

Interarticulator Programming in Speech Production

Anders Löfqvist

Lund University, Lund, Sweden

and

Haskins Laboratories, New Haven, CT, USA

E-mail: lofqvist@haskins.yale.edu

ABSTRACT

This paper presents some issues in interarticulator programming in speech production, using as an example the production of a vowel, a bilabial stop consonant, and a vowel. The mechanism for making the labial closure is presented as well as the control of the duration of the closure. An examination of the coordination of the tongue movement from the first to the second vowel with the lip movements for the consonant shows that most of the tongue movement occurs during the oral closure. Finally, the coordination of oral and laryngeal gestures in voiceless consonant production is discussed.

1. INTRODUCTION

Speech production requires the control and coordination of several systems: the respiratory system, the larynx, the lips, the jaw, the tongue, and the velum. Variations in interarticulator timing are used in many languages to make linguistic contrasts, e.g., the timing between the larynx and upper articulators in producing contrasts of voicing and aspiration. This paper presents some experimental approaches to the study of interarticulator programming in speech, using as an example the production of a sequence of a vowel, a labial stop consonant, and a vowel. In producing such a sequence, a speaker has to do two or three tasks: move the tongue between the positions for the first and second vowels; close and open the lips for the stop consonant; if the stop is voiceless, open and close the glottis. In the following, we will examine the coordination and control of these articulatory processes.

2. METHODS

Oral articulator movements have been recorded using a magnetometer system [1]. The signals have been corrected for head movements and rotated to bring the subject's occlusal plane into coincidence with the x-axis. Laryngeal movements, glottal abduction and adduction, have been recorded using transillumination of the larynx [2]. For perturbing lip movements, a paddle resting on the lower lip and connected to a motor was activated to pull the lip downward [3]. Simultaneous acoustic recording have also been obtained. Some issues in the processing of movement signals are discussed in [4].

3. RESULTS

a. Closing the lips

The upper and lower lips and the jaw assist in making the oral closure for the labial consonant. At the moment of oral closure, both the upper and lower lips are moving at almost their peak velocities. When they collide, tissue compression occurs that makes the air tight seal for the stop consonant. Lip movements for the labial closure are shown in Figure 1.

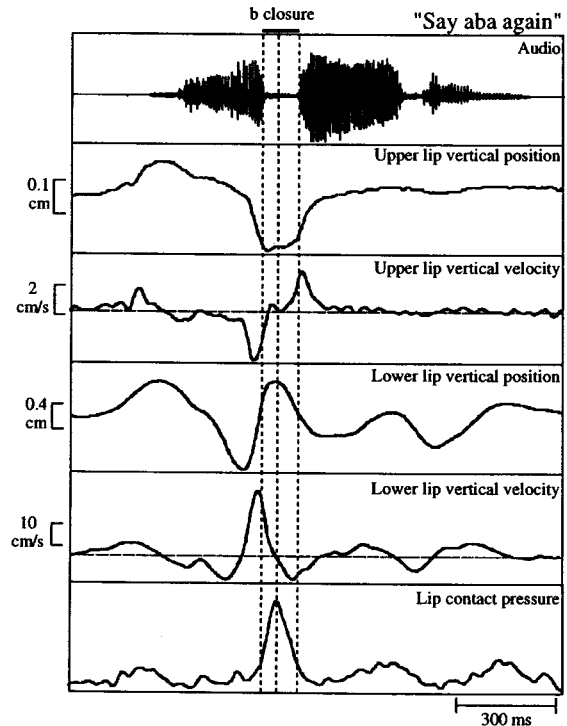


Figure 1. Lip movements during "aba". The signals represent from top to bottom: audio, upper lip vertical position, upper lip vertical velocity, lower lip vertical position, lower lip vertical velocity, and contact pressure between the lips.

Figure 1 presents vertical lip movements, the acoustic signal and the contact pressure between the lips for the sequence "aba". In this figure, the following sequence of

by a Japanese speaker. Several observations can be made about these results. First, the position signals show that the peak position of the lower lip does not occur at the same point in time for the long and short consonants. Second, the velocity signal for the short consonant shows the bell-shape characteristic of simple movements. However, for the long consonants, the velocity of the lower lip shows a change around the second zero crossing. Third, the acceleration signals indicate that the deceleration of the lower lip is momentarily reduced for the long consonants. This adjustment is apparently made to keep the lower lip moving upwards and thus in contact with the upper lip for a longer period of time.

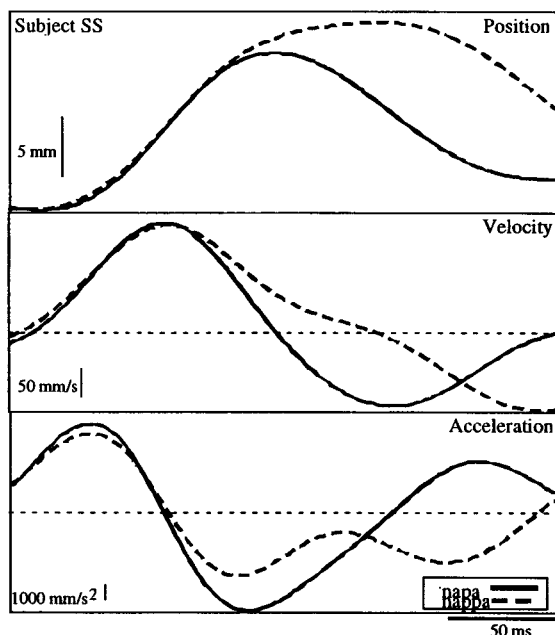


Figure 4. Lower lip position, velocity, and acceleration for long and short bilabial stops produced by a Japanese speaker.

c. Moving the tongue

The tongue movement between the first and the second vowel has to be coordinated with the labial closing and opening gesture. When does the tongue start to move relative to the oral closure? Figure 5 presents the movements of four receivers placed on the tongue in the sequence /abi/, showing the whole trajectory from the first to the second vowel and also the part of the trajectory that occurs during the oral closure. Two things are apparent in this figure. The tongue starts its movement before the oral closure, and most of the trajectory occurs during the closure.

Figure 6 presents a frequency distribution of the interval between the onset of tongue movement from the first to the second vowel and the oral closure for the bilabial consonant. It is evident from this figure that only in less

than 10% of the cases does the tongue begin to move after the closure has occurred. In three other subjects, this never happened [7]. Figure 7 shows the cumulative percentage of the tongue movement during four different intervals of the VC/V sequence, shown in their order of occurrence

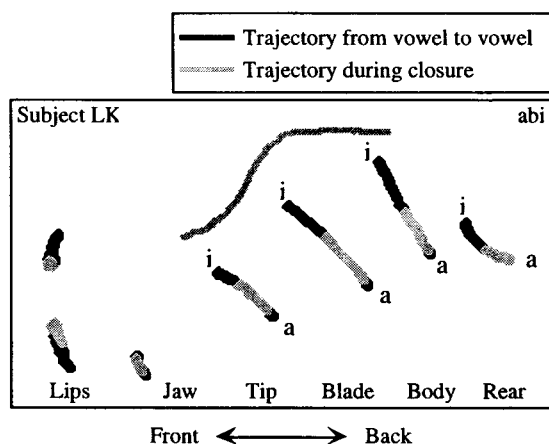


Figure 5. Receiver movements during the sequence /abi/ produced by a speaker of America English. The whole movement between the two vowels is shown and also the part of the movement that occurs during the oral closure. The symbols /a/ and /i/ show the tongue positions for the first and second vowel.

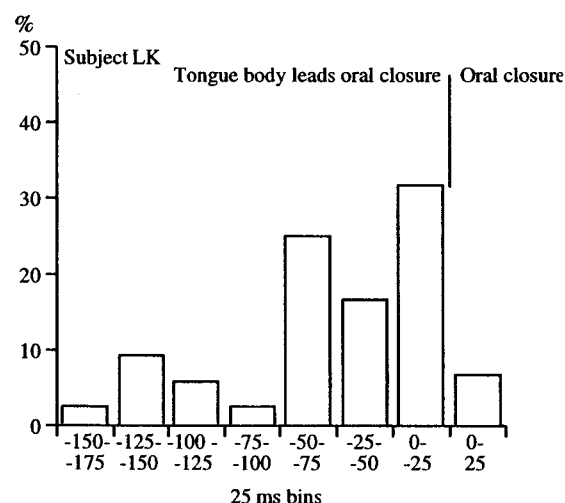


Figure 6. Frequency distribution of the interval between the onset of tongue movement from the first to the second vowel and the oral closure for the bilabial consonant.

from bottom to top in the figure. Overall, the black part of each bar is the largest, indicating that most of the tongue movement took place during the oral closure; for the subject shown in Figure 7, this was 55%. As can be expected, stop consonant voicing influenced the relative amount of tongue movement between the release of the oral closure and the onset of the following vowel. During this interval, the tongue moves a longer path for voiceless

than for voiced stops as a consequence of the aspiration. Conversely, the relative tongue movement during the first vowel to the oral closure is larger for voiced than for voiceless stops, most likely reflecting the longer vowel duration before voiced consonants in American English.

These results are compatible with the idea that there is a temporal window before the oral closure for the labial stop during which the tongue movement can start. Moreover, subjects tend to avoid large tongue movements before and after the stop closure so as not to create perceptual effects of an extra vowel sound [8].

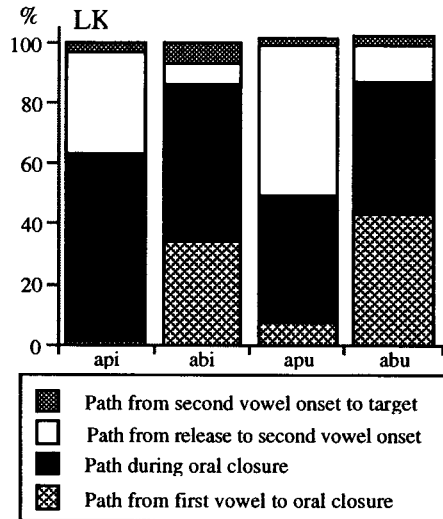


Figure 7. The cumulative percentage of the tongue movement trajectory during four intervals of the VCV sequence, shown in their order of occurrence from bottom to top.

d. Laryngeal gestures

In making a voiceless consonant, a glottal opening gesture is commonly made by abducting and adducting the vocal folds. This gesture assists in both suppressing glottal vibrations and increasing oral air pressure by reducing the glottal resistance. The laryngeal gesture has to be properly phased relative to the oral closing and opening movements for the closure or constriction in the vocal tract. Variations in the timing of oral and laryngeal gestures for making contrasts of voicing and aspiration are shown in Figures 8-11 for four different stop categories. In each figure, the top part shows the activity in the the vocal tract, the middle part shows the glottal gesture, and the bottom part shows the acoustic output. For simplicity, the glottal gesture is shown with the same size, although its size often differs. The figures are based on a number of studies of different languages [9-20].

Figure 8, shows a voiceless aspirated stop, where the glottal gesture begins around the stop closure and the glottis begins to close around the oral release. As a

consequence, the onset of the gottal vibrations for the following vowel is delayed relative to the oral release, resulting in a long voice onset time (VOT). Figure 9 shows a voiceless unaspirated stop, where the gottal gesture is completed during the oral closure, so that the glottal vibrations start shortly after the oral release with a short VOT. Figure 10 shows a voiceless preaspirated stop, where the glottal gesture begins before the oral closure, resulting in aspiration noise before the closure. Figure 11 shows a voiced aspirated, or murmured, stop. Here, the glottal gesture is made around the oral release, resulting in breathy voicing or aspiration noise at the beginning of the vowel following the stop.

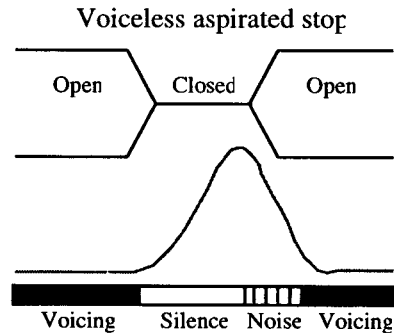


Figure 8. The timing of oral and laryngeal movements in a voiceless aspirated stop.

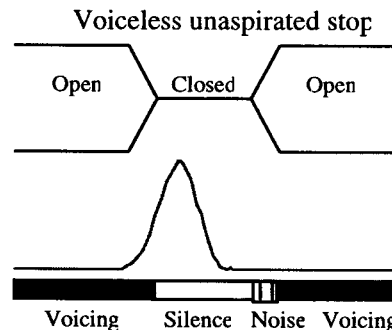


Figure 9. The timing of oral and laryngeal movements in a voiceless unaspirated stop.

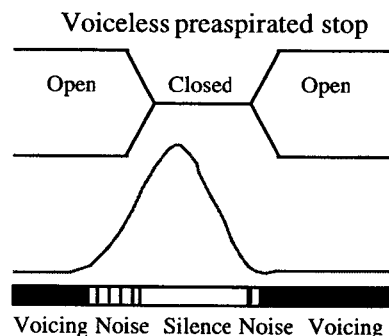


Figure 10. The timing of oral and laryngeal movements in a voiceless preaspirated stop.

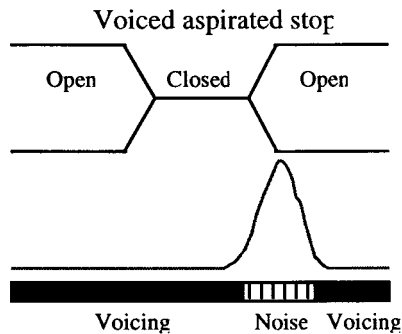


Figure 11. The timing of oral and laryngeal movements in a voiced aspirated stop.

The glottal gesture and its phasing with oral articulators produce a number of source changes in voiceless consonants. At the transition between vowels and voiceless consonants, the laryngeal source varies between modal and breathy voice due to the changes in glottal opening area [21, 22]. This is illustrated in Figure 12. The DC flow, indicated by the black line at the bottom of the

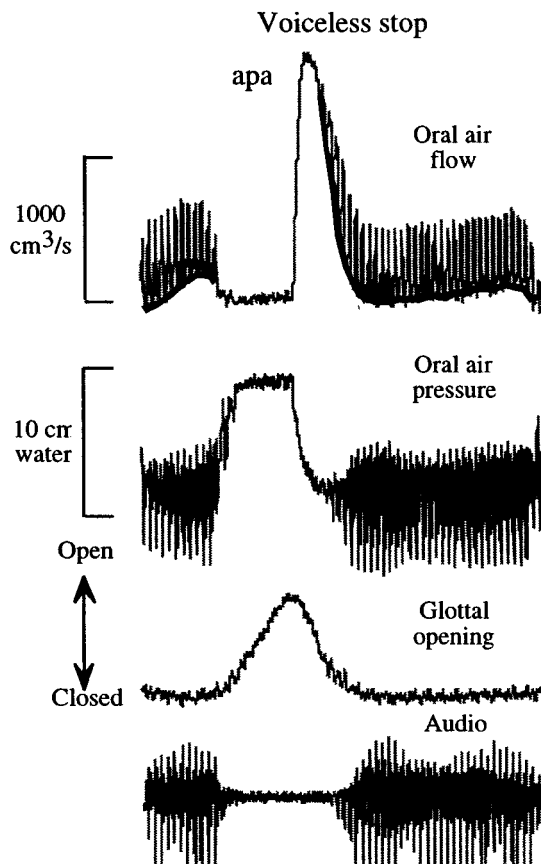


Figure 12. Records of oral air flow, oral air pressure, glottal opening, and audio during the production of a voiceless aspirated stop. The black line at the bottom of the air flow signal indicates the DC flow.

air flow signal increases before the oral closure for the stop and is very high after the oral release. This indicates a more breathy mode of glottal vibrations.

e. Probing programming with perturbations

One valuable experimental paradigm for understanding movement coordination and control is to introduce unexpected perturbations to motor acts in a systematic manner. In a standard experiment, a subject is attached to a small motor that can be activated during some trials to generate a brief load. The rationale for this research is that the nature and time course of the response to the load may reveal the motor organization and reflex structure of the motor act.

This paradigm has been applied to the coordination of oral and laryngeal gestures in speech [3]. When a load is applied to the lower lip during the production of a voiceless bilabial stop, several responses occur. In addition to lip and jaw actions to achieve the labial closure, a laryngeal response was evident by a delay of the onset of glottal abduction, measured relative to the onset of the preceding vowel. This delay was presumably made to maintain lip-larynx coordination at the onset of labial closure, and resulted in an increased acoustic duration of the preceding vowel. However, the period of bilabial closure for the stop was shortened by the perturbation, while the laryngeal abduction-adduction movement increased in duration. The normal phasing between the oral and laryngeal movements was consequently disrupted at the release of the oral closure. As a result, VOT increased in the perturbed trials, since it depends in part on the timing between the oral and laryngeal events in stop production.

These results indicated that the timing between the larynx and the oral articulators was altered by the perturbation. However, this may be due to the experimental design, where the load stay on once it had been activated. Results from a study using a dynamic perturbation and a phase resetting paradigm [23] suggest that the lips and the larynx are coupled together and functioning as a unit.

The goal of phase-resetting analyses [24] is to determine whether perturbations delivered during an ongoing rhythm have a permanent effect on the underlying temporal organization of the rhythm. For speech production, a load can be applied to the lower lip during the production of a repetitive sequence of a bilabial voiceless stop and a vowel. The results showed that the perturbation introduced permanent phase shifts for both the lips and the larynx, after the system had returned to its pre-perturbation steady-state rhythm. In addition to these steady-state shifts in the timing between successive bilabial closing and laryngeal devoicing gestures for the labial stop, steady-state shifts in the relative phasing of these gestures were also found. However, the individual temporal shifts of the bilabial and laryngeal gestures were an order of magnitude

larger than the relative shift between these gestures, and the lips and larynx appear to be phase-advanced as a relatively coherent unit. These results not only demonstrate a resetting of a central "clock" for these utterances, but also imply that the intergestural temporal cohesion is greater within a segment than between segments.

4. ACKNOWLEDGMENTS

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