohen, Svirsky, Matthies, Garabietta, and Jackson (1992). Receivers were placed on the upper and lower lips, the lower incisors, and at four positions on the tongue. For the sake of convenience, the tongue receivers will be referred to by their locations as tongue tip, tongue blade, tongue body, and tongue root, although we acknowledge that the boundaries between these parts of the tongue are imprecise, and the receiver referred to as 'tongue root' actually has a higher and more forward position than is customary for that location, cf. Figure 1. In addition, receivers placed on the bridge of the nose and on the upper incisors were used for correction of head movements. The tongue receivers were attached by means of Ketac-Bond (ESPE) while for the others Iso-Dent (Ellman International) was used. Care was taken during each receiver placement to insure 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 then rotated and translated to bring the occlusal plane into coincidence with the x axis.

Two male subjects were recorded: VG, a native speaker of American English and AL, a native speaker of Swedish (the second and first authors, respectively). For subject VG, the positions of the tongue receivers, measured relative to the tongue tip with the tongue protruded, were 1.2, 2.4, 3.6, and 5.5 cm. The corresponding values for subject AL were 0.8, 2.2, 3.4, and 5.4 cm. The linguistic material consisted of VCV sequences with all possible combinations of the vowels /i, a, u/ and the stop consonants /p, t, k, b, d, g/. The sequences were placed in the carrier phrase "Say ... again" with sentence stress occurring on the second vowel of the VCV sequence. Ten tokens of each sequence were recorded at self-selected speaking rates and intensity levels.

The articulatory movement signals (induced voltages from the receiver coils) were sampled at 625 Hz after low-pass filtering at 300 Hz. The speech signal was pre-emphasized, low-pass filtered at 9.5 kHz and sampled at 20 kHz. 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 18 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. The same algorithm and smoothing process was used to compute the second derivative, i. e. the acceleration.

In order to get an overview of articulatory movement trajectories during the sequences, signal averaging was used to obtain average position and velocity signals for all utterances. For the purpose of averaging, a label was placed at the acoustic onset of the second vowel in the VCV sequence. The averages were then made over a temporal window extending 250 ms to the left of the label and 100 ms to the right of the label. Given that the duration of the oral closure differs for voiced and voiceless stops, the window covered different parts of the articulatory record for different utterances. Since the only purpose of the averaging was to obtain the basic characteristics of the movement trajectories, the use of a fixed window based on an acoustically defined label was judged to be sufficient. Measurements of receiver position and movement amplitude, velocity and duration were always made on signals from individual repetitions of the VCV sequences; these measurements were later subjected to statistical analysis.

A plot of receiver positions during production of the three sustained vowels /i, a, u/ by subject VG is shown in Figure 1. In this and following plots of the same kind, the subject is facing to the left. From left to right in Figure 1, the receivers appear on the upper and lower lip, the jaw, the tongue tip, the tongue blade, the tongue body, and the tongue root. Note that the tongue tip receiver during the production of the vowel /a/ is positioned higher than the tongue blade receiver. This is a somewhat unexpected observation which might possibly indicate that the receiver was misaligned and that the recorded signal is erroneous. We have carefully examined the correction index, however, to see if it revealed any out of range values, or excessive variability for this particular production, but we have found no evidence of receiver misalignment. We thus assume that the subject raised the tongue tip in this particular case. We have, in fact, seen several other instances of the same kind of tongue tip movement in data from this subject.

Receiver positions during sustained vowel production

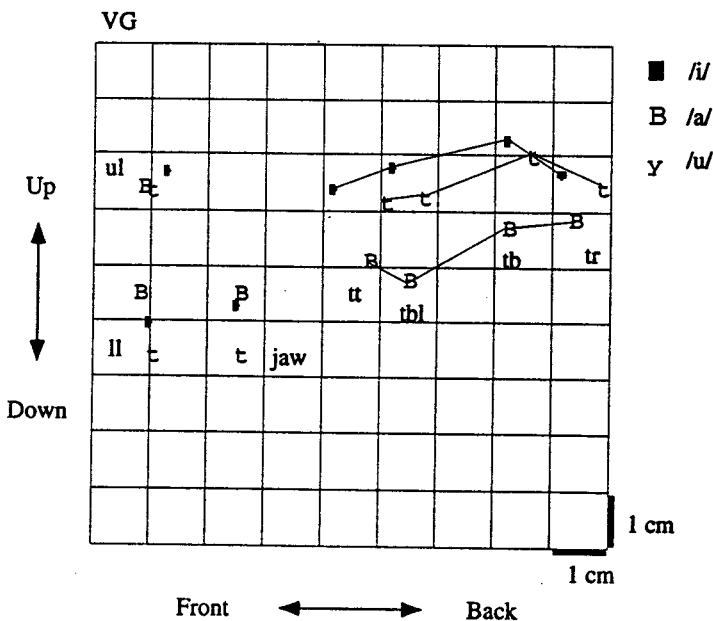


Figure 1. Receiver positions during sustained production of the vowels /i, a, u/ by subject VG. The receivers are identified by the following abbreviations: ul - upper lip, ll - lower lip, jaw, tt - tongue tip, tbl - tongue blade, tb - tongue body, tr - tongue root. The tongue receiver locations for the three vowels have been connected by lines.

3 Linguistic decomposition of articulatory records

In speech research, it is a common practice to associate articulatory and acoustic measurements with linguistic units in order to describe the properties of these units. This practice is not unproblematic, however. The cause of this problem is that the units of speech can be described in two different modes. Let us briefly elaborate on this topic and its potential implications for the measuring process in speech research.

In describing speech and language, it is common to adopt what can be referred to as either the linguistic or the dynamic mode (see Pattee, 1977, for further discussion of this distinction). In the linguistic mode, the units of language are described without a temporal domain. For example, most phonological descriptions use a set of symbols that can be arranged in different ways to produce different messages. Although the primitives used for this type of analysis vary depending on the theoretical framework being adopted, the units are commonly described as being discrete and serially ordered. The dynamic mode is used for describing articulatory and acoustic properties of speech. Here, the focus is on the time-varying properties of articulatory movements and/or the spectral characteristics of the speech signal. This necessarily implies a temporal domain. The linguistic units of speech are no longer discrete, since it is a salient feature of speech production that the units show a considerable amount of articulatory influence and overlap. These effects are commonly referred to as coarticulation, coproduction, blending or aggregation. Thus, the movements associated with different production units blend seamlessly with each other, and in the articulatory record there are very few, if any, identifiable boundaries between units. Consequently, the movements necessary for the production of a given unit differ according to its context, and likewise its acoustic properties also vary according to context. A further result of this overlap is that at any one point in time, the vocal tract is an aggregate of different production units (cf. Fowler and Smith, 1986; Saltzman and Munhall, 1989; Löfqvist, 1990). The obvious acoustic consequence is that a single temporal segment of the signal contains influences from several production units (see Fant, 1962, for an early discussion).

Throughout the history of the study of speech, much effort has been devoted to arguments about these two modes of description. One famous depiction of their different natures is provided by Hockett (1955), who makes an analogy between speech production and a row of raw Easter eggs on a conveyor belt, being smashed between the two rollers of a wringer. The implication is that the linguistic units of speech are distinct and serially ordered before they are all smeared together in the process of articulation: "The flow of eggs before the wringer represents the impulses from the phoneme source; the *mess* that emerges from the wringer represents the output from the speech transmitter." (Hockett, 1955, p. 210; italics added.) We should note that Hockett does not imply that it is impossible to recover the original eggs that went into the mess. He duly comments that an inspector examining the passing mess could "decide, on the basis of the broken and unbroken yolks, the variously spread-out albumen, and the variously colored bits of shell, the nature of the flow of eggs which previously arrived at the wringer" (ibid.) and further notes that the inspector represents the hearer.

Like Hockett's inspector, the scientist studying speech motor control is examining the 'mess' flowing from the wringers and tries to overlay a linguistic segmentation grid onto the continuously changing articulatory record. Since the beginning of this century, speech scientists have discovered over and over again that boundaries between linguistic units are not easily found in the articulatory or acoustic record. For example, 60 years ago in Germany, Menzerath and de Lacerda (1933) published the first systematic treatise on coarticulation and stated emphatically that such boundaries do not exist. Since then, although we know full well that a linguistic segmentation of articulatory and acoustic records

is an elusive art, we still try to do it. Moreover, it appears that this methodological problem is faced anew whenever new techniques for studying speech become available (cf. Lisker, 1974, for a review of different approaches to segmenting acoustic records).

One illustration of this problem is given in Figure 2. The top panel in Figure 2 shows the x-y trajectory of the tongue body receiver during the production of the utterance "Say aki again". The bottom panel shows the acoustic signal and the x and y position signals over time for the same receiver during the same utterance. The movements are continuous. The usual approach to making measurements is to mark zero crossings in the first derivative of the position signal, velocity, and use these marks as onsets and offsets of movements. Movement onsets and offsets can then be used as the endpoints from which movement amplitude and duration are measured. Four points corresponding to zero crossings in the associated velocity signals have been marked in the position signals shown in Figure 2.

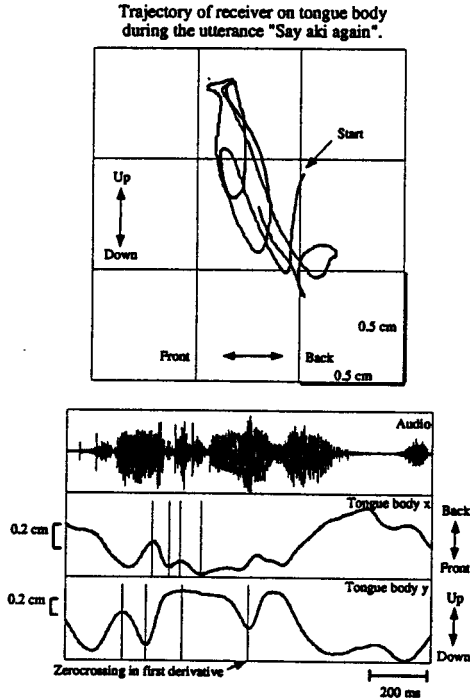


Figure 2. The top panel plots the x-y position of the tongue body receiver during a production of the utterance 'Say aki again' by subject VG. The bottom panel shows corresponding time plots of audio, tongue body x position and tongue body y position.

As long as movements are measured in a single dimension, this approach may not be too problematic. However, when studying movements in two or three dimensions, we are facing a more difficult problem. For example, if one is interested in examining tongue behavior during the production of velar stops, as illustrated in Figure 2, it would be logical to make the measurements of position in x and y at the same point in time. However, as is evident from Figure 2, the zero crossings in the two signals do not occur at the same points in time - a fact which should not be unexpected because the tongue can move independently in the two dimensions. As we will see below, while movement onsets and offsets along the x and y axes do not necessarily coincide in time, they are highly correlated with each other. Moreover, there is, of course, the possibility that during the temporal interval where the velar consonant has its greatest influence over the vocal tract, no zero crossing will occur, or a different number of zero crossings will occur in the x and y velocity signals. This is evident in Figure 2, where there are three zero crossings in the x signal during the period of voicelessness in the acoustic signal but only one in the y signal. The one occurring in the y signal indicates the end of the tongue body raising gesture for the velar closure

One possible way of solving this particular problem is to apply the linguistic segmentation grid to signals that are *derived* from the articulatory record. Two such signals are tangential velocity and curvature:

Tangential velocity:
$$v = \sqrt{\dot{x}^2 + \dot{y}^2}$$

Curvature:
$$c = (\dot{x}\ddot{y} - \ddot{x}y) / v^3$$

These signals have been used in studies of hand movements and writing (Morasso, 1983a, b; Edelman and Flash, 1987) and may be potentially useful in the study of speech movements. In fact, tangential velocity has already proved itself useful for specifying points in time for measurements, while our use of curvature is still at the exploratory stage. Curvature signals, in particular, may provide the opportunity to perform geometric analyses of the movement dynamics and are not limited to measurements at selected points in time. One example of such an approach are studies by Munhall, Ostry and Parush (1985), Ostry and Munhall (1985), and Adams, Weismer and Kent (1993) on the shape of velocity profiles for speech and non-speech movements.

Figure 3 shows plots of x and y position, tangential velocity and curvature over time for a synthesized repetitive movement. An x - y plot of the position signals is also shown. From this plot, the relations between position and the two other signals can be observed. Tangential velocity is at minima at the points marked by circles and at maxima at the points marked by squares in the x - y and the time plots. Curvature has its largest negative values at the points marked by circles. The sign of curvature shows the direction of the movement, negative for clockwise movement and positive for counter-clockwise movement. Hence, changes in the direction of articulatory trajectories can be obtained from zero crossings of curvature. This figure, and the following four figures using the same types of

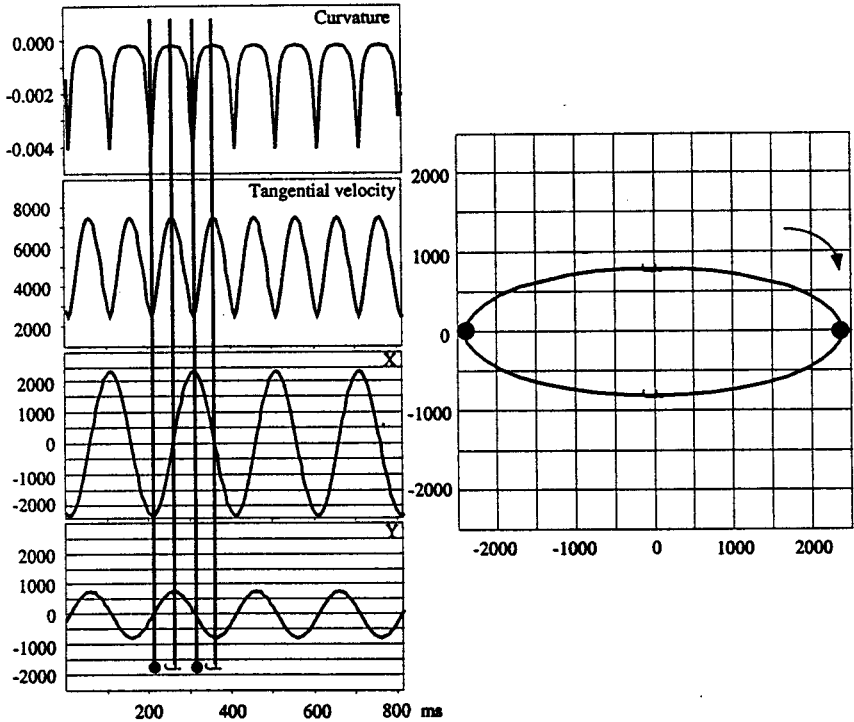


Figure 3. The relationship between x and y position, tangential velocity, and curvature for a synthesized repetitive movement.

plots, further illustrates the usefulness of simultaneous time plots and position-position plots in analyzing articulatory movement trajectories.

Figures 4-7 exemplify plots of x and y position, tangential velocity and curvature during different utterances. In order to avoid unnecessary details in these plots and to make them easier to read, the movement signals represent signal averages based on ten repetitions of each utterance. For purposes of illustration, the acoustic signal of a single token of the same utterance has been added in the top panel of each figure. The shaded portion of the acoustic signal indicates the temporal window used

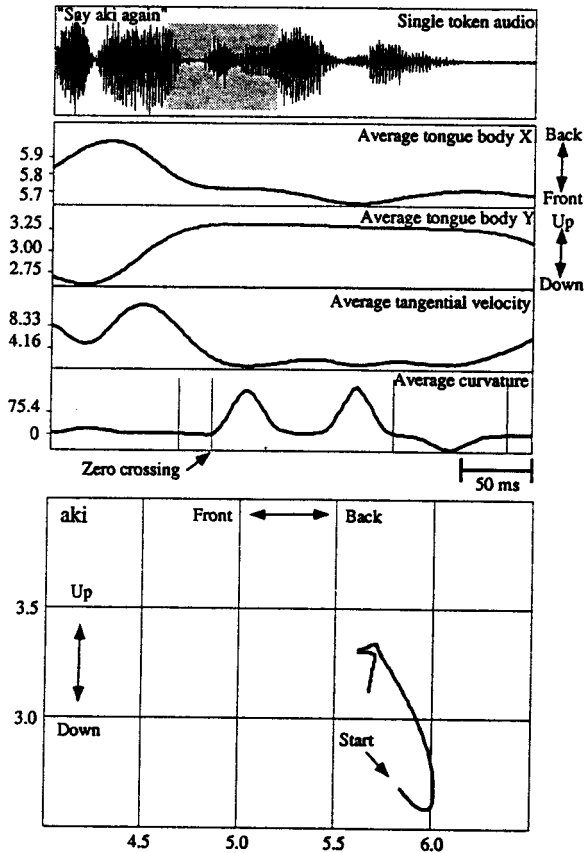


Figure 4. Time and position plots of average tongue body receiver movements during production of the phonetic sequence /aki/. The top panel shows the acoustic signal for a single token of the utterance. The shaded part of the acoustic signal corresponds to the temporal window used for signal averaging.

for signal averaging. Note that the temporal scales for the acoustic and the movement records are thus different.

In the sequence /aki/ in Figure 4, the tongue body receiver moves downwards and backwards from the diphthong in the carrier phrase to the position for the /a/ vowel. From there, the receiver moves upwards and forwards for the velar closure, continuing its forward movement until it reverses direction and begins to move backwards. As the receiver starts moving down, the movement changes direction from clockwise to counterclockwise. This is indicated by the zero crossing in the curvature

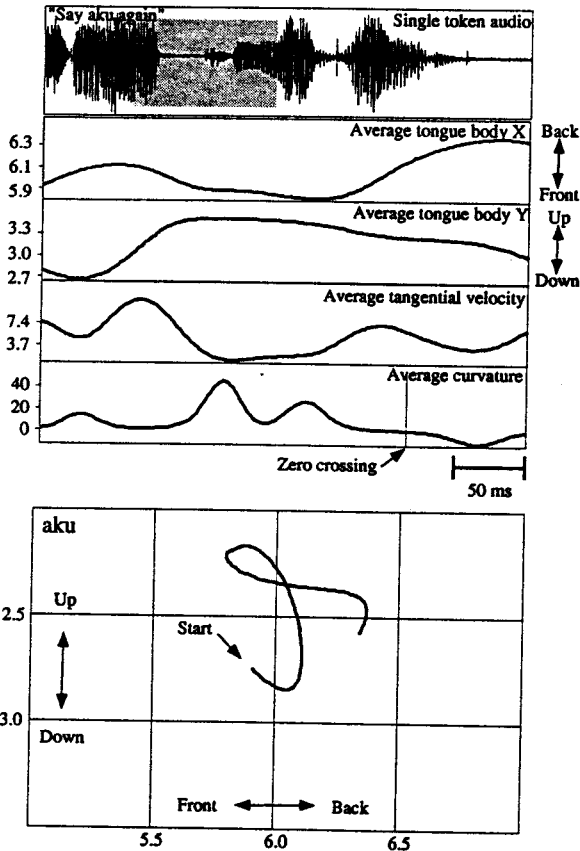


Figure 5. Time and position plots of average tongue body receiver movements during production of the phonetic sequence /aku/. The top panel shows the acoustic signal for a single token of the utterance. The shaded part of the acoustic signal corresponds to the temporal window used for signal averaging.

signal. In the curvature signal, there are four marked peaks, three positive and one negative, associated with the sharp 'bends' in the x-y plot trajectory. At these points in time the tangential velocity shows low values.

Figure 5 shows the same signals for the sequence /aku/. Initially, the receiver moves backwards and downwards to the position for the /a/ vowel. Next, the receiver moves forward and up for the velar closure. The movement then continues forward until it loops downwards and backwards. There is a minimum in the tangential velocity signal that occurs as the receiver reaches its highest point during the velar closure. Again, four peaks occur in the curvature signal, three positive and one negative. The grid in the x-y plots in these figures represents the coordinate system for the movements. Hence,

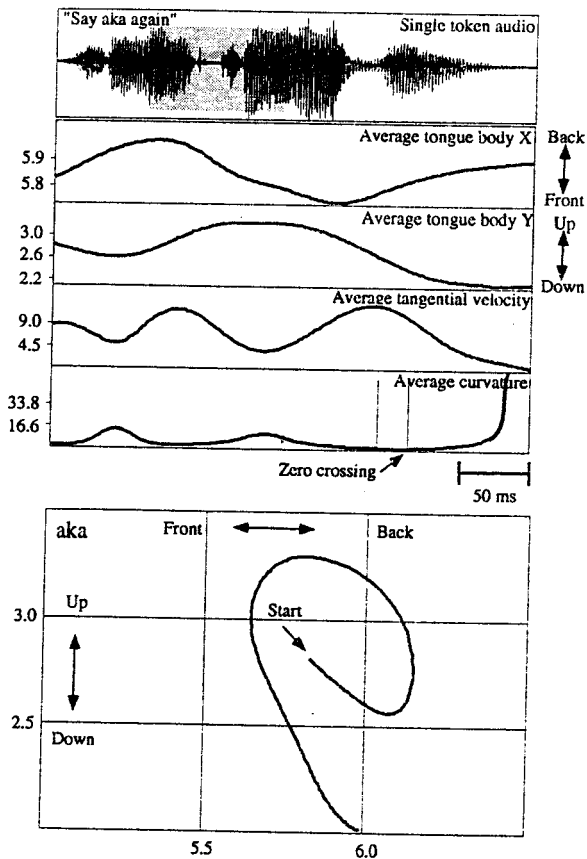


Figure 6. Time and position plots of average tongue body receiver movements during production of the phonetic sequence /aka/. The top panel shows the acoustic signal for a single token of the utterance. The shaded part of the acoustic signal corresponds to the temporal window used for signal averaging.

the absolute positions of the tongue body receiver can be compared across utterances. Inspection of where the highest point of the tongue body receiver occurs in the x dimension in Figures 4 and 5 shows that it is more forward in the /aki/ sequence in Figure 4 than in the /aku/ sequence in Figure 5. This is most likely due to the influence of the following vowel.

The sequence /aka/ is shown in Figure 6. Here, the tongue body receiver shows a counterclockwise semicircular trajectory. All the movements in Figures 4, 5, and 6 are counterclockwise during most of their trajectories, as has been noted in earlier work (cf. Houde, 1967; Perkell, 1969; Kent and Moll, 1972; Schönle, 1988; Munhall, Ostry, and Flanagan, 1992).

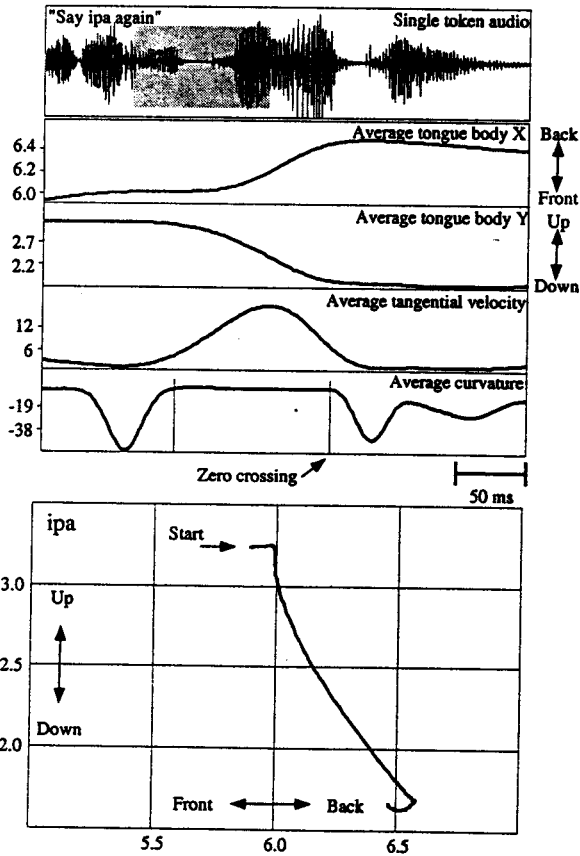


Figure 7. Time and position plots of average tongue body receiver movements during production of the phonetic sequence /ipa/. The top panel shows the acoustic signal for a single token of the utterance. The shaded part of the acoustic signal corresponds to the temporal window used for signal averaging.

Figure 7 shows the sequence /ipa/. Here, the tongue is not involved in the production of the medial consonant, and the receiver moves in a continuous trajectory between the positions for the two vowels. The sign of the curvature indicates that the movement is initially clockwise, then becomes counterclockwise and finally reverts to being clockwise.

In Figures 4-6, a minimum occurs in the tangential velocity signal during the period of voicelessness in the acoustic signal. Since this signal is made up of the x and y position signals, its minimum corresponds to minimum movement of the receiver in both dimensions. It is thus possible to use such a minimum for a measurement of tongue configuration during the consonant. While this approach seems to work for the receiver attached to the part of the tongue most directly involved in making the

closure in the vocal tract, there is nothing to suggest that the tangential velocity signals from the other tongue receivers will show a minimum at the same point in time. There is, in fact, nothing to suggest that such a minimum will consistently occur for all receivers within the temporal window of interest where a given sound dominates the vocal tract. In such cases, several solutions are possible - measurements can be made at different points in time corresponding to the tangential velocity minima of different receivers; measurements can be made from a single point in time corresponding to a minimum tangential velocity for the receiver located on that part of the tongue which is most directly involved in the production of a given sound; or we may choose to ignore those receivers where no reliable criterion can be found for measuring at a given point in time. The last case is illustrated in the sequence /ipa/ shown in Figure 7, where the tongue body is continuously moving during the lip closure for the /p/. The tongue does not appear to have any 'target' for the consonant in this particular context. More generally, the occurrence, or non-occurrence, of tangential velocity minima for different receivers during an interval of the articulatory record may offer a way of assessing how different parts of the tongue are recruited for the production of a given segment. The temporal stability between points in time defined by such minima may provide additional information on how parts of the tongue are coupled together for the execution of a speech task.

In the following sections, we will discuss two aspects of tongue movements using magnetometer data. These aspects are influences of vocalic environment and stop voicing on tongue configuration during velar and alveolar stops, and the timing of vertical and horizontal tongue movements.

4 Contextual influences on receiver positions during stop production

Figure 8 shows mean receiver locations during the velar consonants /k, g/ during VCV sequences where the first vowel is /a/ and the second vowel is /i/, /a/, or /u/. Each position represents the mean of ten measurements. The temporal location of the measurement is based on minimum tangential velocity for each receiver. Hence, the measurements for the different receivers are not necessarily made at the same point in time. We should add, that in our experience so far, it appears to make little difference if measurements are made at points of minimum tangential velocity or at points of zero crossings in the x and y velocity signals for each receiver. The advantage of using tangential velocity is twofold, however. It ensures that the measurement is taken at the same point in time for x and y position, and it establishes a stable criterion for locating this point.

The plots in Figure 8 show the expected influence on the tongue configuration during the velar consonant from the second vowel in the VCV sequence. That is, receiver positions are usually higher and more forward when the following vowel is an /i/ than when it is a /u/. There also appear to be differences in tongue position for the voiced and voiceless velar stops in the same vowel context. For example, the data points associated with the voiced velar stop for subject AL tend to have a more forward position than those for the voiceless cognate. Note, however, that these differences are greater for subject AL than for subject VG. For subject VG, the data points for the tongue body and tongue root receivers are more tightly clustered than those for the tongue blade and tongue tip receivers. While there are several possible reasons for such a difference between subjects, differences in receiver placements may be an important factor. That is, the location of the tongue body receiver relative to the part of the tongue most directly involved in making the closure for the consonant may differ between subjects. Given the tight clustering of the data points for the tongue body receiver of subject VG, in particular in the vertical dimension, this receiver may well be placed close to the point of tongue-palate contact where there is a limited possibility for variations in position. However, the

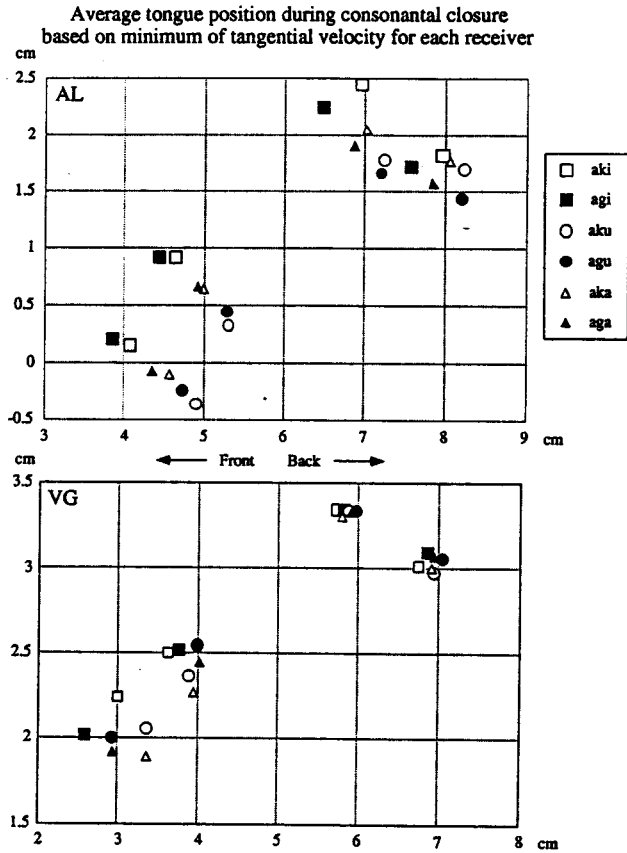


Figure 8. Plot of average receiver positions during consonantal closure for velar stops.

same receiver of subject AL may be placed further away from the point of tongue-palate contact, since it shows a relatively large variability in vertical position (see also Figure 10).

In order to assess the influence of the second vowel and the voicing status of the velar stop on receiver positions, a two-way analysis of variance was used with vowel and voicing as the main factors. There were overall significant main effects of both voicing and vowel for both subjects, with mostly non-reliable interactions. For the sake of brevity, we omit statistical details here.

The same plots for the sequences containing an alveolar stop /t, d/ are shown in Figure 9. Again, clear influences of both the second vowel and the voicing status of the consonant can be seen. Note that for both subjects, the tongue body and tongue root receivers show a pattern of successively lower positions in the order /t/, /u/, /a/. The analysis of variance showed that vowel always has a significant

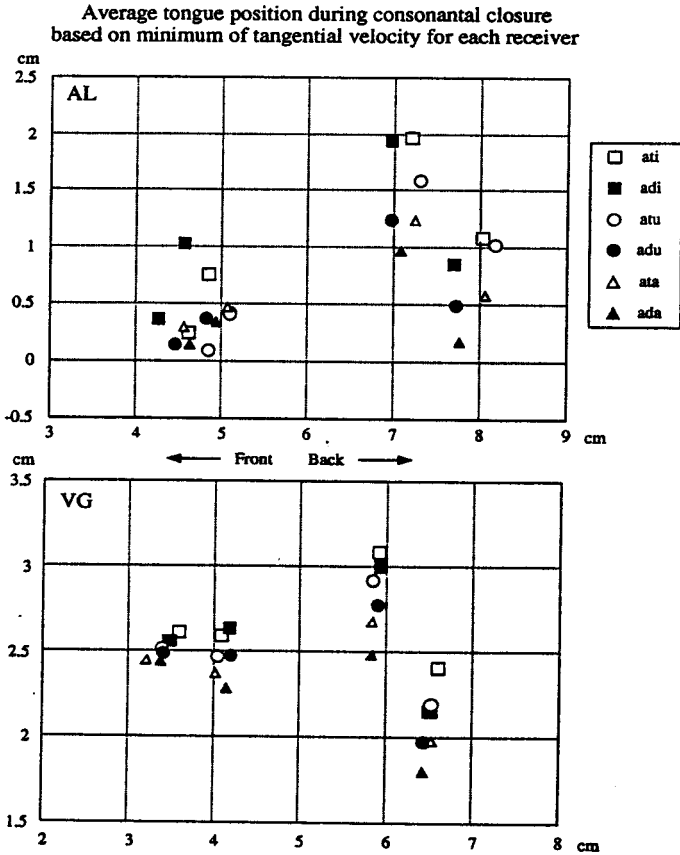


Figure 9. Plot of average receiver positions during consonantal closure for alveolar stops.

main effect for all receivers of subject AL. For subject VG, no significant vowel effect was found for tongue blade x and tongue body x. Voicing showed a less reliable effect, in particular for the tongue tip and tongue blade receivers

Figure 10 shows receiver positions during all productions of the sequences of /aki/ and /aka/ by both subjects. Again, the measurements have been made at the point of minimum tangential velocity for each receiver. In these sequences, visual inspection suggests that there is more variability between tokens for the tongue tip and the tongue blade receivers than for the tongue body receiver. The coefficient of variation showed the same difference. Thus, this evidence suggests that the parts of the

Receiver positions during consonantal closure for single tokens based on minimum of tangential velocity for each receiver

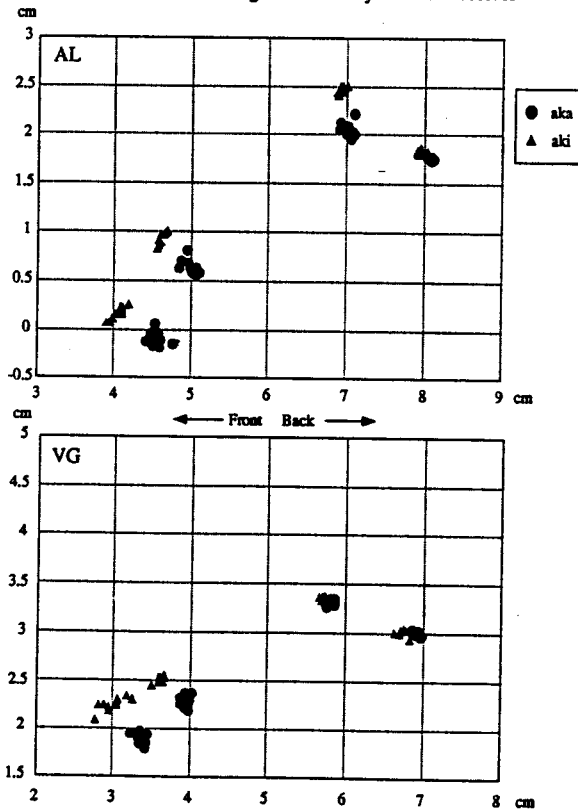


Figure 10. Plot of receiver positions during ten repetitions of the sequences /aka/ and /aki/.

tongue that are less directly involved in making the articulatory closure for the consonant are more free to vary. Again, note the tight clustering of the tongue body receiver data points for subject VG.

5 Temporal coordination of vertical and horizontal tongue movements

Since the tongue can move independently in the vertical and horizontal dimensions during speech, it is of interest to examine the temporal coordination between movements in the two dimensions. Our approach to this problem has been to apply a type of analysis that has proved useful to index temporal cohesion in speech production between the lips and the jaw (see Gracco, 1988, in press; Gracco and Abbs, 1988) and also between oral and laryngeal articulatory movements (e. g. Löfqvist and Yosh-

ioka, 1984). Results are shown in Figure 11. This figure plots the temporal relationship between vertical and horizontal movements in the sequence /aki/ produced by subject VG. The temporal intervals have been defined in the following way. An anchoring point was defined as the occurrence of maximum jaw lowering velocity for the first component of the diphthong in the carrier phrase 'Say'. From this point, the time to reach peak velocity of the x and y movement towards closure for the velar consonant was measured. This point was defined independently in the x and y velocity signals for each receiver. From Figure 11, it is evident that there is a high correlation between the temporal intervals for all receivers. Correlation coefficients for this and other sequences were generally 0.9 or higher. While a detailed analysis of these relationships is beyond the scope of this paper, they can be useful for examining temporal aspects of tongue movement control in speech.

Temporal coordination of vertical and horizontal tongue movements for vowel to stop in "aki"

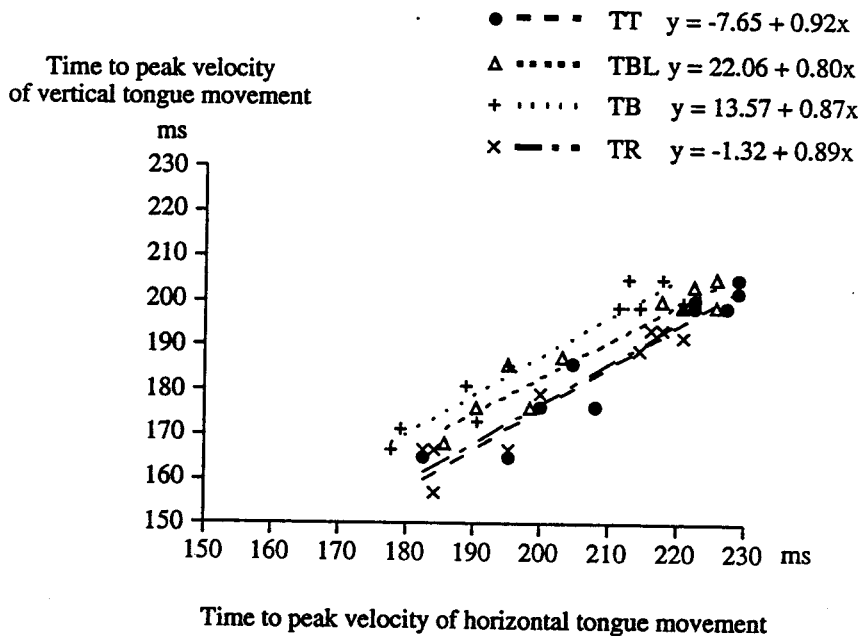


Figure 11. Temporal relationships between vertical and horizontal tongue movements in productions of the phonetic sequence /aki/ by subject VG. See text for further discussion.

6 Summary

In this paper we have suggested that if such measures as *tangential velocity* and *curvature* are computed from the x and y displacements of the articulators obtained by magnetometry, then some encouraging progress can be made toward the long-standing goal of bringing the linguistic and the dynamic perspectives on speech production into greater harmony with one another. Support for this assertion has been drawn from analyses and plots of magnetometer data collected during the production of numerous vowel-stop-vowel sequences. We are currently exploring further the temporal coordination of different parts of the tongue using correlation techniques applied to reference points located by minima in the tangential velocity parameter.

Acknowledgments

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