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# Crosslinguistic Cineradiographic Studies of the Temporal Coordination of Speech Gestures

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## Summary

The research programme outlined here is devoted to the analysis of speech gestures from 7 x-ray motion films of speech from 5 different languages (Southern Swedish, British English, West Greenlandic Eskimo, Cairo Arabic and Bulgarian). The issues specifically addressed are (i) the methodology and feasibility of analysing and identifying individual gestures in these languages and assigning them to their respective phonemes, (ii) the organization of movement in these languages, (iii) an evaluation of the observed patterns of temporal coordination in these languages in the light of coarticulation models, (iv) the relation of coarticulation to assimilation, especially the assimilation of vowels to uvular and pharyngeal consonants in Eskimo, vowels to emphatic consonants in Arabic and palatovelar consonants to palatal vowels in Swedish.

## Background

Investigations of coarticulation have typically comprised just one or two articulators (frequently the lips, mandible, tongue blade or velum), exploiting and depending on the technology currently available, such as e.m.g., movement transduction, optical tracking, dynamic palatography, fibrescopy, cinematography, x-ray motion film (automatic pellet-tracking or manually traced pictures as here), interpretation of acoustic features of the speech wave etc. Very rarely, if at all, has work been reported on the dynamic coordination of gestures in all parts of the vocal tract simultaneously.

A typical definition of coarticulation is that articulators are moving simultaneously but for different phonemes, which explicitly implicates a belief in some sort of underlying "segment" that has its physical expression in articulatory behaviour. Indeed, Liberman & Mattingly 1985 insist that some sort of discrete representation is always implied, even for those who would deny it. The classical arguments in favour of discrete underlying segments in this context, which we also share, have been summarized by e.g. Pisoni & Luce 1987 and Löfqvist 1990. Although most authors seem to prefer not to commit themselves nowadays on what such "segments" might be, an abstract definition of the phoneme is adequate for the moment.

Coarticulation as such has been an object of study ever since Menzerath & Lacerda's 1933 pioneer investigation of lip movement and nasal airflow, but the phenomenon had been noticed much earlier by Sweet 1877:56, 60-63, who saw speech sounds as momentary points "in a stream of incessant change" consisting of inevitable simultaneous transitional on- and offglides between them. This remained the accepted paradigm until Joos 1948:104-108 reported different spectra for a vowel phoneme in different consonant environments, which was interpreted as evidence of coarticulation extending beyond the transitions. The Kozhevnikov & Chistovich 1965 syllable model offered an explanation for simultaneous expression of serially ordered phonemes, although subsequent reports e.g. Öhman 1966 appeared to contradict this since the domain of coarticulation was seen to extend into neighbouring syllables and indeed some investigators reported domains of several syllables.

Incompatible legacies of different scientific traditions have led to controversies concerning the domain of coarticulation, the relation of coarticulation to assimilation, and the nature of coarticulation itself, all epitomized in the debate between Hammarberg 1976, 1982 and Fowler 1980, 1983. Overviews of current work on coarticulation and related theoretical topics have also been given by Daniloff & Hammarberg 1973, Kent & Minifie 1977, Kent 1983 and Lindblom 1986.

Models proposed for coarticulation have tended to fall into two main classes depending on whether their driving principle is coproduction or feature-spreading. But opinions also differ as to whether coarticulation is intentional and preplanned input to the speech motor system or instead the physiological consequences of subcortical control constraints and mechanical properties of the articulators themselves. Opinions differ further as to how knowledge and memory access is handled. "Look ahead" versions of models must have access to at least a major portion of the current syntagm, while subcortical models are restricted to whatever information is initially passed down about the current segment.

Coarticulation studies are also an important source of knowledge from which the organization of motor planning can be inferred and the resulting data should provide insights of value to those working in that field.



## Issues to be adressed

*Methodology and feasibility of gesture analysis*

Coarticulation research has typically been concerned with topics like how far ahead a phoneme may be initiated, how long it may be kept going, what and where its boundaries are, and in what sense simultaneous phonemes are serially ordered. All this implies that articulatory and acoustic attributes can be singled out, delimited, identified and assigned to their respective phonemes, which is also a necessary standpoint for the work outlined here. Liberman & Mattingly 1985 pessimistically observe that it is not clear to them how their *invariant phonetic gesture* (a composite of several articulatory movements) might be related to the actual physical movements and to the resulting vocal tract configurations. To that can be added, how the gestures mould the speech signal. An approach is favoured here that embraces both perturbation theory and the quantal nature of speech, as outlined by Fant 1980 and Stevens 1972 respectively. This approach has recently been presented by both Mrayati & Carré 1991 and Wood 1991b. These are all precisely the issues that our previous work has addressed and that the present work should shed more light on.

A growing area of interest is the study of the gestures themselves and of their place in phonological theory (e.g. Browman & Goldstein 1989 and Boyce et al. 1990) and in speech perception (e.g. Fowler 1986, Liberman & Mattingly 1985, Stevens & Blumstein 1981). A gestural approach has also been preferred for our own work on phonological features and problems (Svantesson 1985; Pettersson & Wood 1987; Wood 1979, 1982b, 1991a,b,c, 1992; Wood and Pettersson 1988).

The identification of many manoeuvres is obvious from the traditional phonological feature specifications of the phonemes they express (bilabiality for [b], a coronal gesture for [t] etc.). Other manoeuvres have less obvious functions, for example larynx depression during rounded vowels. Model experiments by Wood 1986 reveal that an important consequence of larynx depression is diminution of undesirable changes in spectral sensitivity arising from lip activity. Yet another puzzling gesture (Wood 1975, 1991a) was a lingual manoeuvre into the pharynx during apical consonants by Swedish subjects.

It is an elementary but necessary step to document the feasibility of gesture analysis. The work so far reported (Wood 1991a) mostly confirms the phonetic tradition that manoeuvres can be isolated and can be assigned to their respective phonemes, but there are occasions when assignment is obscure or ambiguous. The feasibility of isolating and identifying manoeuvres will be systematically checked, the functions of obscure gestures will be elucidated, particular attention will be given to ambiguous situations and procedures will be evolved for resolving such ambiguities. The reliability of results obtained so far will be checked by analysing more data from the same language and the stability of these results across languages will be checked by analysing data from other films.

Functions of gestures will be checked in model experiments in order to compute their contributions to the spectral output. The model was developed by Wood (1979, 1982a, 1991b) and has been used successfully in theoretical experiments on lip rounding and larynx depression (1986), for evaluating tongue features (1982b, 1992) and for checking solutions for vowel reduction in Bulgarian (Wood & Pettersson 1988).

*Continuous movement and steady states*

An old topic of contention is whether or not there are steady states in continuous speech. This is still relevant to coarticulation today inasmuch as steady states would periodically interrupt or punctuate coarticulation patterns, and coarticulation models would need to be able to handle such behaviour. Steady states are no doubt of limited value for perception, since the auditory system is more attentive to changing signals, but their presence in production invites explanation. The first x-ray motion films seemed to confirm the impression of continuous movement and discredit belief in static positions. Moll 1960 reported that "it appears that the articulatory structures seldom, if ever, assume static positions, even during the production of sustained vowel sounds". However, data so far analysed from our films regularly reveal moments when the entire vocal tract is stationary during stressed monophthongs (data from English and Arabic in Wood 1979, and Swedish in Wood 1991a), usually lasting around 12-25ms., and during occasional instances of consonants (Swedish in Lindblad 1980 and Wood 1991), apart from our unpublished observations. The apparent contradiction must be due to the differences in temporal resolution since Moll's facility was working at the then customary 24 frames/s (40ms/frame), a camera speed that would miss virtually all the steady states reported here (the films were made at 75 frames/s, 13.3 ms/frame, providing a resolution sufficient to reveal these brief events).

A more striking discovery reported in Wood 1991a was that the typical utilization of any articulator involved briefer periods of movement and



longer periods of inactivity. The overall impression was one of articulators being marshalled momentarily as needed and left idle when not needed.

The instances of steady states so far found in this data will be checked against further occurrences in the films and any systematic tendencies examined, with a view to resolving this evergreen controversy. Similarly, the behaviour found so far of utilizing articulators briefly and locally and then leaving them idle will be looked at more closely.

*Evaluation of the data in the light of models of coarticulation*

The coproduction approach usually sees coarticulation as a low level phenomenon, the inevitable physiological consequence of e.g. the intrinsic timing requirements of the gestures involved due to constraints of the vocal tract (Fowler 1980). In contrast, Liberman et al. 1967 emphasized the necessity for restructuring phonemes to overcome the inability of the ear to resolve discrete elements arriving at the rates of phoneme flow customary in speech, or of the articulators to produce distinct gestures at such rates. They suggested that "dividing the load among the articulators allows each to operate at a reasonable pace, and tightening the code keeps the information rate high. It is this kind of parallel processing that makes it possible to get high speed performance with low speed machinery...". If such restructuring of articulation is indeed part of the encoding process, as they believe, then it should be under close high level control, i.e. a preplanned and integral part of the programming.

Coproduction models as a class emphasize the simultaneous articulation of especially vowels and consonants, but individual instances of these models can be mutually incompatible. For example, Kozhevnikov & Chistovich 1965, chapt. 4, posit that all the several manoeuvres of the (open) syllable can be initiated at once provided there is no antagonism between them (in which case some gestures must be delayed), whereas Öhman 1966 maintains that coarticulation is precisely the result of the summation of (sometimes) antagonistic consonant features superimposed on a continuous diphthongal vowel to vowel movement. Gesture analysis offers an opportunity to evaluate these two different approaches by comparing how speakers time antagonistic gestures. Data reported in Wood 1991a appear to favour the Kozhevnikov & Chistovich model: clusters of gestures were initiated simultaneously for a new syllable (for K&Ch), antagonistic gestures were sequenced by being delayed (for K&Ch and against Ö), and incompatible gestures for the new vowel were delayed, giving precedence to sequentially earlier consonants (for K&Ch and against Ö, especially against the continuous underlying vowel to vowel movement).

The Kozhevnikov & Chistovich and Öhman models have been acclaimed as universally valid, although they were based exclusively on Russian and Swedish data respectively (which is no different to the more common practice in phonetics of drawing universal conclusions from English data). It is therefore in order to relate the gesture timing patterns exhibited by the subjects of our films to the predictions of these models, and it is particularly valuable that the languages are taken from totally unrelated families – Indo-european (Germanic and Slavonic), Semitic and Eskimo.

*Coarticulation and assimilation*

Each expansion of the domain of coarticulation (as the theory progressed from Sweet to Joos to Kozhevnikov & Chistovich to Öhman) has encroached on the concept of assimilation. Traditionally, (e.g. as early as Jespersen 1897:500), assimilated gestures were said to be started earlier or held longer than the transitions, which was taken to indicate revision of the motor programme. This is essentially the feature spreading approach, where assimilated segments are assigned phonetic attributes found in adjacent segments. Menzerath & Lacerda concluded that their results did not contradict this traditional distinction between assimilation and coarticulation. This paradigm was virtually abandoned after Joos 1948, when assimilation and coarticulation seemed to become synonymous. Thus Daniloff, Schuckers & Feth 1980:326 present one single phenomenon seen from different vantage points: *encoding* for psychologists, *coarticulation* for phoneticians, and *assimilation* for linguists. And yet many phoneticians still seem to feel a need to differenciate between coarticulation as a physiological necessity and assimilation as a language-specific activity (e.g. Fowler 1983). The following example demonstrates that this conceptual distinction can be upheld by limiting the coproduction approach to local transitional phenomena and by applying the feature-spreading approach to more distant contextual effects.

The regular everyday Swedish pronunciation of *en brandbil*, morphologically *#{en}#{brand}{bil}#*, 'a fire engine', is [em brambil], where the nasals are assimilated to the bilabial stops (and the sandwiched /d/ elided). The feature-spreading approach would say that the dental nasals are assimilated by assigning to their programmes bilabiality from the adjacent stops, so that the articulation of the nasal segment is intentionally altered to [m]. The coproduction solution would say that the intrinsic duration of the bilabial gesture of the stops necessitates lip closure already during the nasals, incidentally making them sound like [m]. However, that solution overlooks the habitual and voluntary character of these assimilations, illustrated by the frequently unassimilated pronunciation [en branbil]. The speaker apparently has the option to either initiate the lip closure earlier than necessary or to wait, i.e. the option to reorganize motor planning. The domain of this particular language-specific activity extends beyond the range of the intrinsic demands of coproduction. This argument can be extended to reported coarticulation domains of two or more syllables. For example, nasalization of the first two vowels of *free Ontario* (Moll & Daniloff 1971) appears to be an instance of habitual language or dialect-specific contextual adjustment since it is well beyond the range of inevitable intrinsic physiological constraints on velum movement.



The material available on our films was designed to include cases of assimilation so that the coordination and timing of assimilated gestures might be studied: the assimilation of vowels to uvular and pharyngeal consonants in West Greenlandic Eskimo, of vowels to "emphatic" consonants in Cairo Arabic, and of palatovelar stops to palatal vowels in Southern Swedish. This palatalization of palatovelar stops is an especially critical test as it is frequently cited as an example of coarticulation (e.g. Öhman 1966, Löfqvist 1990), yet the parallel alternation between [x] and [ç] in German is usually called assimilation.

## Materials and procedures

*The x-ray films*

The speech gestures are studied on x-ray motion films of speech that were made at the Lund University Hospital with the assistance of the Röntgen Technology Unit. Each film consists of one 35mm reel of some 3000 picture frames, running time about 40 s/subject at a camera speed of 75 frames/s (13.3 ms/frame): (1) Southern British English, (2) Egyptian Arabic, (3) West Greenlandic Eskimo, (4) Bulgarian (in collaboration with Thore Pettersson), (5) Southern Swedish (in collaboration with Gösta Bruce), (6,7) Southern Swedish (in collaboration with Per Lindblad).

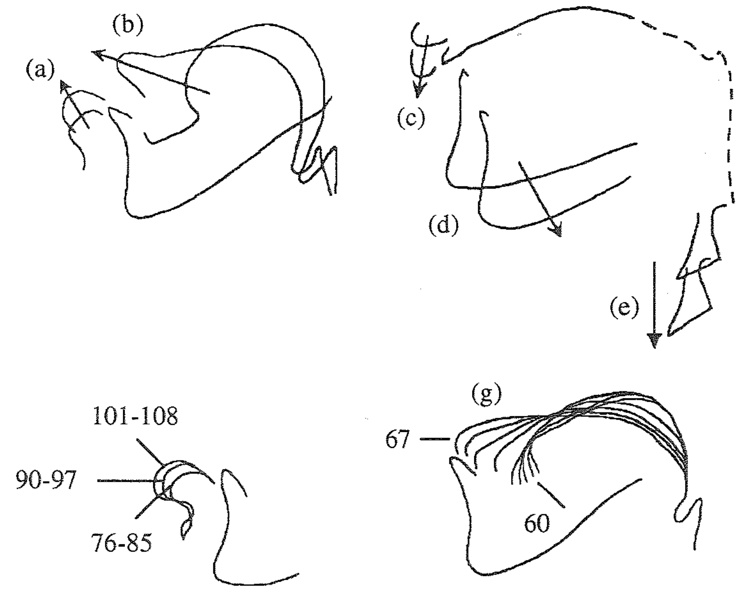


Figure 1. Examples of gestures analysed from midsagittal profiles traced from film 6: (a) lower lip approximation, (b) apex elevation (an example starting from a previous palatovelar configuration), (c) upper lip approximation, (d) mandible depression, (e) larynx depression, (f) lower lip protrusion showing three periods of no movement, and (g) frame by frame apical elevation. From Wood 1991a.

Sound and picture were synchronized by means of a sync pulse (taken from the camera shutter) that appears on every tenth picture frame and that was recorded on a separate tape channel alongside the microphone signal. The general conditions under which the films were made and processed are described in Lindblad 1980:108-109 and Wood 1979, 1982a:27-31.

Details from films (1,2,3) have previously been reported in Wood 1979 on vowel constriction locations, from films (1,2) in Wood 1982b, 1992 on palatal vowels and on tense and lax vowels, from films (1,5) in Wood 1975 on apical and laminal articulations, and from films (6,7) in Lindblad 1980 on fricative production and Wood 1991a on temporal coordination.



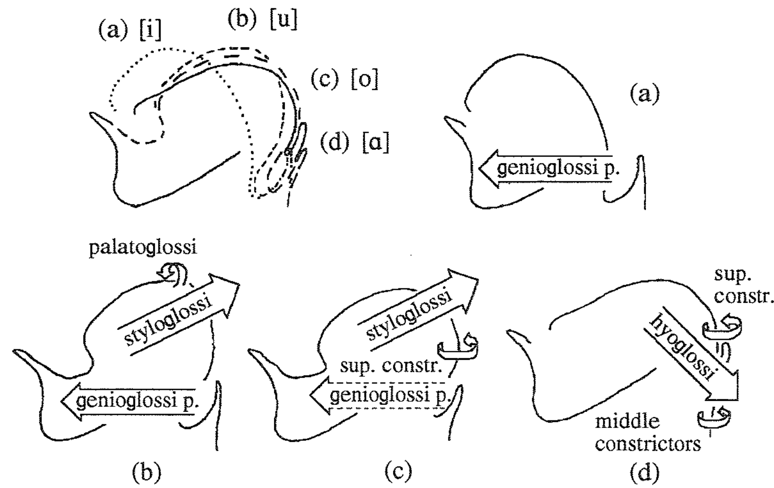


Figure 2. Tongue body manoeuvres: (a) palatal, (b) palatovelar, (c) pharyngovelar (uvular), and (d) low pharyngeal, and the associated muscular activity. From Wood 1979.

*Gesture analysis*

Midsagittal profiles are traced frame by frame throughout selected film sequences, and individual gestures then tracked through each sequence. Strictly speaking, all parts of the vocal tract are floating with respect to each other, and the nearest one can get to a fixed reference structure is the hard palate, which is used here as a reference for mandible, upper lip and larynx movement; lower lip and lingual manoeuvres are then defined in relation to the mandible (Figure 1). This corresponds to the primary (active) movement attributed to the musculature of the articulator itself, and excludes secondary (passive) movement due to some other articulator moving. The gestures tracked are tongue body manoeuvres (palatal, palatovelar, pharyngovelar, pharyngeal, see Figure 2), apical and laminal elevation, mandibular depression, lip protrusion and/or approximation, and larynx depression.

*Articulator movement* is defined as a discernible change of articulator posture when successive midsagittal profiles are superimposed and compared (Figure 1g). A positive movement is in the direction of the named gesture, e.g. *apex elevation* (Figure 1b). A negative movement is withdrawal of the named gesture, e.g. negative *apex elevation* is depression. No movement means that there was no discernible change of articulator posture when comparing successive profiles (Figure 1f). Whenever there were sequences of several frames with an inactive articulator, the current profile was compared with all previous profiles in such sequences in order to check for the possibility of very gradual creeping movement that would otherwise go undetected. Frame by frame resolution of movement is about 1 mm.

*The speech material*
Films (1,2,5,6,7) contain nonsense sentences that conform to the syntax of the respective languages and that are composed of systematic combinations of vowels and consonants. The consonant environments are pVt (film 1), bVd (films 2,5), kVk (film 5) and fricatives (films 6,7). Film (5) also contains a natural sentence. Films 6,7 contain identical material by two subjects.

Films (3,4) contain a large selection of natural words that cover a wide range of vowel and consonant combinations.

Differences between stressed and unstressed syllables are controlled in all films. Focus effects are controlled in films (1,2,5,6,7). The material in film (1) is repeated at normal and fast tempo.

Films (2,3,5) include material on assimilation (vowels to emphatic consonants in film 2, vowels to uvular and pharyngeal consonants in film 3, palatovelar consonants to palatal vowels in film 5).

## Expected outcomes

Apart from the specific issues of gestural timing and coordination, and their relation to coarticulation, speech planning and assimilation, the results are expected to be of relevance for the following fields:

- The methodology of gesture analysis will contribute to phonetic theory generally
- The elucidation of gestures will be valuable for phonological feature theory
- The articulatory studies will add to knowledge of the phonetics and phonologies of these particular languages
- Evaluation of the relative merits of coarticulation models will contribute to an understanding of speech motor control



- Data on normal gesture timing and coordination provide valuable background knowledge for evaluating e.g. apraxias and dysarthrias in speech pathology
- The material itself will be a useful source of data for others working on problems requiring information on time-related vocal tract configurations and temporal organisation.

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