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Temporal Aspects of Articulatory Movements for /s/-Stop Clusters

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Abstract. Cinefluorographic tracking of pellets on the tongue body, tongue tip, jaw, and lips of three subjects indicates that there are certain basic strategies used for initial /sp/, /st/ and /sk/ clusters. The data reveal an economy of effort in tongue movement, and support the concept of the tongue as a multiple articulator. In addition, the shorter fricative duration of /s/ before /p/ is seen to be a result of early lip closure relative to the occlusions for /st/ and /sk/, which are delayed due to tongue involvement with the /s/.

Consonants, when clustered together, have shorter durations than when they occur as singles [SCHWARTZ, 1970; KLATT, 1971, 1974; HAGGARD, 1973]. This fact is not only of interest to those who formulate rules for synthetic speech, but also to those who wish to specify the articulatory operations of natural speech. Consonant clusters are especially interesting because the individual events are so closely timed that they presuppose a complex motor program. There are several theoretical models of how such programs are organized. KOZHEVNIKOV and CHISTOVICH [1965] have proposed the concept of the 'articulatory syllable' as a basic unit of speech. ÖHMAN [1965] has proposed a vowel-to-vowel organization with the consonants superimposed to account for consonant-vowel coarticulation. HENKE [1966] has proposed a motor organization which scans ahead and initiates as many features of future phonemes as are not contradictory. In KOZHEVNIKOV and CHISTOVICH's model, the syllable commands are bonded, in ÖHMAN's model, the vowel and consonant commands interact but are in some sense separate, and in HENKE's model, the phonemes are discrete but features of them are specified ahead when possible.

In this paper, we present some findings which support KOZHEVNIKOV and CHISTOVICH's observations of coarticulation and HENKE's scan

ahead model, although they do not test the extent of these influences across syllables. ÖHMAN's coarticulation of vowel with consonant, observed spectrographically, is here verified with cine X-ray, along with the idea of the tongue as a multiple articulator.

The focus of this paper is on a comparitive analysis of the clusters /sp/, /st/, and /sk/, achieved by inspection of acoustic information and movement information as recorded on X-ray motion pictures, recorded from three normal speakers of English.

Method

Before noting the features common to all of the speakers, a few of the individual variations should be mentioned. Subject G.B. produces /s/ with the tongue tip low behind the lower incisors and the blade high to form the tongue-palate constriction [BORDEN and GAY, in press], whereas subjects F.C. and G.S. elevate the tongue tip to a position posterior to the upper incisors. In all cases, it was the blade of the tongue, not the tip, forming the constriction; but for the tongue-tip-high subjects, a more anterior portion of the tongue blade was involved. These two variant articulations of /s/ are common.

It was noted too that subject G.S. moves his tongue front and back more than the other subjects, but for all subjects vertical movement was more extensive than horizontal movement; that is, all subjects move their jaws, lips, and tongue primarily up and down with much less front-back movement.

The instrumentation used for subject G.B. has been reported by BORDEN and GAY [1975]. The two subjects recorded since then were recorded and analyzed under a newer system. It is the more recent recording and analysis system that we shall describe in this paper.

Figure 1 shows the position of the subjects for the X-ray films. The subject's head was stabilized and lead pellets of 2.5 mm diameter were attached by means of a cyanoacrylate adhesive to the upper and lower lips and to three positions on the tongue – the tip, the blade and the dorsum – approximately 1 in apart, and a reference pellet was attached at the embrasure of the upper central incisors. The X-ray generator delivered 1-msec pulses at 100 kV to a 9-in image intensifier tube. The film was recorded with a 16-mm camera at a speed of 60 frames per second.

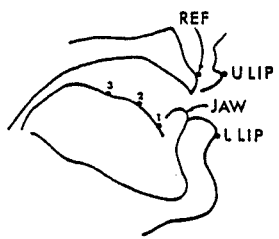

Fig. 1. Lateral X-ray motion pictures record movement of lead pellets attached to the tongue, with pellet on incisors used as reference.

Analysis of the film was semi-automated. The film image was projected onto a writing surface via an overhead mirror system in order to mark pellet positions and frame numbers that were input to a computer via a digitizing tablet. The computer measured the x- and y-coordinate positions relative to the reference pellet position, converted the measurements to millimeter distances, and stored the data on digital magnetic tape. A second program drew axes and plotted the measured data on a display scope from which hard copies were made.

Patterns of Movement

The simplest way to view the strategies used by the subjects for the production of /sp/, /st/ and /sk/ before the low vowel /*a*/, is to refer to schematic representations of relative jaw, tongue and lip movement. The acoustic signal and the movement data are lined up at the moment of closure for the stop consonants.

Subjects had similar strategies for /st/ and /sk/, but one subject differed for /sp/. Therefore, two strategies will be shown for this cluster. The subjects agreed essentially on articulator movement irrespective of the high or low tongue tip difference.

Figure 2 represents the first strategy for producing the utterance /sp*a*p/: the simple synchronous opening of the jaw with the tongue and the lower lip. The upper lip moves relatively little. Notice that the jaw carries the tongue and is free to lower for /*a*/ immediately upon lip closure for the preceding /p/.

Subjects G.B. and G.S. however, used a less streightforward strategy for /sp*a*p/ in which the tongue lowered before the jaw and lips. In figure 3 the line-up point for the acoustic and movement data is lip closure for the first /p/. Note that as the lower lip is being elevated, the tongue is beginning to lower for the /*a*/. The movements are not only asynchronous but in opposite directions, the lip coming up as the tongue is going down. Notice too that the tongue lowers a bit on its own before being carried the rest of the way by the lowering of the jaw.

For /st/, all three subjects used the same strategy, which is schematized in figure 4. Instead of the tongue lowering as a unit, as was the case for /sp/, the tongue tip and blade rise to form the blade-alveolar ridge occlusion for /t/, but the more posterior portion of the tongue is free to descend early for the low vowel. Note too that the blade is high for the /s/ as the tongue tip is rising to take a more active part in the stop closure. (Subject G.B., who produced /s/ with the tongue tip low, uses this basic strategy for /st/, but the tongue tip is kept relatively low for the alveolar stop as well).

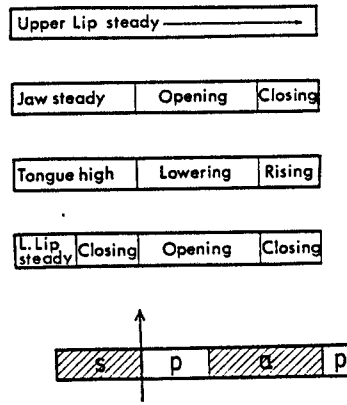

Fig. 2. Schematic of relative movements of articulators for /spɑp/. Strategy 1: synchronous opening of jaw with tongue and lower lip; jaw lowers for /a/ immediately upon lip closure for /p/.

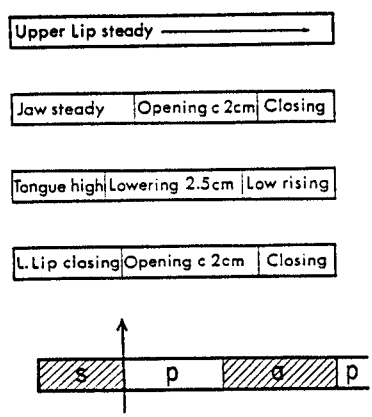

Fig. 3. Schematic of asynchronous movements of articulators for /spɑp/. Strategy 2: Tongue lowers as a unit, before jaw and lips.

If we look at one example of the strategy for /st/, in figure 5, we can see the differential movement of the tongue pellets. The horizontal line represents the position of the reference pellet that was placed between the upper central incisors. The vertical line represents the lip closure for the /p/. The utterance here is /stɑpə/. The pellet on the tip of the tongue represented by a square can be seen to elevate slowly for the fricative /s/, rise even more for the alveolar stop /t/, and rapidly descend

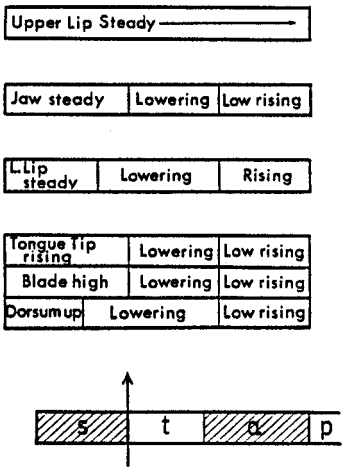

Fig. 4. Schematic of differential tongue movements for /stapə/. Posterior pellet lowers ahead of anterior pellets. Strategy: back of tongue descends early for /a/.

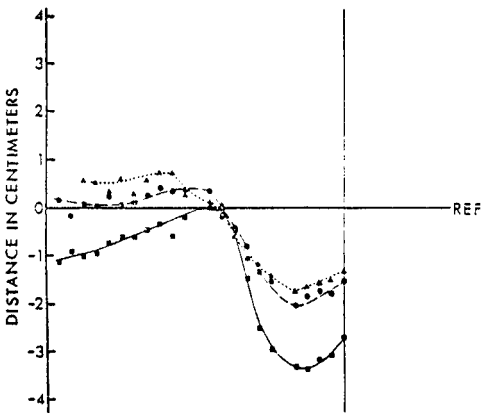

Fig. 5. Raw data of pellet positions for one subject during utterance /stapə/, hand-smoothed. Up-down movement. ■ = tongue 1; ● = tongue 2; ▲ = tongue 3.

for the low vowel /a/. The blade pellet (the circles) also remains high for the /st/ and descends upon release of the stop. The more posteriorly placed tongue pellet, however, represented by the small triangle, can be seen to start its descent for /a/ during the /st/ production, in this case three frames or 50 msec before the more anterior portions of the tongue are free to move. The data presented in the figures have been smoothed.

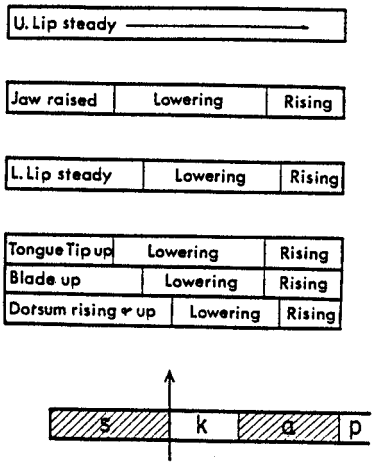

Fig. 6. Schematic of differential tongue movement for /skɑpə/. Strategy: tongue starts lowering (and backing) tip first, then anterior blade, then posterior blade.

Figure 6 shows that for /skɑpə/ as well, the tongue moves differentially and not as a unit. In this case, the more posterior part of the tongue is involved with the stop and the anterior part with the fricative, so that while the tongue tip and blade are up for the /s/ constriction, the dorsum is rising for the /k/ and is not free to lower until the release of the occlusion. Note, however, that first the tip lowers, then the blade. The tongue-tip-low subject followed the same strategy as the other subjects with the exception that the tip remained low, lowering further simultaneously with the blade as the more posterior dorsum of the tongue concluded the /k/ gesture. The jaw movement is interesting in the case of the /sk/ cluster. Recall that for /sp/ and /st/ the jaw remained high during /s/, whereas here for /sk/ it starts to lower during the fricative. Not only do the high lip position necessary for /p/ and the high tongue position necessary for /t/ put constraints upon jaw lowering, but jaw lowering may facilitate the elevation of the back of the tongue necessary for the /k/. Also, for /k/ an elevated mandible is not needed to maintain high intraoral pressure as it is for /p/ and /t/. The high pressure area for /k/ is in the pharynx and back of the oral cavity.

One example of the differential tongue movement for /sk/ can be seen in figure 7. The more anteriorally placed pellets lower before the dorsal pellet, in the case of the tip, by 50 msec and the blade by 17

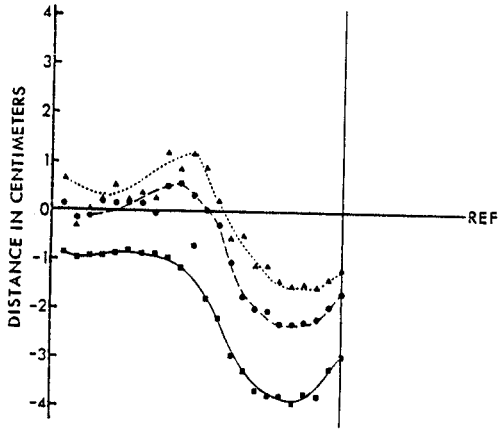

Fig. 7. Raw data of pellet positions for one subject during utterance /skapə/, uncorrected for measurement errors. Up-down movement. ■ = tongue 1; ● = tongue 2; ▲ = tongue 3.

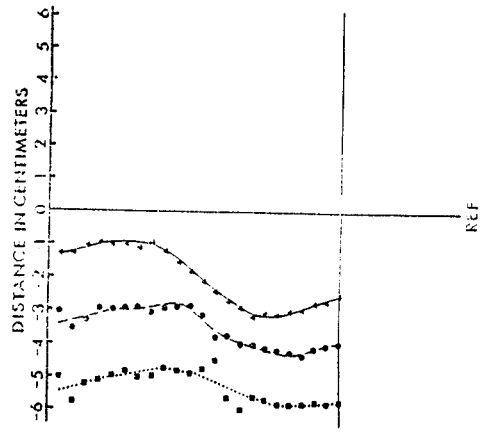

Fig. 8. Raw data of horizontal tongue pellet movement for one subject during utterance /skapə/. Tongue backing proceeds tip first, then blade, and finally dorsum. Front-back movement. ■ = tongue 1; ● = tongue 2; ■ = tongue 3.

msec. Figure 8 represents horizontal tongue movement. This is the subject who used more fronting and backing of the tongue than the other subjects. Here it can be seen that the tongue tip started back for /a/ 85 msec before the dorsum, and the blade 35 msec before the dorsal pellet. It seems then that when the tongue is not involved in the stop

for an /s/-stop cluster, it is free to move toward the vowel immediately after its involvement with /s/ production in /sp/, whereas for /st/ and /sk/, since the tongue is involved in both parts of the cluster, only the uninvolved portions of the tongue are free to move toward the vowel position during the consonant cluster production.

The strategies used by all three subjects for /st/ and /sk/ indicate a remarkable economy of effort in that only those portions of the tongue primarily involved in a high tongue gesture remain elevated. Other parts of the tongue lower for the following vowel as soon as they are free to do so; for /st/, the more anterior portion of the tongue is involved with both /s/ and /t/, but the dorsum lowers early; whereas for /sk/, the reverse is true, with the anterior portions of the tongue lowering for the vowel during dorsal elevation for /k/. These observations are compatible with ÖHMAN's ideas about consonant and vowel coarticulation; that is, movements for the vowel can occur during production of the preceding consonant, and the tongue can be considered to have functionally independent subsystems.

Durations of Movement

It has been reported that the duration of the acoustic noise for /s/ is shortened when clustered with a stop, and that there is a tendency for the /s/ in /sp/ to be shorter than the /s/ in /st/ or /sk/. SCHWARTZ [1970] reported the /s/ before /p/ to be about 129 msec on the average compared to the 154 msec before /t/ and 146 msec before /k/. To assess acoustic durations of the speakers in the present study, spectrograms were measured to the nearest 0.1 in and the measurements were converted into milliseconds. The results are shown in table I. Subjects were consistent in the shortening of the /s/ before the labial stop relative to the palatal stops. The differences were approximately 20 and 10 msec for G.B., 9 msec for F.C., and 18 and 37 msec for G.S. Note that G.S. was consistent in both stop-closure duration and vowel durations.

Figure 9 relates the acoustic data to the movement data by showing the critical movements for the stop closure for /p/, /t/ and /k/. Subject G.S. in this figure is the one who conveniently produced stop closures of 75 msec and vowels of 150 msec across the clusters. Using the closure of the lips after /a/ as the line-up point for the movement comparisons, we can see that the back pellet (marked T dorsum) rises during /s/,

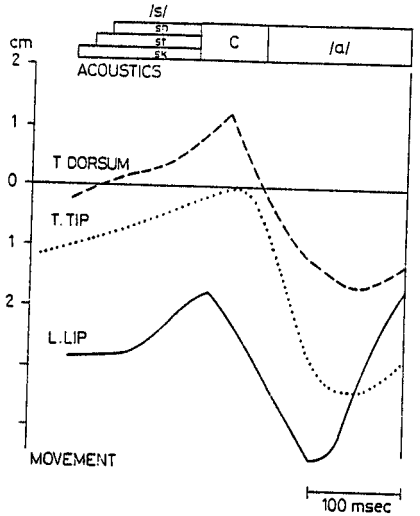

Fig. 9. Subject G.S. Movements of pellets critical for /p/, /t/ and /k/ closure plotted against acoustic signal, lined up at onset of stop. —— = /sp/; . . . = /st/; – – – = /sk/.

Table I. Acoustic durations (msec)

Subjects	/s/	/p/	/a/	/s/	/t/	/a/	/s/	/k/	/a/
G.B.	130	112	168	150	70	200	140	103	200
F.C.	94	112	140	103	131	131	103	103	159
G.S.	94	75	150	112	75	150	131	75	150

continues rising to a maximum for the /k/ closure, and then moves down for /*a*/. The pellet on the tongue tip moves for the /t/, and the pellet on the lower lip for the /p/. The difference in timing is evident here, but it is easier to compare them if we track from left to right by changing the line-up point.

In figure 10, we have lined up the tongue- and lip-movement curves at the onset of /s/, since that is the segment differing in duration. It is obvious that the movement toward closure for the stop is temporally different for /p/, /t/ and /k/. Peak amplitude of lower lip movement for /p/ occurs closer in time to the onset of the /s/ noise than does the peak amplitude of tongue movement for either /t/ or /k/. The /s/ seems to be shorter in the case of /sp/, not because the lips close with any more

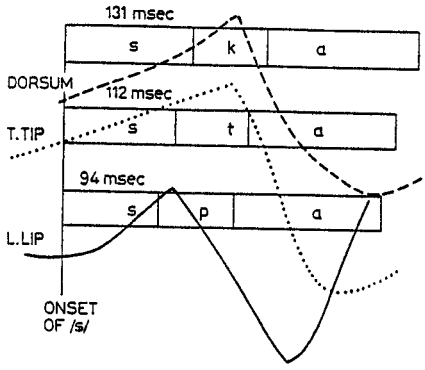

Fig. 10. Movements of pellets critical for /p/, /t/ and /k/ closure plotted against acoustic signal, lined up at onset of /s/. Lip closure for /p/ precedes tongue closure for /t/ or /k/.

force, but because they are not involved in any conflicting gesture. The lips are free to close. The tongue, however, is involved with the /s/ constriction, and movement toward closure is delayed and gradual.

In summary, patterns of tongue, lip, and jaw movement evidenced for /sp/, /st/, and /sk/ support the idea that CCV organization seems to be planned in units of at least syllable length, and that a given articulator, if not committed to a present configuration, is free to move toward a future configuration. The tongue coarticulates with itself, with anterior and posterior portions acting differentially for two different phonemes.

Zusammenfassung

Zeitliche Aspekte in den artikulatorischen Bewegungen für /s/-Plosiv

Kinefluorographisches Verfolgen kleiner Bleikügelchen auf dem Zungenkörper, der Zungenspitze, dem Kiefer und den Lippen von drei Versuchspersonen weist darauf hin, daß gewisse Grundstrategien für anlautende /sp/-, /st/- und /sk/-Gruppen gebraucht werden. Die Daten enthüllen eine Anstrengungsökonomie in der Zungenbewegung und unterstützen den Begriff der Zunge als vielfältiges Ausspracheorgan. Außerdem enthüllt sich die kürzere Geräuschdauer des /s/ vor /p/ als Ergebnis eines frühen Lippenschließens im Vergleich mit den Absperrungen des Luftstromes bei /st/ und /sk/, die dank der Zungenverwicklung mit dem /s/ verzögert werden.

Résumé

Aspects temporels des mouvements articulatoires employés pour articuler des groupes /s/-occlusives

Le tracé cinéfluorographique de grains de plomb sur le corps et le bout de la langue, la mâchoire et les lèvres de trois sujets indique qu'il existe certaines stratégies fondamentales employées pour articuler les groupes initiaux /sp/, /st/ et /sk/. Ces observations révèlent une économie d'efforts dans le mouvement de la langue et soutiennent le concept de la langue comme organe articulatoire multiple. La durée fricative moindre de /s/ devant /p/ s'avère être due au fait que l'occlusion labiale se produit plus tôt que pour /st/ et pour /sk/, ces dernières étant retardées par l'engagement de la langue pour l'articulation de /s/.

Acknowledgments

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