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ELECTROMAGNETIC TRANSDUCTION TECHNIQUES IN THE STUDY OF SPEECH MOTOR CONTROL

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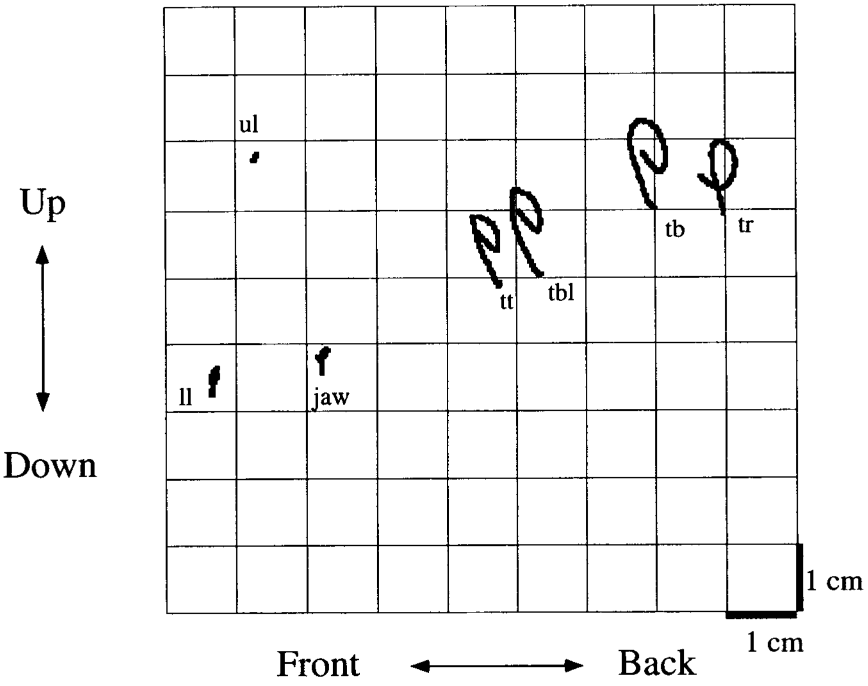
INTRODUCTION

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 most of the necessary signal processing can be automated and simplified. The aim of the present paper is to discuss some approaches to the processing of two-dimensional speech movements, with particular emphasis on tongue movements.

PROCEDURE

The movement data to be discussed here were recorded using a three-coil transmitter system described by Perkell, Cohen, Svirsky, Matthies, Garabieta, 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.

Average receiver trajectories for /aka/



Single token audio signal of "Say aka again"

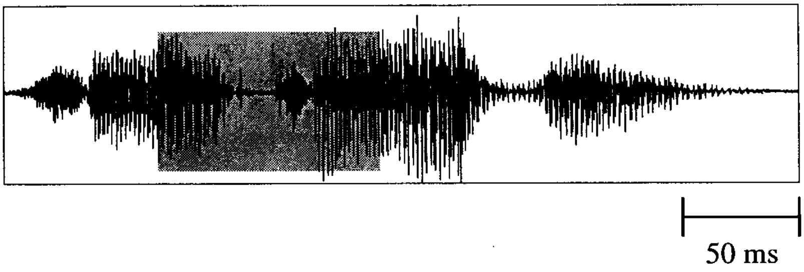


Figure 1. The top panel plots average receiver trajectories for the sequence /aka/ produced by subject VG. The bottom panel plots the audio signal for a single utterance. The shaded portion of the audio signal shows the approximate location of the window used for signal averaging. All four tongue receivers move counterclockwise.

Two male subjects have been recorded: VG, a native speaker of American English and AL, a native speaker of Swedish. 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.

Figure 1 shows articulatory trajectories during the production of the sequence /aka/ by subject VG. This figure plots averages of the horizontal and vertical position signals for all receivers; the trajectories of all tongue receivers move counterclockwise. These averages were made in the following way. 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.

LINGUISTIC AND DYNAMIC DESCRIPTION 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, referred to as either the linguistic or the dynamic mode (see Pattee, 1977, for further discussion of this distinction). Since we have discussed this problem in more detail elsewhere (Löfqvist, Gracco and Nye, in press), only a brief summary of it will be made here.

In the linguistic mode, the units of language are described without a temporal domain. 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. 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).

The scientist studying speech motor control tries to overlay a linguistic segmentation grid onto the continuously changing articulatory record. 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 locate the temporal window where a given production unit has its greatest influence on the vocal tract, mark zero crossings in the first derivative of the position signal, velocity, and use these marks as onsets and offsets of movements. These 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.

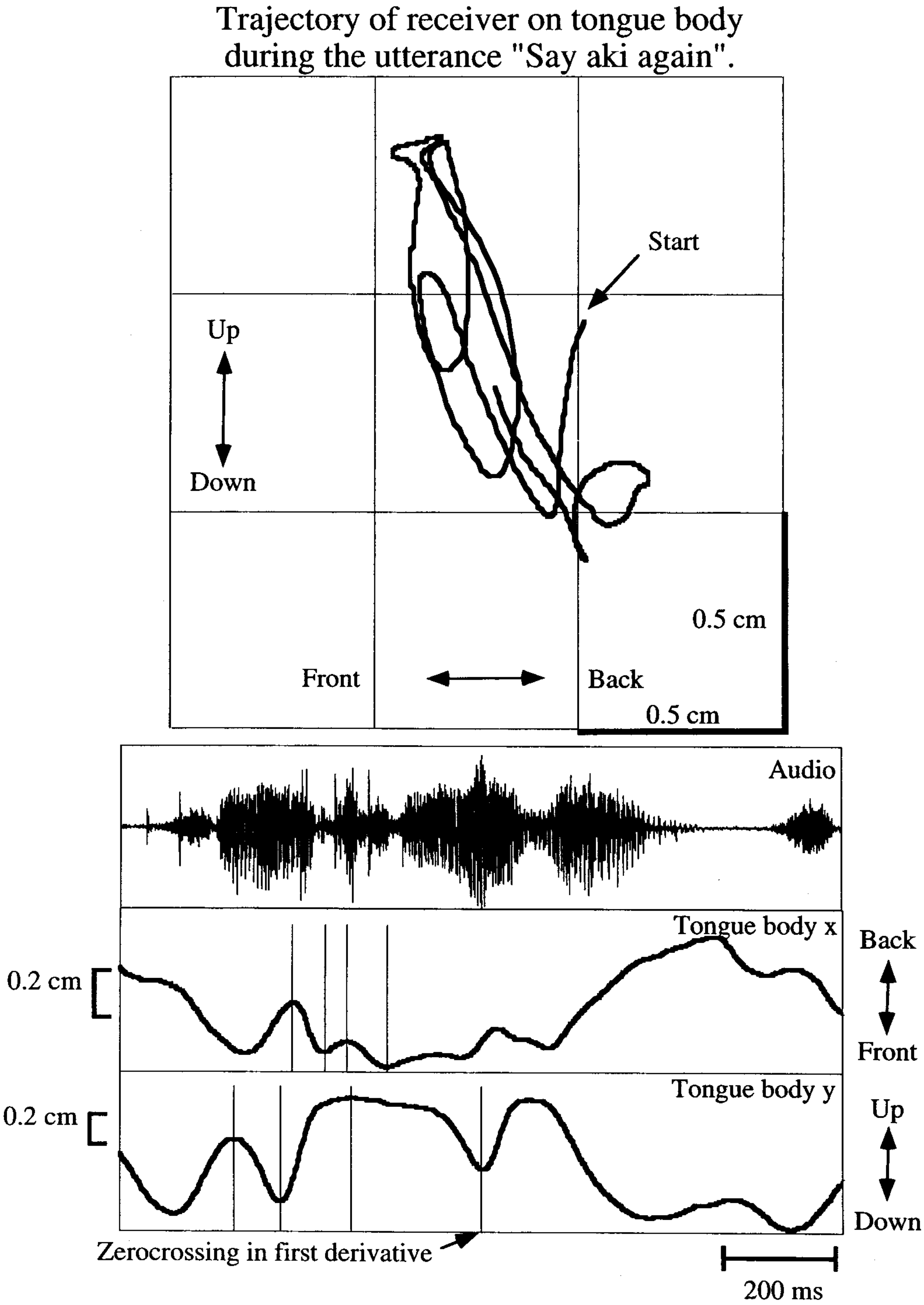
As long as movements are measured in a single dimension, this approach may not be too problematic. However, when studying movements in two or three dimensions, we are facing a more difficult problem. For example, if one is interested in examining tongue behavior during the production of velar stops, as illustrated in Figures 1 and 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. 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 movement 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:

$$\text{Tangential velocity:}\quad \upsilon = \sqrt{(\dot{x}^2 + \dot{y}^2)}$$

$$\text{Curvature:}\quad c = (\dot{x}\ddot{y} - \ddot{x}\dot{y}) \,/\, \upsilon^3$$

These signals have proved useful 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



Trajectory of receiver on tongue body during the utterance "Say aki again".

Figure 2. The top panel plots the trajectory of the tongue body receiver during a production of the utterance "Say aki again". The bottom panel shows the corresponding time plots of audio signal, x position and y position.

points in time for measurements. 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 rotational direction of the movement, negative for clockwise movement and positive for counterclockwise movement. Hence, changes in the direction of articulatory trajectories can be obtained from zero crossings of curvature. This figure, and the following three figures using the same types of plots, further illustrates the usefulness of simultaneous time plots and position-position plots in analyzing articulatory movement trajectories.

Figures 4-6 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 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 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, 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. All the movements in Figures 4 and 5 are counterclockwise during most of their trajectories, as has been noted in earlier work (cf. Houde, 1967; Perkell, 1969; Kent and Moll, 1972; Coker, 1976; Schönle, 1988; Munhall, Ostry, and Flanagan, 1992).

Figure 6 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.

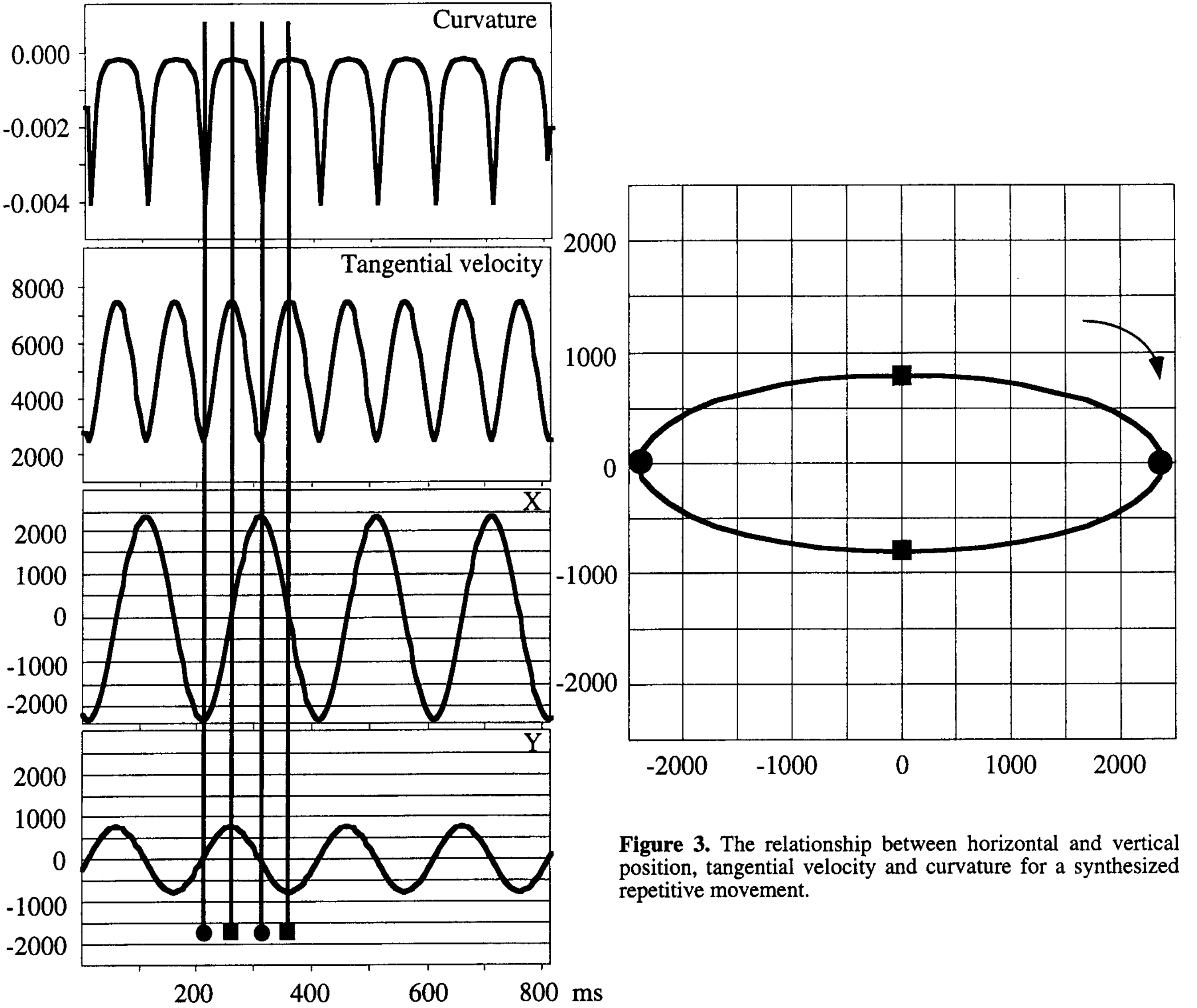


Figure 3. The relationship between horizontal and vertical position, tangential velocity and curvature for a synthesized repetitive movement.

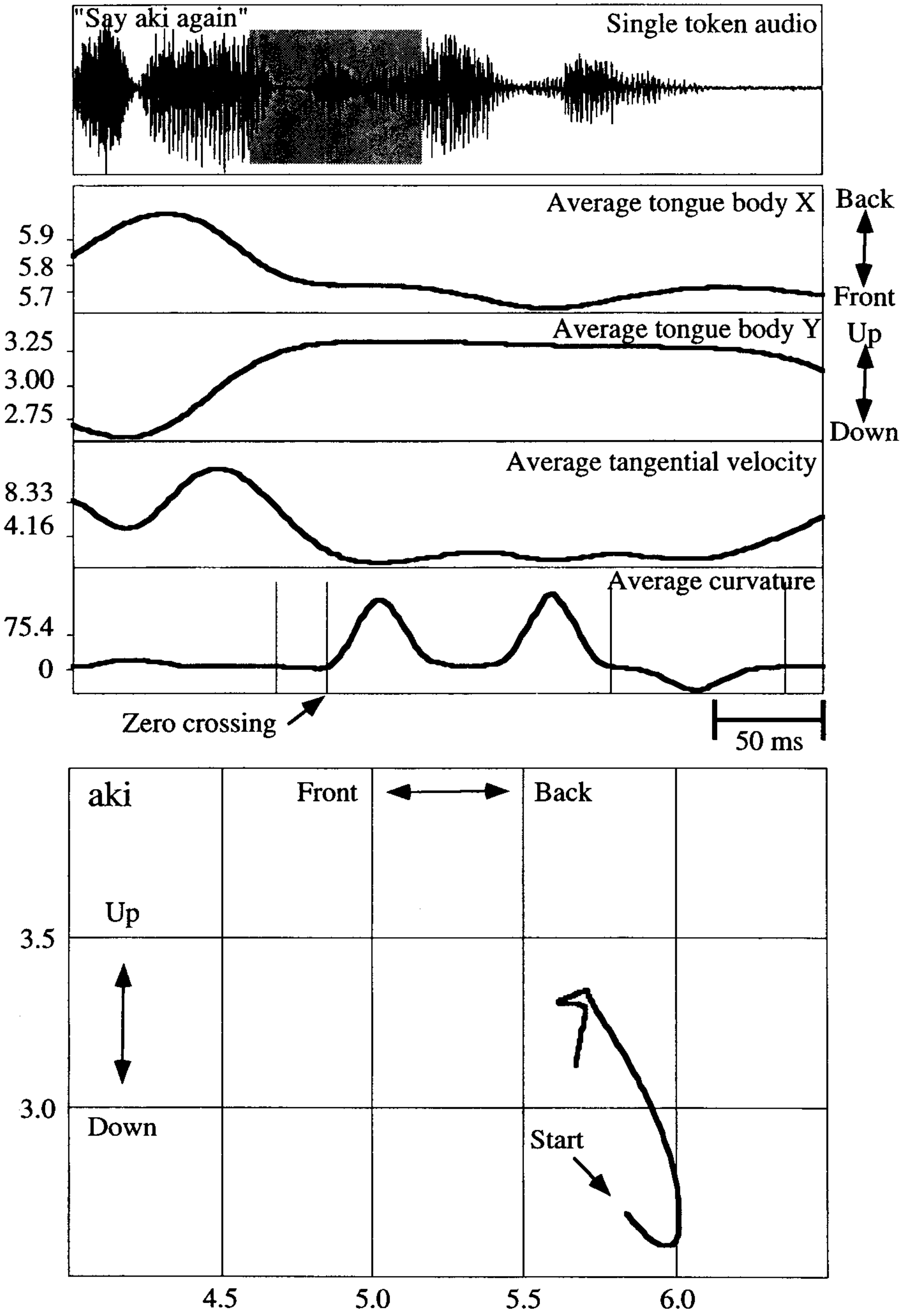


Figure 4. Time and position plots of average tongue body receiver movement during production of the sequence /aka/. The topmost panel shows the audio signal for a single production of the utterance "Say aka again". The shaded part of the acoustic signal shows the location of the temporal window used for signal averaging.

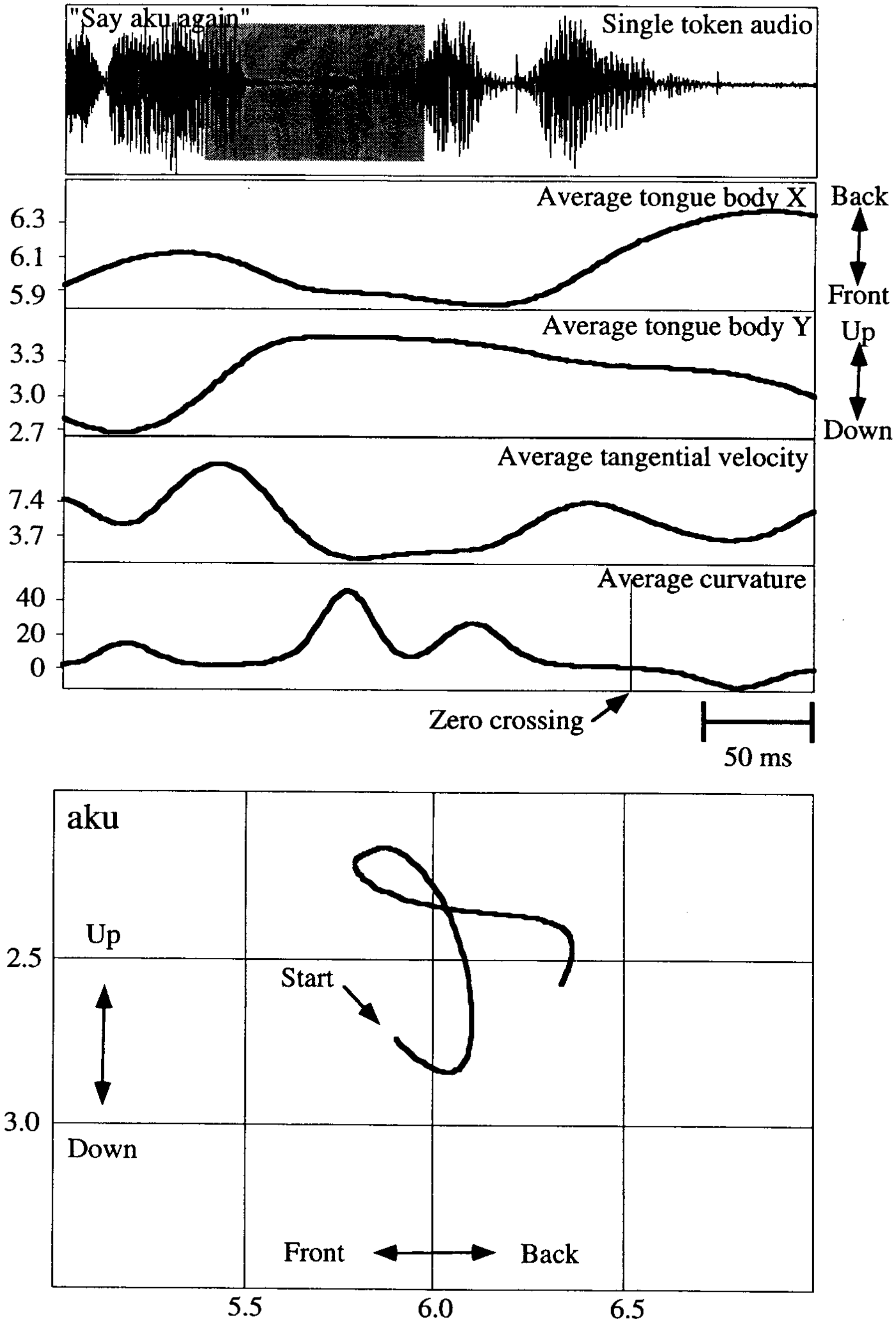


Figure 5. Time and position plots of average tongue body receiver movement during production of the sequence /aku/. The topmost panel shows the audio signal for a single production of the utterance "Say aku again". The shaded part of the acoustic signal shows the location of the temporal window used for signal averaging.

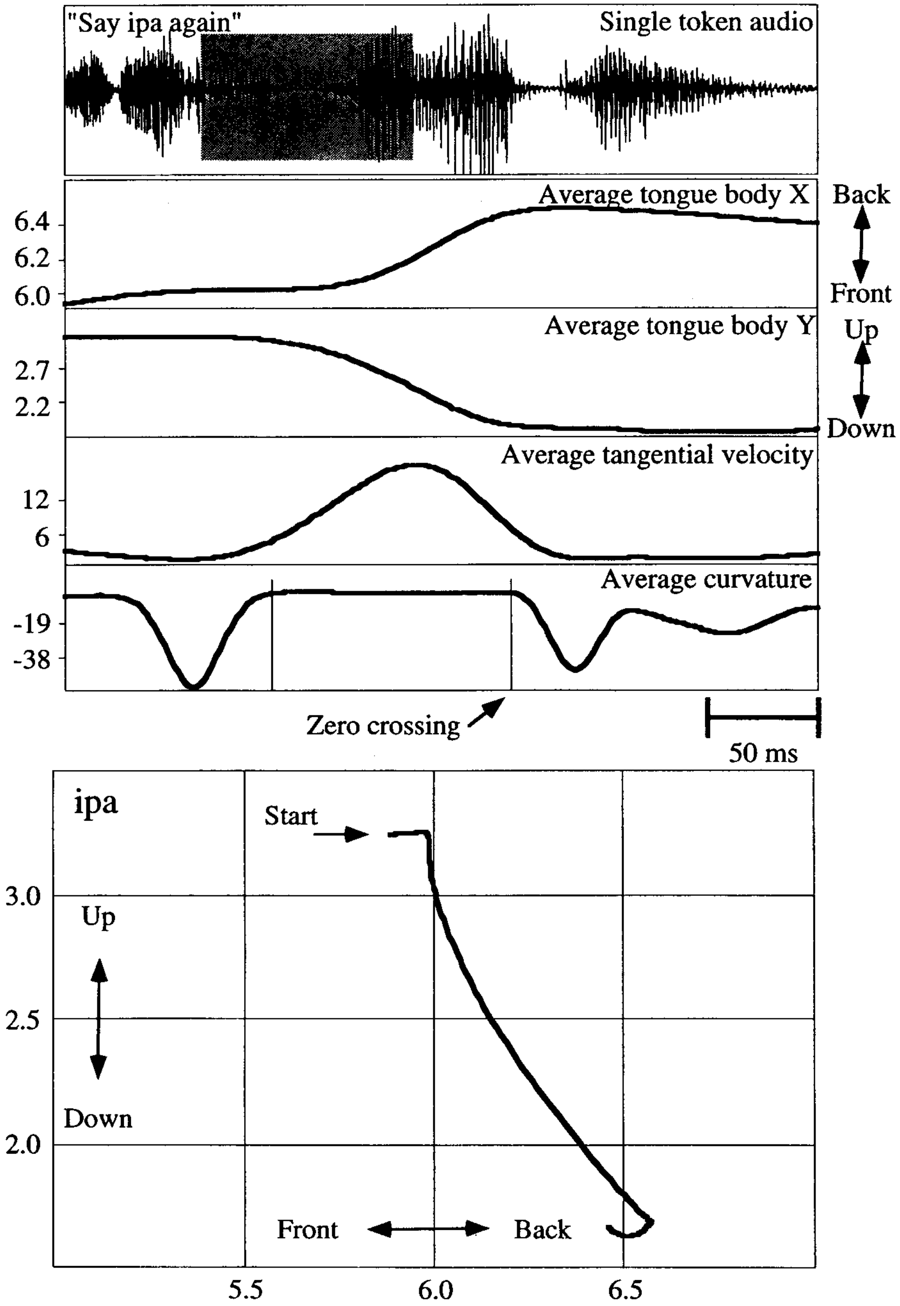


Figure 6. Time and position plots of average tongue body receiver movement during production of the sequence /ipa/. The topmost panel shows the audio signal for a single production of the utterance "Say ipa again". The shaded part of the acoustic signal shows the location of the temporal window used for signal averaging.

In Figures 4 and 5, 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 chose 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 6, 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.

INFLUENCE OF CONSONANT VOICING ON TONGUE KINEMATICS

We will exemplify this approach to the processing of articulatory signals by examining the influence of stop consonant voicing on tongue kinematics. Consonant voicing is well known to influence the acoustic properties of adjacent sounds. For example, the acoustic duration of a preceding vowel is generally longer when the following consonant is voiced than when it is voiceless. These acoustic results are based on measurements made between points identified by amplitude changes and/or voicing onsets/offsets. While these acoustic differences appear to be robust within and across languages (e.g. Chen, 1970), the relationship between acoustic measurements and articulatory kinematics is less well known. That is, the apparent extra time of a vowel preceding a voiced consonant could be taken up by a longer opening movement for the vowel, a longer closing movement for the consonant, or by both movements being longer. Chen (1970) found that the duration of the lower lip closing movement for a bilabial stop was longer for a voiced than for a voiceless stop. In addition, the results presented by van Summers (1987) on jaw movements suggest that different parts of the opening-closing movement cycle for a vowel and a consonant may be influenced differently by consonant voicing for different subjects.

In order to address this issue for tongue kinematics, movements of the tongue body receiver were measured for the VCV sequences where the first vowel was /a/, the middle consonant was /k/ and /g/, and the second vowel was /i/, /u/, and /a/. The measurement procedure is illustrated in Figure 7. This figure shows the audio signal, the horizontal and vertical position and velocity signals, and the tangential velocity signal during the production of the utterance "Say aka again". Points of measurements were identified in the tangential velocity signal. In Figure 7, the two points labeled in this signal correspond to minimum tangential velocity during the first vowel /a/ and minimum tangential velocity during the middle consonant /k/. From the position signals, it can be seen that the first point corresponds to a relatively more back and low position of the receiver, while the second point corresponds to a more front and high position of the receiver. Recall from Figure 1 that the tongue body receiver moves upward and forward during the transition

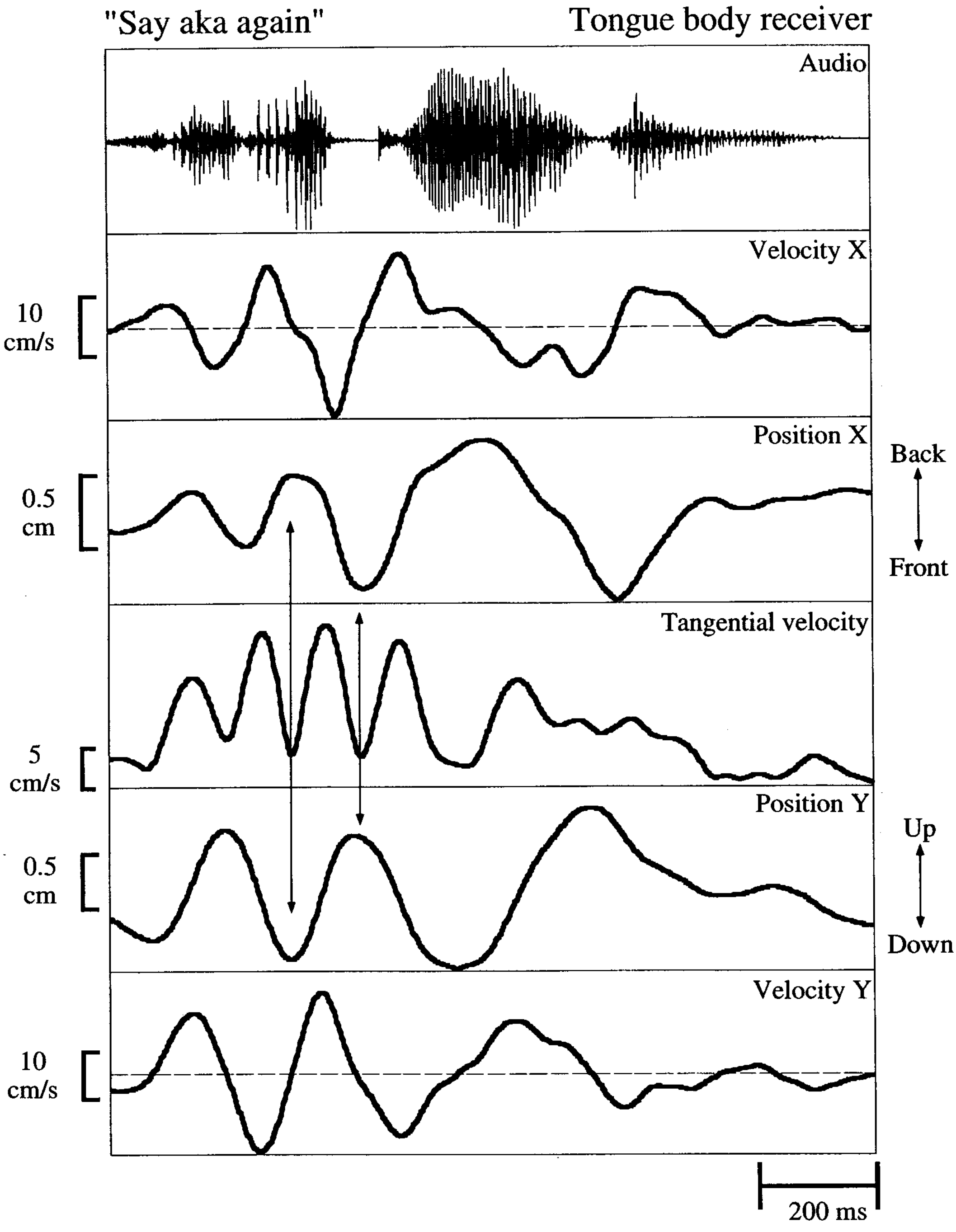


Figure 7. Plots of audio signal, horizontal and vertical tongue body receiver position and velocity signals and tangential velocity for the utterance "Say aka again". The arrows indicate points of minimum tangential velocity used for measurements.

from the vowel to the consonant. The temporal interval between these points was measured as an index of movement duration. Movement displacement was measured in the following way. At the points in time identified by minimum tangential velocity, the horizontal and vertical positions of the tongue body receiver were obtained from the corresponding signals. The Euclidean distance between these positions was taken as a measure of displacement. Note that this measure represents a straight line between movement onset and offset position, whereas the actual trajectory has a curved path, as can be seen in Figure 1. In addition to these measures of movement displacement and duration, peak tangential velocity of the movement was measured.

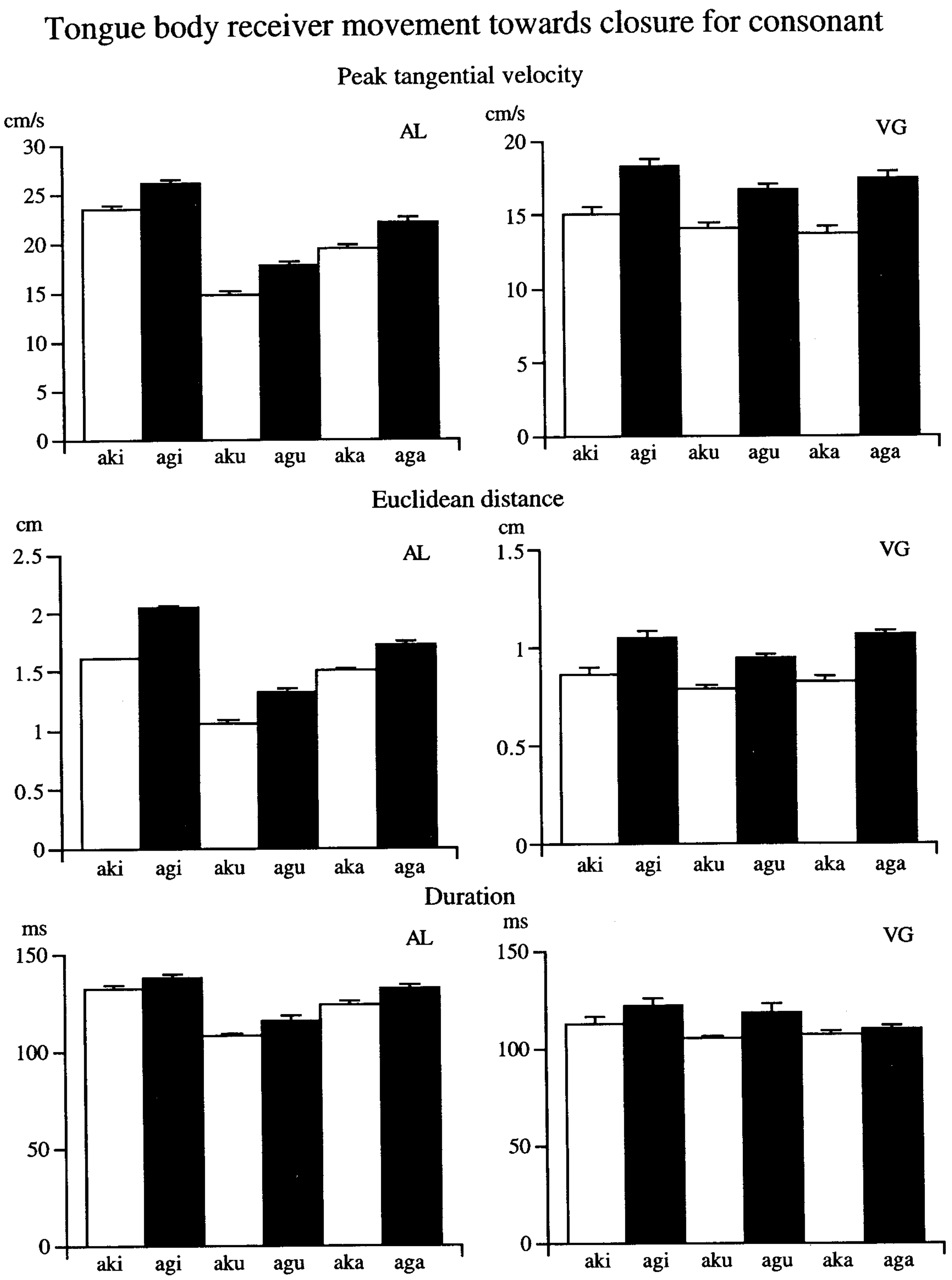
A two-way analysis of variance with consonant voicing and the quality of the second vowel in the VCV sequence as main effects was used to assess influences on movement kinematics. The degrees of freedom in the ANOVA are 1,54 for voicing and 2,54 for vowel and interaction. Post hoc analysis of differences was carried out using pairwise t-tests (Bonferroni procedure). A p-value of ≤ 0.05 was adopted as significant.

Here, we shall concentrate on the effect of consonant voicing; the effect of the quality of the second vowel will be discussed in less detail. The results for the movement of the tongue body receiver towards closure for the consonant are summarized in Figure 8 for the two subjects; this figure shows the mean and the standard error of the mean. From Figure 8, it appears that peak tangential velocity is reliably higher when the following consonant is voiced. The results of the ANOVA indicated that both voicing and vowel were significant main effects for both subjects, with no reliable interaction. The F values for subject AL were 68.67, 245.68, and 0.11 for voicing, vowel, and interaction, respectively. The corresponding values for subject VG were 80.51, 4.82, and 0.8.

As peak velocity of movement has commonly been found to scale with movement displacement, it is of interest to compare the displacement of the raising movement towards consonantal closure across voicing conditions. The plots in Figure 8 shows that movement displacement is reliably greater for the voiced consonant for both subjects. Both voicing and vowel were significant main effects for both subjects with F values of 184.43 and 262.76 for subject AL and 72.56 and 6.34 for subject AL. There was a significant interaction between voicing and vowel for subject AL ($F = 7.14$), but not for subject VG ($F = 1.1$).

These results indicate that peak tangential velocity and displacement are larger for the raising movement when the consonant is voiced. Figure 8 also shows that the duration of this movement is longer when the consonant is voiced. Voicing and vowel had significant main effects on movement duration for both subjects ($F = 26.13$ and 78.98 for subject AL; $F = 11.76$ and 5.42 for subject VG), with no interaction ($F = 0.53$ and 1.26 for subject AL and VG). On the other hand, post hoc comparisons within vowel context and across voicing conditions revealed that the voiced voiceless difference was significant only when the second vowel was /a/ for subject AL, and in no contexts for subject VG.

The results for the raising tongue body movement towards consonantal closure thus show that the peak tangential velocity is reliably higher, the displacement is reliably larger, and the duration tends to be longer when the consonant is voiced. The difference in displacement could be related to a different vertical and/or horizontal position at the onset of the raising movement, a different horizontal and/or vertical offset position, or a combination of both. Figure 9 presents a plot of mean onset and offset positions of the raising movement for all voicing and vowel contexts; the error bars represent the standard error of the mean. Since the tongue body receiver moves forward and up (cf. Figures 1, 3, and 4), the onset positions are in the lower right of the plots, while the offset positions are in the upper left. From Figure 9, it is apparent that the tongue body receiver has a lower vertical onset position for both subjects when the consonant is voiced than when it is voiceless. The effect of voicing and vowel on vertical onset position was significant for both subjects, with a reliable interaction for subject AL but not for subject VG. For



Tongue body receiver movement towards closure for consonant

Peak tangential velocity

Euclidean distance

Duration

Figure 8. Results for movement towards closure for consonant (mean and standard error of the mean).

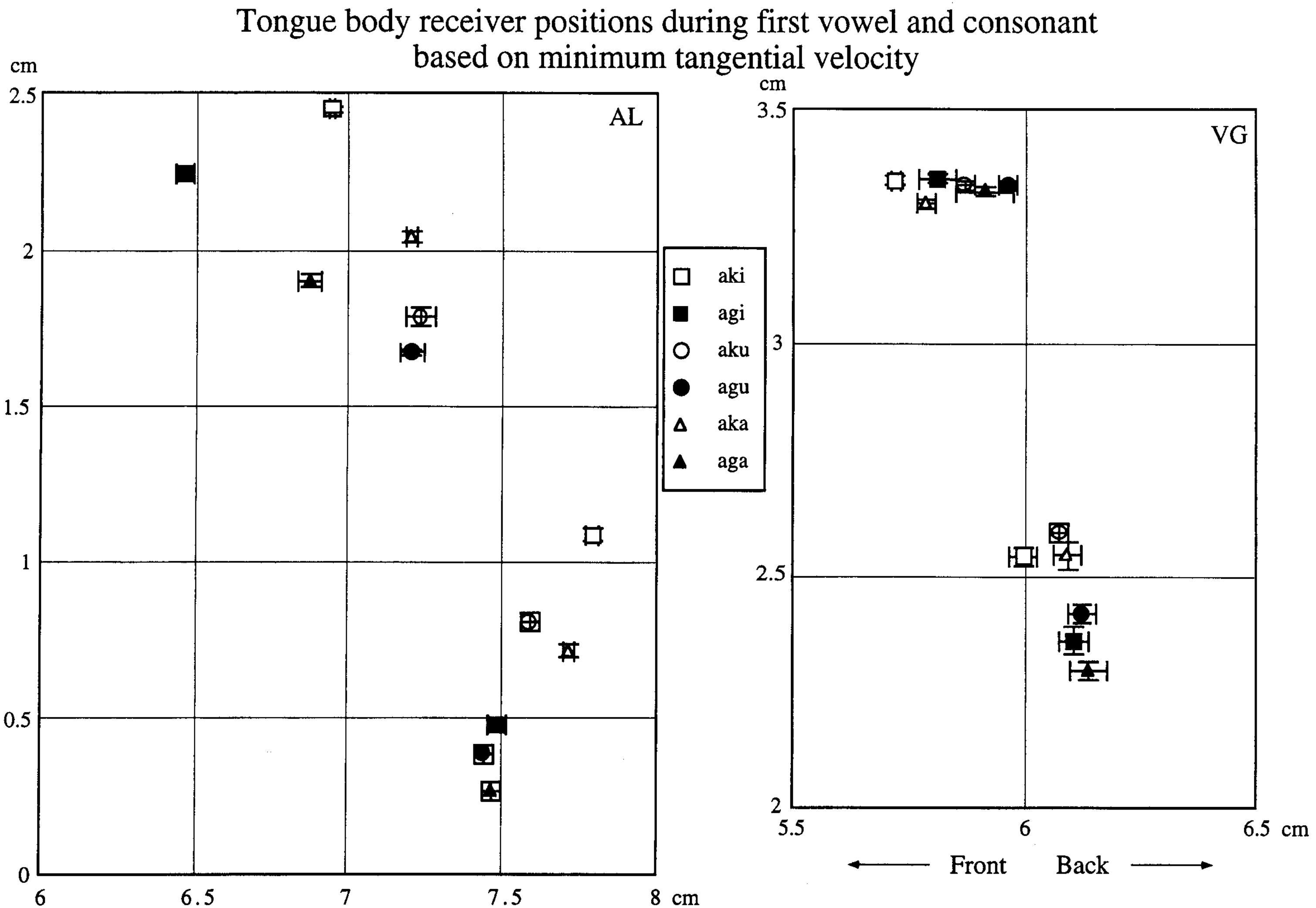


Figure 9. Plot of tongue body receiver positions during the first vowel and at consonantal closure based on minimum tangential velocity. Vowel positions are in the lower right, consonant positions in the upper left (mean and standard error of the mean).

subject AL, the F values were 566.82, 67.68, and 8.31. The corresponding values for subject VG, were 100.67, 6.05, and 1.26.

For the horizontal onset position, both voicing and vowel were significant main effects for subject AL (F = 127.89 and F = 11.68), with a reliable interaction (F = 5.0). For subject VG, on the other hand, only voicing was a significant effect (F = 7.2) but vowel was not (F = 2.25), with no interaction (F = 0.68). Furthermore, the post hoc tests showed the voiced voiceless difference to be significant in all vowel contexts for subject AL, but in none for subject VG. Note that for subject AL, the horizontal onset position is more forward when the consonant is voiced.

The vertical offset positions in Figure 9 tend to be lower for subject AL when the consonant is voiced, whereas the results for subject VG do not show any apparent differences. The analysis of variance revealed significant main effects of voicing (F = 110.94), vowel (F = 604.09), with a reliable interaction (F = 3.67) for subject AL. For subject VG, vowel was the only significant main effect (F = 16.51), while voicing was not (F = 2.73).

The horizontal offset position was significantly influenced by both voicing and vowel for both subjects (voicing: F = 61.19 and F = 17.12; vowel: F = 111.31 and F = 12.06). There was an interaction for subject AL (F = 23.0), but not for subject VG (F = 0.19). The post hoc analysis revealed a significant difference in horizontal offset position only for the /i/ and /a/ vowel contexts for subject AL. In these cases, the offset position is more forward in the voiced consonantal context.

The data plotted in Figure 9 suggest that the larger displacement of the tongue body receiver during the closing movement is mainly due to a lower onset position. For subject AL, the vertical offset position was also lower in the voiced consonantal environment. However, the vertical difference between voicing condition within vowel context is larger at the onset than at the offset position, 0.4 - 0.6 cm compared to 0.1 - 0.2 cm. Note also that for subject AL, the horizontal offset position is more forward in the voiced context when the second vowel is /i/ and /a/.

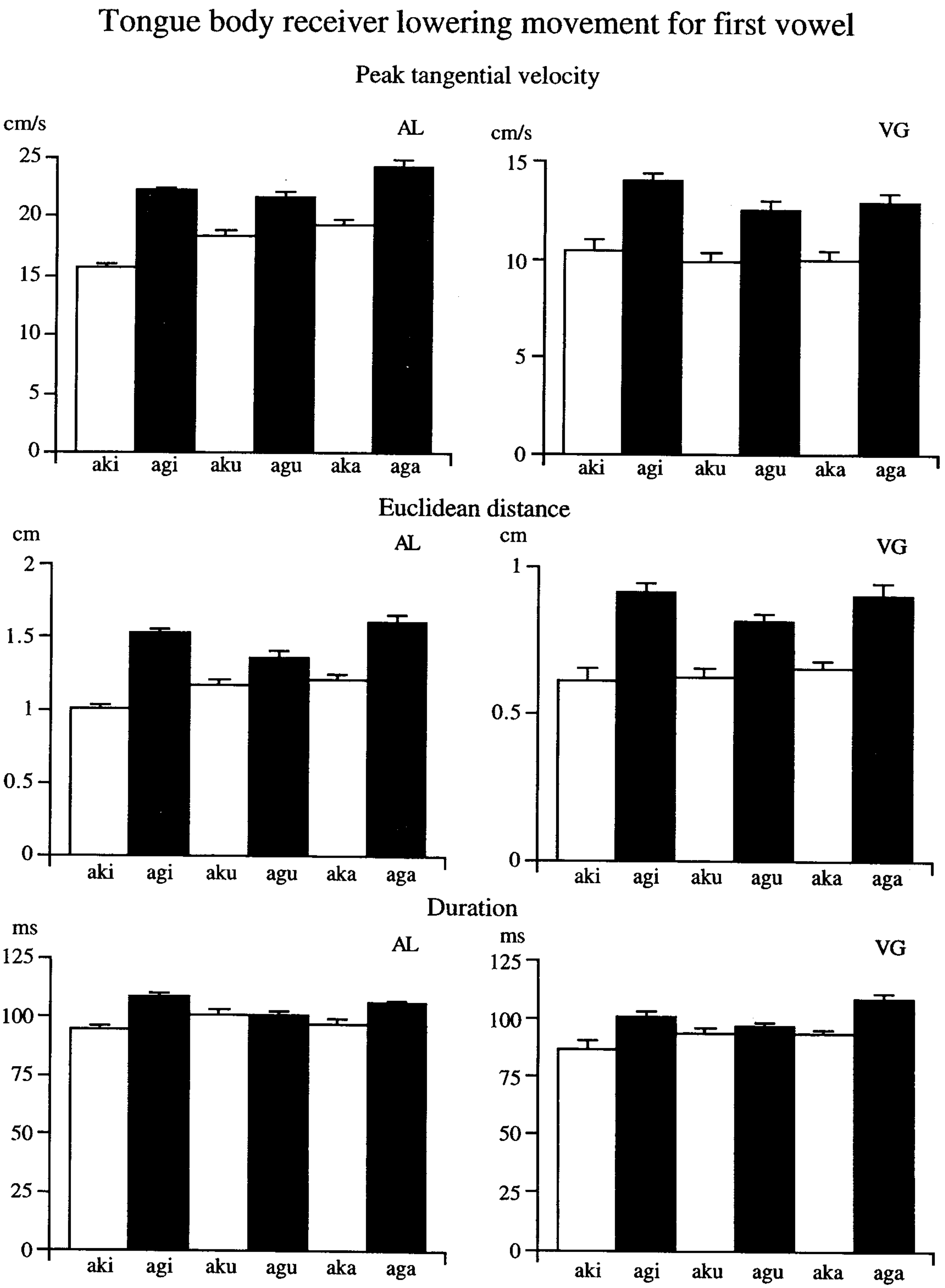
The difference in onset position between the voiced and voiceless consonantal contexts strongly suggests that the opening movement for the vowel is affected by the voicing status of the following consonant. Thus, the properties of this opening movement were analyzed.

The onset of the movement was taken as the point in time where the minimum tangential velocity of the tongue body receiver occurred during the second component in the diphthong in "Say". Examination of Figure 7 shows that this point in time corresponds to a relatively more frontal and higher position of the receiver.

The results for the opening movement are summarized in Figure 10. Peak tangential velocity of the opening movement appears to be higher when the following consonant is voiced. The analysis of variance showed voicing to be a significant main effect for both subjects (AL: F = 211.2; VG: F = 61.51). Vowel was a significant effect for subject AL (F = 23.5), but not for subject VG (F = 2.5). There was a reliable interaction for subject AL (F = 8.37).

Movement displacement was also larger in the voiced context. Voicing was a significant effect for both subject AL (F = 159.93) and subject VG (F = 77.63). Vowel was a significant effect for subject AL (F = 9.53), but not for subject VG (F = 1.63), with a significant interaction for subject AL (F = 11.53).

Movement duration was also affected by consonant voicing. Figure 10 shows it to be longer in the voiced context. For subject AL, voicing was a significant main effect (F =



Tongue body receiver lowering movement for first vowel

Peak tangential velocity

Euclidean distance

Duration

Figure 10. Results for opening movement for first vowel (mean and standard error of the mean).

25.96), vowel was not (F = 0.23). The results for subject VG showed the effect of both voicing and vowel to be significant (F = 28.35 and F = 4.37), with no reliable interaction (F = 4.11). The post hoc tests showed that the durational difference between the voicing contexts was significant for both subjects when the second vowel was /i/ and /a/, but not when the vowel was /u/.

In summary, the present results suggest that both the opening and closing tongue body movement for the first vowel and middle consonant in a VCV sequence are affected by the voicing status of the consonant. Both movements have consistently higher peak tangential velocity, larger displacement and often longer duration when the consonant is voiced than when it is voiceless. The present results for tongue movement converge with those obtained for lip and jaw movements in other experiments in showing longer movement durations associated with voiced consonants. They differ, however, in showing higher movement velocities for the voiced consonants. Studies of lip and jaw movements have often reported higher velocity for voiceless consonants (e.g. Chen, 1970; Sussman, MacNeilage and Hanson, 1972; Fujimura and Miller, 1979; van Summers, 1987; Gracco, in press). The present results on tongue movement velocity agree with those reported by Kent and Moll (1969), who also noted a higher velocity in a voiced consonantal context.

According to Figure 9, the receiver offset positions for subject AL show quite large variations in vertical position, while the same positions for subject VG are much more tightly clustered. Since the hard palate forms a boundary and a closure was made for the consonant, this variability may seem puzzling. The most likely explanation is that the receiver positions on the tongue differed for the two subjects, in particular with respect to the part of the tongue that was used in making the tongue-palate closure. Receiver placement was made without regard for anatomical differences. Hence, differences in receiver positions probably also account for the differences in movement velocity and displacement that were found for the two subjects in the present study.

While limited to two subjects, the present results exemplify the usefulness of magnetometer systems for studies of speech motor control. Data obtained using such systems should be very useful for investigating articulatory-acoustic relationships.

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